Net protein contribution of beef feedlots from 2006 to 2017

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ABSTRACT: Feedlot efficiency increases as technologies are adopted and new feed ingredients, especially byproducts, become available and incorporated into diets. Byproduct availability increased in response to the renewable fuels standard of 2005, creating substantial amounts of feedstuffs best used by ruminants. Cereal grains have been partially replaced with human-inedible byproducts, as they provide comparable levels of energy in cattle diets. To evaluate the effects of changes in diet and feedlot production practices on net protein contribution (NPC) and human-edible protein conversion efficiency (HePCE) across time, a deterministic NPC model was used. NPC was assessed for the feedlot industry using lot level production data from 2006 to 2017 for eight commercial feedlots. Ingredient and nutrient composition was collected for a representative starter and finisher diet fed for each year from each feedlot. NPC was calculated by multiplying human-edible protein (HeP) in beef produced per unit of HeP in feed by the protein quality ratio (PQR). Systems with NPC >1 positively contribute to meeting human protein requirements; NPC < 1 indicates competition with humans for HeP. NPC was regressed on year to evaluate temporal change in NPC. Feedlots were categorized as increasing NPC (INC; slope > 0) or constant NPC (CON; slope = 0) according to regression parameter estimates. Four feedlots were categorized as INC and four were CON. The rate of change in PQR was similar for CON and INC ($P \geq 0.79$), although rates of change among INC and CON differed for byproduct and cereal grain inclusion ($P \leq 0.01$) across years evaluated. Feedlots categorized as INC reduced HeP consumed by 2.39% per year, but CON feedlots did not reduce HeP consumed each year (0.28%). Cattle received and shipped by INC were lighter than those in CON feedlots ($P < 0.01$). Across years, INC produced more HeP (20.9 vs. 19.2 kg/hd) than CON ($P < 0.01$), and both feedlot types tended to improve HeP gained over time (0.1 kg per year; $P = 0.10$). Differences in slope over time for INC and CON were observed for conversion efficiency of HeP ($P < 0.01$). NPC increased 0.027 units per year for INC ($P < 0.01$) and was 0.94 in 2017. NPC by the feedlot sector improved from 2006 to 2017, decreasing the amount of human-edible feeds required to produce more high-quality protein from beef.

Key words: beef; byproducts, cereal grain, feedlot, human-edible protein, net protein contribution

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INTRODUCTION

Sustainable production systems seek to optimize economic, environmental, and societal

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outcomes. Beef production systems produce high-value protein for human diets, and sustainability of these systems depends on the ability to efficiently produce protein capable of meeting nutrient requirements of humans. Net protein contribution (NPC) is a measure of a system's capability to generate human-edible protein (HeP) with outputs scaled to protein quality (Ertl et al., 2016a; Baber et al., 2018).

NPC assesses a production system's ability to contribute to meeting humanity's protein requirements. An NPC above 1 indicates a system is positively contributing to meeting human protein requirements, and an NPC below 1 indicates a system is in competition with the human population for HeP. Feedlot production potentially competes with humans for HeP as indicated by NPC, which ranged from 0.73 to 1.07 in previous work (Ertl et al., 2016a; Baber et al., 2018). Beef's amino acid profile more adequately meets human protein requirements compared to the amino acid profile of cereal grains (Young and Pellet, 1994). Beef cattle improve the quality of HeP consumed as cereal grains (Ertl et al., 2016a; Baber et al., 2018) and also contribute to both the quantity and quality of protein supply by upcycling human-inedible products (i.e., roughages, byproducts of grain processing) into high-quality HeP.

Beef cattle fed for slaughter typically spend less time in the feedlot phase than in cow-calf and stocker phases; however, the majority of cereal grain consumption in the beef value chain occurs during the feedlot phase. Samuelson et al. (2016) report grain inclusion in feedlot diets ranges from 50% to 90% of diet dry matter (DM). Although cereal grains are relatively low in crude protein, over 90% of HeP consumed by beef cattle is fed during the feedlot phase (Baber et al., 2018). Since 2000, corn milling has increased to provide human food ingredients and fuel products; byproducts from these processes have become more available to feedlots as dietary ingredients (Hoffman and Baker, 2010). In 2007, nutritionists reported that 83% of feedlot clients included grain byproducts in diets; the mean inclusion rate was reported at 16.5% of the finishing diet (Vasconcelos and Galyean, 2007). In 2015, 97% of feedlot clients reported inclusion of grain byproducts in finishing diets, and those byproducts were the primary dietary protein source (Samuelson et al., 2016). Increasing byproduct inclusion potentially improves NPC of the feedlot (Ertl et al., 2015; Flachowsky et al., 2017). In addition, feedlots continue to finish cattle at heavier end weights (USDA-ERS, 2018), which may affect NPC. Cattle finished at a heavier weight have greater amounts of HeP, but generally consume greater amounts of HeP.

Because of observed increases in byproduct inclusion and finished weights of feedlot cattle, we theorize feedlots have improved NPC from 2006 to 2017. Our objective was to evaluate this hypothesis in commercial settings and to determine which factors in feedlot production systems impact changes in NPC.

MATERIALS AND METHODS

NPC of 8 commercial feedlots located in the Southern Great Plains (Kansas = 2; Texas panhandle = 6) was modeled across time to evaluate change in NPC. Lot level production and diet data were collected from each feedlot from 2006 to 2017, representing 14 million head of finished cattle. Individual feedlots finished 4,333 to 13,604 lots of cattle during this time. Production variables obtained for each feeding group (lot) at each feedlot were number of cattle placed and finished, mean initial and final body weight (BW), β-agonist use, days on feed, and dry matter intake (DMI) of starter and finisher diets. Production values were calculated within each feedlot and year combination, and mean annual values were incorporated into an existing model of NPC described by Baber et al. (2018). Methodology presented by Wilkinson (2011), Ertl et al. (2015, 2016a, and 2016b), and Baber et al. (2018) were used to estimate annual NPC for each feedlot.

Human-edible protein in beef (HeP_b) was estimated with the body protein content equation (NASEM, 2016) using adjustments described by Baber et al. (2018). Human-edible protein gained (HeP_g) was calculated as the change in HeP_b between received cattle and finished cattle (i.e. initial and ending HeP_b).

Diet formulation changes occur frequently in feedlots; therefore, the starter and finisher diet formulations fed for the greatest number of days each year were used to represent diets for each feedlot within each year. All feedlots in this dataset use variable blends of the two primary diets for transitioning cattle from starter to finisher, thus total feed amounts are inclusive of transition diets.

Feed ingredients for each diet were categorized as edible, inedible, or partially edible by humans according to Wilkinson (2011) and Ertl et al. (2016a). HeP (% DM) of each diet was calculated based on the crude protein content of human-edible ingredients and the proportion of human-edible feed ingredients in the diet. The HeP proportion of the diet

(% DM) was multiplied by DMI of each diet type. Because intake data were at the lot level, intake of starter and finisher diets were divided by the number of head harvested from each lot to obtain human-edible protein fed (HeP_f) per animal harvested for the feeding period. This approach allocates all feed delivered to the lot among only those harvested for human consumption directly from the feedlot.

Digestible indispensable amino acid score (DIAAS) was calculated for each edible or partially edible feed ingredient (Baber et al., 2018). The DIAAS represents the quality of the protein (amino acid profile) in relation to the amino acid profile required by a 0.5- to 3-year-old child (FAO, 2011). A DIAAS of 100 (or above) meets (or exceeds) a child's amino acid requirements. Whole-diet DIAAS was calculated for each ration fed based on percent inclusion of each human-edible feed ingredient and its individual DIAAS. Finally, a yearly DIAAS was calculated as the weighted average of the whole-diet DIAAS for starter and finisher diets and the yearly average of HeP_f from the starter and finisher diets.

Protein quality ratio (PQR) was calculated to describe the quality of protein produced vs. the quality of the protein fed using the DIAAS of beef and of the diets fed. A PQR above 1 indicates that produced protein is more capable of meeting human dietary requirements than the feedstuffs used for production, whereas a PQR below 1 indicates that the diet has greater protein quality than contained in the beef. Human-edible protein conversion efficiency (HePCE; the ratio of HeP_g vs. HeP_f), PQR, and NPC were calculated according to Ertl et al. (2016a) and Baber et al. (2018).

Statistical Analysis

Summary statistics of mean feedlot NPC by year were calculated using PROC MEANS in SAS 9.4 (SAS Institute Inc., Cary, NC). Data were analyzed using PROC MIXED in SAS 9.4 (SAS Institute Inc.). To determine if feedlots were improving NPC over time, a regression of NPC on time was estimated for each feedlot, where year 2006 was adjusted to year 0. Feedlot and feedlot × adjusted year were fixed effects in the model, and a unique intercept was estimated for each feedlot (Littell et al., 2006). When the feedlot × adjusted year effect was significant ($P < 0.05$), the individual parameter estimates for each feedlot were evaluated. If the coefficient for feedlot × adjusted year (i.e., the slope for an individual feedlot) was greater than zero ($P < 0.15$), the feedlot was categorized as an increasing NPC (INC) feedlot type; otherwise, feedlots were categorized as a constant NPC (CON) feedlot type. Because no feedlot had a negative slope for feedlot × adjusted year, no feedlot was categorized as having a declining NPC.

Differences in feedlot production variables and their overall change (difference between year 2006 and year 2017) dependent on feedlot type, INC or CON, were evaluated using PROC MIXED with feedlot type as class variable and adjusted year as a covariate. Regressions of each attribute were created using feedlot type, adjusted year, and feedlot type × adjusted year as fixed effects, and unique intercepts were estimated for each feedlot type (Littell et al., 2006). When an interaction was observed, indicating that slopes differed by feedlot types, ESTIMATE statements were used to determine differences between feedlot types within years. When no interactions were observed ($P > 0.05$), a common slope for adjusted year was estimated for feedlot types. Slopes were considered significantly different from zero when ($P < 0.05$).

RESULTS

NPC describes the net capacity of a production system, or system phase, to contribute to meeting human protein requirements. Minimum and maximum NPC among feedlots were 0.57 and 0.72 in 2006 (Table 1). For the most recent year evaluated (2017), NPC ranged from 0.47 to 1.15. Standard deviation of NPC ranged from 0.05 to 0.12 between 2006 and 2011; whereas standard deviations ranged from 0.11 to 0.27 between 2012 and 2017. Across all feedlots, increases in both the overall range of NPC and within year standard deviations suggest increased variability, potentially resulting from divergence in production practices among feedlots.

When NPC was regressed on year for each feedlot observed, slope was greater than zero (increasing NPC over time) for feedlots 2, 3, 5, and 7 ($P \leq 0.14$; Table 2); these feedlots were categorized as INC. Rates of NPC change across years for feedlots 1, 4, 6, and 8 were not different from zero ($P \geq 0.49$), and these feedlots were categorized as CON.

Feedlots were pooled by type (CON or INC), the regression of NPC over time was estimated for each type (Figure 1). For feedlots classified as improving, NPC increased 0.027 ($P < 0.05$) units per year. In comparison, CON feedlots had nearly constant NPC, with an estimate not different from zero (0.004; $P = 0.01$) for NPC change over time. The difference in slope suggests divergence of NPC over time rather than a constant difference among

Table 1. Summary statistics of net protein contribution by year

Year	No. of observations	Mean	Standard deviation	Maximum	Minimum
2006	7	0.66	0.06	0.72	0.57
2007	7	0.63	0.06	0.68	0.51
2008	8	0.66	0.05	0.72	0.59
2009	8	0.67	0.08	0.83	0.57
2010	8	0.75	0.10	0.91	0.63
2011	8	0.76	0.12	0.98	0.61
2012	8	0.69	0.27	1.14	0.41
2013	8	0.59	0.20	1.03	0.44
2014	8	0.78	0.11	0.96	0.62
2015	8	0.79	0.09	0.91	0.68
2016	8	0.76	0.13	0.95	0.58
2017	8	0.84	0.23	1.15	0.47

Table 2. Predicted equation of net protein contribution regressed over year for each feedlot

Feedlot	Feedlot type	Intercept	Year[a]	*P*-value[b]
1	CON	0.747 ± 0.0675	–0.002 ± 0.0104	0.88
2	INC	0.610 ± 0.0675	0.020 ± 0.0137	0.14
3	INC	0.540 ± 0.0675	0.029 ± 0.0104	<0.01
4	CON	0.600 ± 0.0675	0.007 ± 0.0104	0.49
5	INC	0.585 ± 0.0675	0.028 ± 0.0104	0.01
6	CON	0.655 ± 0.0675	0.002 ± 0.0104	0.85
7	INC	0.726 ± 0.0675	0.030 ± 0.0104	<0.01
8	CON	0.587 ± 0.0675	0.006 ± 0.0104	0.54

[a] Number of years analyzed for feedlots 1 and 3–8 = 12; Number of years analyzed for feedlot 2 = 10.

[b] Coefficient for year was considered different from zero when *P*-value < 0.15.

feedlots and is consistent with the overall increasing range in NPC described earlier.

Production and diet characteristics of feedlots were compared to determine potential sources of observed differences in NPC between INC and CON feedlots (Tables 3 and 4). There were feedlot type × adjusted year interactions for byproduct inclusion, cereal grain inclusion, and HeP fed (HeP_f; $P < 0.01$). Both feedlot types were increasing byproduct inclusion each year ($P < 0.05$; Figure 2); however, greater increases in byproduct inclusion (2.83% per year) were observed for INC compared to CON (1.52% per year; $P < 0.01$). Byproduct inclusion rates were similar until 2010 ($P > 0.05$), afterward INC feedlots included greater amounts of byproducts than CON ($P \leq 0.01$). Proximity to SweetBran (Cargill, Inc., Dalhart and Bovina, TX) plants was used to approximate distance to a common byproduct source used in these feedlots. Feedlots categorized as CON were further from a plant (105 km) compared to INC feedlots (59 km; $P < 0.01$). As inclusion rates increased over time, it is possible that a threshold for transportation costs resulted in different upper limits for cost-effective coproduct inclusion, such that feedlots closer to a coproduct source continued to increase inclusion rates while those beyond a critical distance reached a lower optimal inclusion rate.

Both feedlot types reduced cereal grain inclusion over time (2.0% and 1.26% reduction per year; $P < 0.01$), but INC feedlots had greater reductions (74.7%–52.7% inclusion from 2006 to 2017; $P < 0.01$) compared to CON feedlots (76.0%–62.1% inclusion from 2006 to 2017, respectively). Feedlot types did not differ in amount of cereal grains in diets for 2006 and 2007 ($P \geq 0.23$), but for all years following inclusion rates in INC feedlots were less than CON feedlots ($P \leq 0.05$; Figure 3). Cereal grain reductions resulted in similar decreases in HeP_f (Figure 4). Feedlots categorized as INC reduced HeP_f during a feeding period by 2.3 kg per animal each year ($P < 0.01$) whereas CON feedlots did not reduce HeP_f over time ($P = 0.61$). From 2012 to 2017, INC feedlots fed less HeP than CON feedlots ($P \leq 0.03$).

A yearly DIAAS was estimated for the starter and finisher ration fed at each feedlot each year. For CON and INC feedlots, DIAAS was 37.2 and 36.9, respectively ($P < 0.01$), and DIAAS did not change across time ($P = 0.57$). Greater PQR was observed for INC compared to CON ($P < 0.01$), and PQR did not change across time ($P = 0.79$).

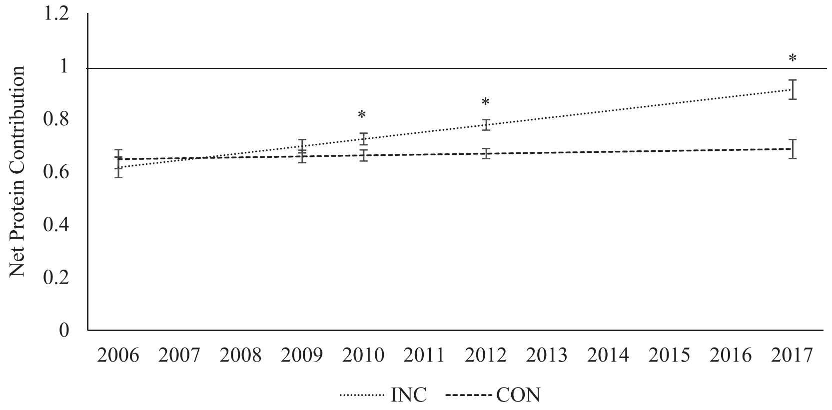

Figure 1. Time series of increasing net protein contribution (NPC) feedlots (INC) and constant (CON) NPC. CON = constant NPC over time; INC = increase in NPC over time. Feedlot type: $P < 0.01$; Feedlot type × year interaction: $P = < 0.01$. Estimated line for CON: 0.647 + 0.0035X. Estimated line for INC: 0.616 + 0.0267X; * differences between CON and INC within a year ($P < 0.05$).

Table 3. Estimated intercepts and year coefficients for feedlot type (CON or INC) for net protein contribution (NPC) and key output variables in feedlots from 2006 to 2017

			P-value	
Item	β_0	β_1[1]	β_0	β_1
NPC				
CON	0.64 ± 0.04	0.004 ± 0.006	<0.01	<0.01
INC	0.62 ± 0.04	0.027 ± 0.006		
Byproduct, % DM of diet				
CON	5.8 ± 1.6	1.5^a ± 0.25	<0.01	<0.01
INC	4.2 ± 1.7	2.8^a ± 0.26		
Cereal grain, % DM of diet				
CON	76.0 ± 1.3	-1.3^a ± 0.20	<0.01	<0.01
INC	74.7 ± 1.4	-2.0^a ± 0.21		
HeP_f, kg/animal for total feeding period				
CON	95.8 ± 3.55	–0.3 ± 0.55	<0.01	<0.01
INC	102.6 ± 3.80	-2.3^a ± .57		
HePCE				
CON	0.211 ± 0.01	0.002 ± 0.002	<0.01	<0.01
INC	0.205 ± 0.01	0.008^a ± 0.002		

[1] Superscript denotes year coefficient is statistically different from zero ($P < 0.05$).

[a] It indicates that B1 is different from zero.

Days on feed was greater for INC feedlots compared to CON feedlots (186 vs. 172 days; $P < 0.01$), and days on feed did not change across time ($P = 0.29$). Mortality rate was different between feedlot types (1.59% and 1.78% for CON and INC, respectively; $P < 0.01$) and did not change across time ($P = 0.70$). Beta-agonist usage, ractopamine hydrochloride or zilpaterol hydrochloride, based on number of lots fed a beta-agonist increased approximately 3.7% per year ($P < 0.01$), and was greater for INC compared to CON feedlots ($P < 0.01$).

Initial BW and initial HeP_b were greater for CON than INC ($P < 0.01$), and both feedlot types had increasing initial BW (1.8 kg/year) and HeP_b (0.19 kg/year) over time ($P < 0.01$). Ending BW and HeP_b were greater for CON than INC ($P < 0.01$), but both feedlot types increased final BW by 3.8 kg/year and HeP_b by 0.25 kg/year ($P < 0.01$). Amount of HeP_g was greater for INC than CON ($P < 0.01$) and tended to increase over time for both feedlot types at the same rate (0.10 kg HeP_g/year; $P = 0.10$).

An interaction between feedlot type and adjusted year was observed for HePCE ($P < 0.01$; Figure 5), thus separate intercepts and coefficients for each feedlot type were estimated. Feedlots categorized as INC increased HePCE over time ($P < 0.01$) whereas the change in HePCE over time was not different from zero ($P = 0.22$) for CON. Beginning in 2010, HePCE was greater for INC feedlots compared to CON ($P \le 0.02$), but before 2010, HePCE was not different between feedlot types ($P > 0.05$).

DISCUSSION

We hypothesized that NPC from feedlots would have increased from 2006 to 2017. For half of the feedlots evaluated in this study, our hypothesis was correct; NPC was 48% greater in 2017 than 2006 for INC. Notably, in 2017, INC feedlots were approaching NPC of 1.0, with an average value of 0.91. Across the time span of our evaluation, the rate of improvement in NPC was 0.027 units per year for INC feedlots. Rate of NPC change for feedlots in the CON group (0.004 units per year) was not different from zero. The greatest NPC observed for an individual yard was 1.15 in 2017 and the lowest was 0.41 in 2012, demonstrating the wide range in this indicator of protein production (Figure 6). Baber et al. (2018) estimated an NPC of 1.07 for feedlots in the United States, which is greater than the estimate of 0.91 for the INC class of feedlots in 2017. For growing-finishing bull production systems in

Table 4. Estimates of intercepts and the common year coefficient for feedlot types (CON and INC) for variables impacting net protein contribution

Item	β_0	β_1	*P*-value	
			β_0	β_1
Feedlot characteristics				
Proximity to byproduct, km[a]				
CON	105 ± 7.3	0.00 ± 1.00	<0.01	1.00
INC	59 ± 7.3			
Production characteristics				
Initial BW, kg/animal				
CON	335 ± 3.9	1.8 ± 0.54	<0.01	<0.01
INC	316 ± 4.0			
Initial HeP, kg/animal				
CON	40.7 ± 0.4	0.19 ± 0.1	<0.01	<0.01
INC	38.8 ± 0.4			
Ending BW, kg/animal				
CON	578 ± 3.6	3.8 ± 0.49	<0.01	<0.01
INC	564 ± 3.7			
Ending HeP, kg/animal				
CON	61.7 ± 0.23	0.25 ± 0.3	<0.01	<0.01
INC	60.8 ± 0.24			
Days on feed				
CON	172 ± 3.4	0.49 ± 0.46	<0.01	0.29
INC	186 ± 3.5			
Mortality rate, %				
CON	1.59 ± 0.11	–0.01 ± 0.02	<0.01	0.70
INC	1.78 ± 0.12			
Beta-agonist usage, %				
CON	52.7 ± 7.3	3.69 ± 1.0	<0.01	<0.01
INC	58.8 ± 7.5			
Diet characteristics				
DIAAS				
CON	37.2 ± 0.6	0.05 ± 0.08	<0.01	0.57
INC	36.9 ± 0.6			
HeP_g, kg/animal				
CON	19.2 ± 0.29	0.1 ± 0.04	<0.01	0.10
INC	20.9 ± 0.29			
PQR				
CON	3.01 ± 0.08	–0.002 ± 0.01	<0.01	0.79
INC	3.06 ± 0.08			

[a] No interactions were observed between feedlot type and year (*P* > 0.10).

Austria, NPC was 0.73 (Ertl et al., 2016a), which is lower than 2017 estimates of INC feedlots in the United States, but comparable to CON feedlots (0.69) in 2017.

There were a number of differences among CON and INC feedlots that drive the differences over time in NPC. Byproduct inclusion in both INC and CON feedlots increased over time and across the industry as corn milling byproducts became more readily available (Vasconcelos and Galyean, 2007; Samuelson et al. 2016). Ethanol production in the United States is a major source of corn milling byproducts domestically and worldwide, with up to 25% of corn byproducts exported annually (Makkar, 2012). Rapid increases of corn milling byproducts in the mid-2000s (Hoffman and Baker, 2010) created new feed ingredient opportunities for feedlots. For example, production of DDG increased from 1.6 to 33.2 million metric tons from 2000 to 2010 (Hoffman and Baker, 2010). The feedlot type × year interaction observed for rate of byproduct inclusion resulted from INC feedlots having greater inclusion rates beginning in 2010 vs. CON feedlots. Before 2010, INC and CON had similar byproduct inclusion rates and the inclusion rate in both feedlot types was increasing steadily. Both feedlot types increased byproduct inclusion over time; however, INC feedlots increased byproduct inclusion rates to a greater extent than CON (4.2% to 35.0% vs. 5.8% to 22.5%, respectively). Byproduct inclusion level in finishing diets (approximately 26.0% DM) modeled by Baber et al. (2018) was intermediate to the levels observed for CON and INC feedlots. Feedlots categorized as INC were observed to be located (on average) 75 km closer to primary byproduct sources than CON feedlots. Shorter distances reduce transport expense and lower total byproduct ingredient cost, resulting in a greater substitution rate for other ingredients for feedlots with a proximity advantage.

Corn milling byproducts have high concentrations of CP (Makkar, 2012). Thus, as inclusion of these byproducts increased from 2006 to 2017, concentration of CP (% of DM) increased as well. Corn milling byproducts are initially included in feedlot diets to replace protein sources and non-protein nitrogen sources; i.e., the substitution was driven by the value of dietary protein. Soybean meal, human-edible and a protein source in feedlot diets (DIAAS of 96.0), was not used at any of the feedlots in this study. Once protein targets are met, corn milling byproducts begin replacing the primary energy source (i.e. corn; Makkar, 2012) when the unit cost of energy was competitive. The feedlot type by year interaction observed for cereal grain was indicative of cereal grain replacement with byproducts. Decreased amounts of cereal grain (% of diet DM) were observed for both feedlot types over the time period analyzed, but INC reduced cereal grain inclusion to a greater extent than CON feedlots. Although byproduct inclusion became different between feedlot types in 2010, cereal grain inclusion was less for INC feedlots than CON beginning in 2008. Byproduct inclusion replaced more of the diet than just cereal grain. Feedlots categorized as INC only reduced cereal grain by

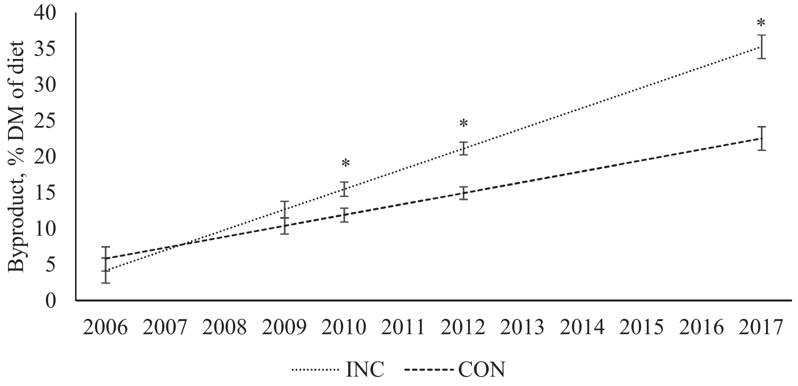

Figure 2. Inclusion of corn milling byproducts in feedlot diets over time. CON = constant NPC over time; INC = increasing NPC over time. Feedlot type: $P < 0.01$; Feedlot type × year interaction: $P = 0.01$. Estimated line for CON: 5.85 + 1.52X. Estimated line for INC: 4.18 + 2.82X; * differences between CON and INC within a year ($P < 0.05$).

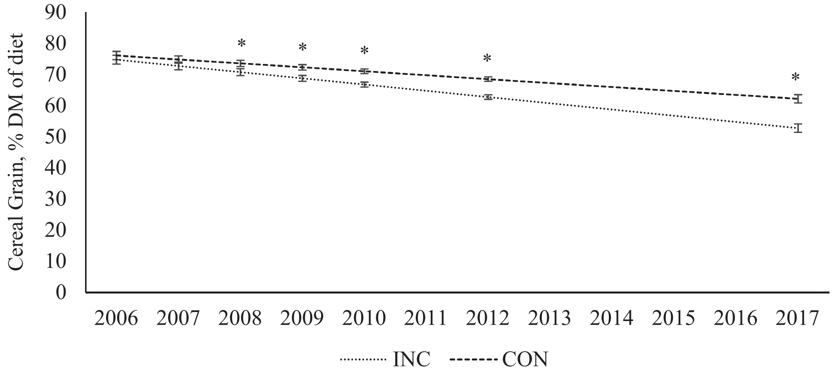

Figure 3. Inclusion of cereal grain in feedlot diets over time. CON = constant NPC over time; INC = increasing NPC over time. Feedlot type: $P < 0.01$; Feedlot type × year interaction: $P = 0.01$. Estimated line for CON: 76.05 – 1.26X. Estimated line for INC: 74.71 – 2.00X; * differences between CON and INC within a year ($P < 0.05$).

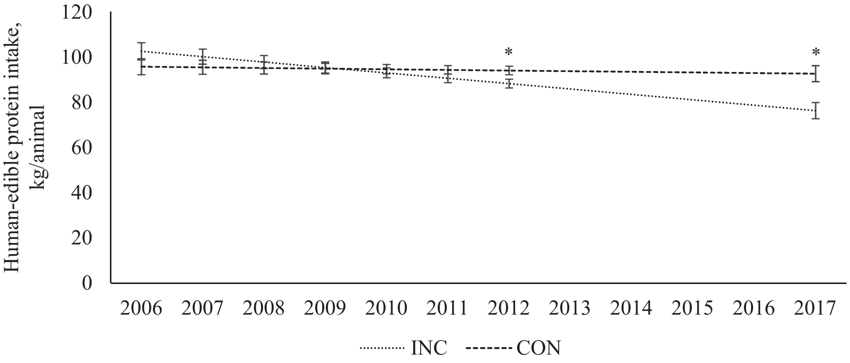

Figure 4. Intake of human-edible protein per animal during a feeding period in feedlots from 2006 to 2017. CON = constant NPC over time; INC = increasing NPC over time. Feedlot type: $P < 0.01$; Feedlot type × year interaction: $P = 0.01$. Estimated line for CON: 95.8 – 0.3X. Estimated line for INC: 102.6 – 2.4X where X is year; * differences between CON and INC within a year ($P < 0.05$).

22%, but increased byproduct inclusion by 31% over the 12-year period suggesting that byproducts were substituted for roughage and silage (non-human-edible ingredients).

Reductions in cereal grain, a human-edible feed ingredient, inclusion resulted in a feedlot type × year interaction for HeP_f (kg/animal). In 2011, six of eight feedlots adopted a starting diet that contained no cereal grain, thus removing all HeP from starter diets at these feedlots. Although cereal grain inclusion became different between feedlot types in 2008, HeP_f was not significantly different between feedlot types until 2012. In addition, although CON feedlots were reducing cereal grain inclusion (% of the diet) over time, HeP_f (kg) was not decreasing over time. Discrepancies between cereal grain inclusion and HeP_f suggest reductions in the proportion of cereal grain in the diet were not able to overcome increased intake of feeding heavier cattle in CON feedlots.

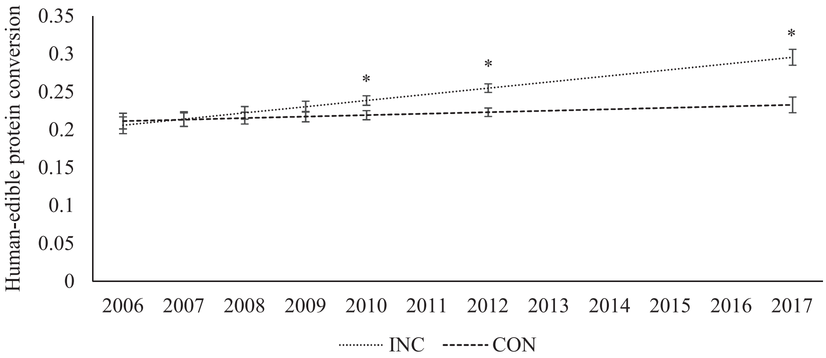

Figure 5. Conversion efficiency of human-edible protein in feedlots from 2006 to 2017. CON = constant NPC over time; INC = increasing NPC over time. Feedlot type: $P < 0.01$; Feedlot type × year interaction: $P = 0.01$. Estimated line for CON: 0.21 + 0.002X. Estimated line for INC: 0.21 + 0.008X where X is year; *differences between CON and INC within a year ($P < 0.05$).

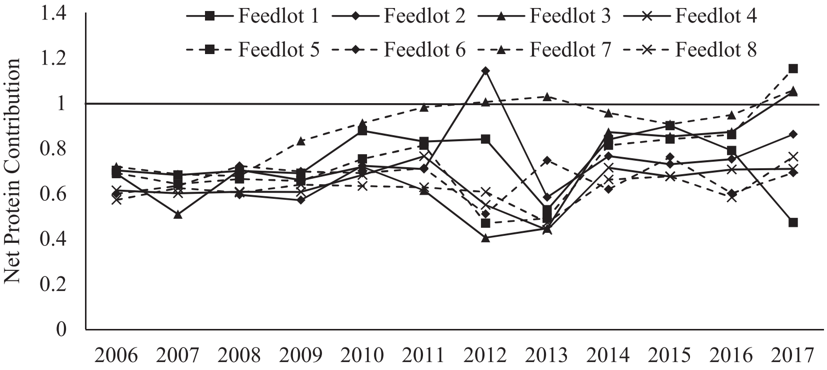

Figure 6. Times series of eight feedlots' net protein contribution (NPC). An NPC above 1 represents a feedlot positively contributing to human protein's requirements. An NPC below 1 represents a feedlot competing with humans for human-edible protein.

Ingredient inclusion in feedlot diets is based on least-cost formulation; therefore, inclusion level of an ingredient changes when its price changes relative to prices of comparable, available ingredients. Corn, the main HeP ingredient used in feedlots, has a DIAAS of 36.8, which is similar to intercepts estimated for DIAAS for CON and INC, 37.2 and 36.9, respectively. Flaked wheat grain (DIAAS of 43.1) was included in diets used at six of the eight feedlots during 2013 because of competitive pricing compared to corn, resulting in a greater DIAAS (40.6) and lower PQR (2.77) for 2013 compared to other years (data not shown). Flaked wheat grain was also fed in 2007, 2012, and 2017 but was only fed at one feedlot during each of these years.

PQRs for CON and INC did not change over time. This was a result of no change over time for diet DIAAS for either feedlot type, and because beef has a fixed DIAAS of 112.0. From our results, DIAAS and PQR are driven primarily by choice of primary energy source rather than differences in inclusion percentage of various human-edible feed ingredients. Intercepts for PQR observed in our study (3.01 and 3.06 for CON and INC, respectively) were greater than that estimated for growing-fattening bulls in Austria, (1.66; Ertl et al. 2016a). Specific diet formulations were not provided by Ertl et al. (2016b); however, the dietary ingredients described in that study have greater DIAAS than corn (i.e., soybeans [99.6] and oats [56.7]) resulting in higher diet DIAAS and resulting reductions in PQR.

There has been a trend over time to increase both feedlot entry and harvest weight in US feedlots (LMIC, 2018), and this trend was evident in the feedlots evaluated in our study. Finished weights have increased from 560 to 612 kg from 2003 to 2017 (USDA-ERS, 2018) which correspond with the values of 558 and 601 kg observed for cattle in our study. Feedlots for which NPC increased over time typically placed 19 kg lighter cattle and harvested cattle at 14 kg lighter weights compared to CON feedlots. In spite of lighter placement and harvest weights, INC feedlots generated 5 kg greater BW gain during feeding, resulting from a longer time on feed.

Differences in placement weight and cumulative gain drive differences in HeP_g, which was greater for INC feedlots than CON. HeP_g is the change in HeP_b while cattle are in the feedlot and is calculated based on a quadratic function using EBW (NASEM, 2016). Beef cattle deposit less protein and more body fat for each kilogram of additional live weight gain (Jesse et al., 1976; Oltjen and Garrett, 1988). Placing calves at a lighter BW results in greater amounts of protein deposited compared to calves placed at a heavier weight, even if cumulative gain is similar. Therefore, the combined effects of lighter placement weight and greater cumulative gain for INC compared to CON drive the differences observed for $\mathrm{HeP_g}$ among feedlot types.

Greater HePCE was observed for INC feedlots than CON. This can be attributed to combined effects of reduced $\mathrm{HeP_f}$ and increased $\mathrm{HeP_g}$ for INC feedlots. Despite increased days on feed for INC feedlots, $\mathrm{HeP_f}$ was lower for INC than CON feedlots, indicating that lower diet HeP concentration influenced $\mathrm{HeP_f}$ more than days on feed. Over the period analyzed, INC and CON feedlots reduced $\mathrm{HeP_f}$ by 14% and 3%, respectively. In addition, INC and CON feedlots increased $\mathrm{HeP_g}$ by 6.3% and 5.7%, respectively, resulting in the feedlot type × year effect observed for HePCE. HePCE increased 43% from 2006 to 2017 for INC feedlots and 10% for CON feedlots during the same period, but only increases observed for INC were statistically different from zero. Ertl et al. (2015) demonstrated that replacing cereal grains with byproducts increased HePCE in a dairy cattle system, which is consistent with the differences in byproduct inclusion between feedlots observed in the present study. In addition, Flachowsky et al. (2017) reported that HePCE nearly doubled (0.7–1.3) when byproducts replaced 50% of human-edible ingredients fed to steers gaining 1 kg per day.

Observed levels of HePCE in the current study were lower than that modeled by Baber et al. (2018), primarily due to differences in $\mathrm{HeP_f}$. In this study, diets for CON and INC averaged 64% to 70% cereal grain whereas 55% of the diet was cereal grain in Baber et al. (2018). In Austria, growing-fattening bulls are reported to have a HePCE of 0.45 (Ertl et al., 2016a), but the diet was 19.8% HeP and feed ingredient composition was not reported. Worldwide the estimate for HePCE of beef from feedlots is 0.21 (Mottet et al., 2017), similar to our estimate of HePCE in 2006 and CON feedlots throughout the time period.

Compared to poultry and swine production systems, beef production is more complex with multiple segments contributing to NPC of the beef value chain. Cow-calf and stocker segments primarily graze forage and use other human-inedible feeds, and the majority (66%) of HeP is gained in these two sectors, both of which have NPC greater than 1 (8,036.0 and 15.9 for cow-calf and stocker, respectively; Baber et al., 2018). When the aforementioned estimates of NPC for the cow-calf and stocker segments are combined with this study's estimates of NPC for feedlots in 2017 using the summative model described by Baber et al. (2018), NPC for the entire beef value chain was approximately 3.50 and 2.82 for INC and CON, respectfully. In addition, when estimated using the best and worst-case scenarios of feedlot NPC observed (1.15 and 0.41), NPC of the beef value chain was approximately 4.60 and 1.51. This study only estimated NPC for feedlots; however, when the range of feedlot NPC observed were combined with NPC values from the other segments of beef production, NPC remained greater than 1 indicating that these production systems positively contribute to addressing human protein requirements.

Estimates of NPC for competing meat proteins (pork and poultry) are limited to Ertl et al. (2016), which estimated pork and poultry production systems in Austria to have NPC of 0.64 and 0.76, respectively. The values are similar to NPC of CON in this study; however, HePCE of pork (0.36) and poultry (0.52) were greater than CON and INC feedlots (0.23 and 0.29 in 2017), whereas PQR was greater for INC and CON feedlots (3.06 and 3.01, respectively) compared to pork and poultry production (1.74 and 1.43, respectively). Furthermore, when comparing US feedlot production with Austria's pork and poultry production, it is clear NPC observed between production systems is driven by the ability of beef cattle to upcycle protein.

CONCLUSIONS

Replacing a portion of cereal grains with corn milling byproducts and increasing weight gain has allowed feedlots to improve NPC since 2006. Feedlots located closer to ethanol plants or feed facilities with corn milling byproducts use these feed ingredients to a greater extent to improve NPC. Heavier initial BW allows more beef protein to accumulate before the feedlot, usually on non-human-edible feedstuffs. Although some feedlots in this study were not adding to HeP supply, none of the feedlots had a declining NPC over the time period analyzed. Production efficiency has continued to increase over the past 12 years contributing to the improvement in NPC; however, substantial improvements made in NPC were driven by reductions in $\mathrm{HeP_f}$. Further research designed to quantify the effects of available production technologies on NPC and how their potential removal affects sustainability is warranted.

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