DECISION SUPPORT TOOLS FOR SUSTAINABLE BEEF PRODUCTION

A Dissertation

by

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ABSTRACT

Net protein contribution (NPC), enteric methane emissions and profitability were modelled to evaluate the sustainability of beef production under various management strategies. In experiment 1, methodology, production characteristics, and diet characteristics of the 3 sectors of the beef value chain were established. In experiment 2, evaluated the effects of increasing length of confinement for the cow-calf sector (0, 4, 8, or 12 months of confinement) on NPC, enteric methane, and profitability. Experiment 3 analyzed trends in NPC from 2006 to 2017 using 8 commercial feedlots in Texas and Kansas and categorized feedlots into improving NPC (INC) or constant NPC (CON). Ratio of protein quality (PQR) of diets fed and beef produced were calculated using digestible indispensable amino acid scores (DIAAS). Additionally, human-edible protein conversion efficiency (HePCE) was calculated. Net protein contribution was calculated by multiplying PQR and HePCE. Beef value chains and all sectors within are contributing positively to human protein requirements as indicated by a NPC above 1. Net protein contribution was reduced when length of intensification of cow-calf sector increased, however enteric methane production was reduced as length of intensification increased. Feedlots have improved net protein contribution over time. Feedlots categorized as INC have improved NPC from 2006 to 2017 ($P = 0.02$). Greater cereal grain inclusion and lower byproduct inclusion was observed for INC compared to CON ($P < 0.01$).

Experiment 4 was conducted to compare nutrient utilization and energy balance of limit-fed diets consumed by pregnant heifers. Heifers were randomly assigned to 1 of 2 treatments, a forage diet (**FOR**; 2.10 Mcal ME/kg) or a concentrate diet (**CONC**; 2.94

Mcal ME/kg), and individually fed to meet maintenance energy requirements (0.135 Mcal ME/kg $BW^{0.75}$). Dry matter and organic matter digestion was greater for CONC than FOR ($P < 0.01$). Energy lost as methane (% of GE intake) was not different between treatments ($P = 0.49$). The ratio of ME to DE was greater for CONC (86.8 vs 82.8; $P = 0.01$). The ratio of ME to DE may be dependent on diet and level of intake and is more dynamic than current feeding systems describe.

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INTRODUCTION AND LITERATURE REVIEW

Introduction

Global population is predicted to grow from 7.5 billion (2017) to 9.9 billion by 2050 (FAO, 2018; Kaneda et al., 2018). While population has grown, the proportion of protein consumed from animal products has also increased from 32 to 40% and the proportion of animal products in the diet (as % of kcal) has increased 2.4% over the last 50 years (FAO, 2018). A major driver of increased global animal product consumption is rising consumption in countries with emerging economies (Bodirsky et al., 2015). San and Combris (2015) reported increased meat consumption (21.9 to 45.4% of total protein consumed) as income level rises from low to upper middle class. These two factors, increased population and growing affluence are expect to drive increased demand for beef products across the coming decades.

While meeting increased demand is a positive challenge for beef producers, it remains that some groups frequently malign beef products as a source of protein in human diets. One concern is beef production systems consume significant amounts of human-edible grains, decreasing the amount of grain available for human consumption (i.e. feed-food competition). To illustrate food-feed competition for livestock production, Mottet et al. (2017) estimated 14% of land suitable for crop production was utilized by livestock and 31% of cereal grain production was used for livestock feed. Goodland (1997) reported livestock consume half of global grain production.

In addition to food-feed competition, opponents of beef production express concern over the environmental cost of beef and the assumption that beef production is inefficient. Ruminants produce enteric methane; a greenhouse gas (GHG) and a significant source energy loss from beef production systems, specifically grazing systems. Westhoek et al. (2014) estimated GHG would be reduced 25 to 40% if meat and dairy consumption were cut in half. Greenhouse-gas production related to livestock is projected to increase by 39% by 2050 (Pelletier and Tyedmyers, 2010). In comparison to pork and poultry production systems, beef cattle are the least efficient at converting feed to meat products because GHG produced in the rumen during fermentation. Goodland (1997) proposed taxation on inefficient production systems (beef) as a means to combat environmental sustainability. More efficient animal protein production systems (ocean fish) would be taxed less and no taxes on grains for humans as a means to ensure a dietary shift away from food production systems considered harmful (Goodland, 1997).

Opponents to beef production often point to the environmental costs failing to identify any value in beef production. However, ruminants have the ability to upcycle low-quality proteins found in plant biomass and coproducts both of which can be inedible by humans and convert those proteins into beef, a high-quality protein source for humans (Oltjen and Beckett, 1996; Wilkinson, 2011; Ertl et al., 2016a). Understanding the protein upcycling value of beef relative to other protein sources in human diets is essential to understanding the impacts of beef production on the human food supply. Beef products provide a more complete source of dietary protein (i.e., greater biological value) than plant sources, which often 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 the costs associated with beef production is essential for addressing societal concerns and optimizing beef's value. Bywater and Baldwin (1980) redefined feed efficiency of livestock by accounting for human-edible proteins and energies consumed and produced, and Ertl et al. (2016b) built on Wilkinson's (2011) work by accounting for quality of human-edible protein (HeP) and by predicting net protein contribution (NPC) of livestock systems. Ertl et al. (2016a) reported dairy cows and beef cattle to have the greatest NPC followed by poultry and swine.

Sustainability of beef production

Beef production sustainability is the ability of the industry to exist in a manner that allows the industry to continue to persist in the future. Sustainability has been divided into three pillars: environment, economy, and society (Figge et al., 2012). When focusing on sustainability, environmental impacts are managed to prevent resource depletion. Economic sustainability is built on the concept that individual operations comprising the beef industry must be profitable to continue to operate in the future, and part of a profitable beef industry is improvement in the cattle performance. The beef industry has been successful in documenting the environmental and economic pillars of sustainability; however, the societal pillar has posed a greater challenge. Indicators like employee safety and welfare are included in the societal pillar, and it could be expanded to animal safety and welfare indicators also. The U.S. Roundtable for Sustainable Beef (2018) defined 6 indicators for sustainability: animal health and well-being, efficiency and yield, water resources, land resources, air and greenhouse gas emission, and employee safety and well-being. However, creating metrics rather than indicators to assist sustainable improvement of the industry is required.

The inherent difficulty is determining what metrics to include and how to weigh the metrics. Pillars that have directly quantifiable metrics are generally easier to work towards. For example, metrics of economic sustainability are quantitative and easily compiled allowing real-time tracking and comparisons across the industry. Environmental measures of sustainability can range from GHG emissions to water quality, and waste management. Metrics available for measure societal impact of the industry are not as readily available; this pillar is difficult to quantify which creates challenges when determining metrics. Animal welfare and health should be considered a societal metric since it is ensuring proper care for the animals; however, this metric overlaps with economic and environmental sustainability as it touches on herd performance and efficiency.

In various life cycle assessments, Capper (2011), Wiedemann et al. (2014), and Legesse et al. (2015) described decreased environmental impact of beef production while producing slightly greater amounts of beef. It is noteworthy that these improvements came largely as the result of producers optimizing economic returns and not directly attempting to reduce the environmental effects. Capper (2011) compared 1977 beef production with 2007 in the United States, while Legesse et al (2015) and Wiedemann et al. (2014) evaluated the similar time periods for beef production in Canada and Australia, respectively. To produce 1 billion kg of beef in the United States in 2007, it required 69.9% fewer animals and methane from beef production was reduced by 17.7% versus 1977 (Capper, 2011). Similarly, Legesse et al. (2015) and Wiedemann et al. (2014) observed a 14% reduction in methane emissions. Additionally, Legesse et al. (2015)

reported a 24% reduction in land-use from 1981 to 2011 to produce the same amount of beef in 2011 compared with 1981. All authors attributed improvements in greenhouse gas intensities to increase slaughter weights and cattle performance and improved reproductive efficiency (Capper, 2011; Wiedemann et al., 2014; Legesse et al., 2015).

Consumers from developed economies have questioned the cost of beef cattle production systems as a source of human-edible nutrients. Consumers are increasingly interested in how their food is produced and what the environmental impact of food production might be (Hartmann and Siegrist, 2017). In a survey to 1,000 households, consumers indicated the level of interest they have in various categories of food production (Perez and Howard, 2007). From of scale of 1 to 10 (1= no interest; 10 = great amount of interest), consumers ranked safety (9.4), nutrition (8.9), treatment of animals (7.4), and environmental impacts (7.3) as the top four categories of interest. However, their actual knowledge of what occurs and the actual environmental costs of food production maybe minimal and based on slanted information. Perhaps the increased interested of animal production by consumers is a result of the continual reduction in number of people associated with agriculture. In the last century, the number of farm workers in the United States has decreased from approximately 14 million to 3 million people (USDA-NASS, 2018) Opponents of beef production have suggested that a dietary shift away from animal products will increase food availability (Pimental and Pimental, 2003; Garnett, 2011; Peters et al., 2016). When the global impact of feeding less food-competing feeds to livestock was assessed, Schader et al. (2015) suggested human diets in 2050 should contain 71% less protein from livestock products. If no human-edible foods were fed to livestock, reductions in GHG emissions (-18%), arable land occupation (-26%), non-renewable energy use (-36%), and freshwater use (-21%; Schader et al., 2015). In the suggested diet in 2050, there will be 5 g less protein per person and legume will increased by 242 g per day, likely to make up for decreased animal protein (Schader et al., 2015). In contrast, Wu et al. (2014) expects animal protein consumption to increase 73% from 2013 to 2050 to meet demands of the growing population and increased meat consumption per capita.

Culturally, Fiddes (1991) suggests meat consumption authenticates power over the natural world and is symbolic, not just nutritional. van der Veen (2003) defined a food to be a luxury when it is desired by many and consumed or attained by few. Although protein consumption is required for a nutritional adequate diet, animal protein can be a luxury (van der Veen, 2003). Animal-sourced proteins are regarded as a prestigious food because these protein sources have historically been difficult to secure which resulted in higher prices (Jelliffe, 1967). Thus, diets in developing countries evolve to include more animal-sourced proteins because of the historical and cultural significance animal-source proteins carry.

To address the role of livestock in human food production, Ertl et al. (2016) developed a model for estimating net food production from livestock production systems. Net food production from various livestock production systems in Austria accounts for the protein quality improvement and the conversion efficiency of human-edible feeds to human-edible product. From findings by Ertl et al. (2016), beef and dairy production had a greater net food contributions (2.81 and 3.78, respectively) compared to swine and poultry production (0.64 and 0.76, respectively). Additionally, beef and dairy were above one, indicating these systems were increasing food supplies; whereas, swine and poultry were below one, indicating these systems were competing with humans for human-edible foods. Wilkinson and Lee (2018) suggest limiting intake of human-edible feeds and utilizing human-inedible byproducts to create a more sustainable beef production system and to increase the efficiency of human-edible protein conversion.

Estimating protein quality

A significant benefit of beef cattle to society is the production of high-quality protein for human consumption. Typically, human nutritionists focus on 20 amino acids, and of those, additional emphasis is placed on the 10 that are considered indispensable. These amino acids must be consumed in sufficient quantities to meet the body's amino acid requirements. Dietary protein from plant sources often do not contain indispensable amino acids in sufficient concentrations to reasonably be expected to meet human requirements. However, animal products (i.e. meat, milk, and eggs) provide a high-quality source of complete protein (Hoffman and Falvo, 2004). Animal foods contain 85 mg of Lysine/g protein on average, whereas legumes, cereals, and nuts contain 64, 31, and 45 mg Lysine/g protein, respectively (Young and Pellet, 1994). In agreement, Friedman (1996) reported greater Lysine concentrations for beef and egg whites (79.4 and 69.8 mg/g protein, respectively) were greater than soy protein and wheat flour (63.4 and 26.6 mg/g protein, respectively).

Children ranging from 0.5 to 3 years old in age have the highest amino acid requirements as these children have growth requirements of at least 0.20 g of protein·kg $BW^{-1}\cdot d^{-1}$ (FAO, 2011). All other age groups require less than 0.10 g of protein·kg $BW^{-1}\cdot d^{-1}$ (FAO, 2011). Therefore, when assessing protein quality of various human-edible foods, amino acid requirements of this age group are used as the reference protein and all foods can be standardized to this reference protein. Protein efficiency ratio, net protein utilization, biological value, and relative nutritive value are some common methods used to assess protein quality (Friedman, 1996; Millward et al., 2008). In 1991, the FAO and World Health Organization proposed the use of protein digestibility-corrected amino acid score (PDCAAS) as the best method to assess protein quality (FAO, 1991). Protein digestibility-corrected amino acid score includes a reference protein (i.e. a 0.5 to 3 year old child), digestibility of the protein, and the limiting amino acid (Millward et al., 2008). However, PDCAAS is a truncated score with values ranging from 1 to 100. Food with greater value than the reference proteins (i.e. red meats, milk, eggs) are greater than 100, and their value is not fully realized because of truncation. Additionally, protein digestibility does not always reflect digestibility of individual amino acids (Schaafasma, 2000).

To correct the deficiencies in PDCAAS, digestible indispensable amino acid score (DIAAS) was developed to assign an individual digestibility for each indispensable amino acid (FAO, 2011). Cervantes-Pahm et al. (2014) compared the DIAAS of eight cereal grains using experimental determined ileal digestibility values of amino acids and DIAAS was calculated using older children and adults as the reference protein. Corn was limiting in lysine (DIAAS of 48), and wheat was lower than corn with a DIAAS of 43 (Cervantes-Pahm et al. (2014). Overall, rice had the greatest DIAAS (64) compared to corn, barley, wheat, oats, sorghum, and rye (Cervantes-Pahm et al., 2014). Whenever ileal digestibility of amino acids in humans are not available, the FAO (2011) suggests ileal digestibilities should be taken from pigs or rats. An equation presented by Delglaire and Moughan (2012) illustrates the relationship between ileal digestibilities in pigs to the ileal digestibilities in humans. Using this equation and ingredients in the swine NRC (2012), a DIAAS can be estimated for many of the human-edible ingredients in the NASEM (2016). The FAO

(2011) reported whole milk powder to have greater protein quality (DIAAS of 122) compared to wheat and peas (40 and 64, respectively). Ertl et al. (2016) proposed using DIAAS over PDCAAS when estimating protein quality of livestock feeds. Overall, DIAAS is a more conservative measure of protein quality. For example, protein quality for corn grain was reduced from 47.3 to 42.4 when switching from PDCAAS to DIAAS as the assessment of protein quality (Ertl et al., 2016).

Soy protein is comparable to meat protein when consumed by young men (Wayler et al., 1983). Similar DIAAS of soybeans and beef (99.6 and 111.6, respectively) reported by Ertl et al. (2016a) supports the findings by Wayler et al. (1983). However, most plants have lower DIAAS compared to animal products (FAO, 2011; Ertl., 2016), which supports findings by Hoffman and Falvo (2004) mentioned previously. Ertl et al. (2016) reported DIAAS of various animal products: sheep/goat milk (123.5.8), sheep/goat meat (116.8), whole chicken egg (116.4), cow milk (115.9), pork (113.9), beef (109.3), sheep milk (109.1), chicken meat (108.2), and turkey meat (83.1). It is important to note animal products are mostly greater than 100, with the exception of turkey, indicating these protein sources contain greater amounts of required amino acids compared to the reference protein (0.5 to 3 year old child's protein requirements). In a study by Barron-Hoyes et al. (2013), turkey had lower concentrations of lysine (7.37 g/100g CP), threonine (3.06 g/100g CP), and histidine (3.00 g/100g CP) compared to beef (10.20, 3.85, 3.34 g/100g CP, respectively), pork (7.42, 3.43, 3.98 g/100g CP, respectively), and chicken (8.07, 4.31, 3.12 g/100g CP, respectively).

In addition to protein quality, red meat is a good source of healthy fatty acids and micronutrients (McNeill, 2014 and McAfee et al., 2010). The majority of the fat humans consume from beef is intra-muscular fat, which is approximately 50% unsaturated fatty acids (McAfee et al., 2010). Additionally, the ratio of polyunsaturated fatty acids to saturated fatty acids is 0.11 which is below the recommended level (0.40; McAfee et al., 2010). Iron, zinc, and vitamins B6 and B12 are found in beef, and beef is considered a major source of these micronutrients to the human diet (McAfee et al., 2010; McNeill, 2014), and reducing consumption of red meat can create deficiencies if the diet is not adjusted accordingly.

Estimating human-edible protein

Models explaining beef production efficiency utilize diets not common in actual beef cattle production in the United States or over simplify diets fed (Rotz et al., 2013; Peters et al., 2014, 2016). For example, Peters et al. (2014) considered soybean meal (9%), corn (85%), and pasture (6%) as the diet for feedlot cattle. Rotz et al. (2013) expanded dietary feed ingredients slightly compared to Peters et al. (2014), but considered grass, triticale, corn, soybeans, and alfalfa the only feed sources. Although roughage inclusion is similar to Peters et al. (2014) ranging from 6 to 10% DM of the diet, cereal grain inclusion is typically 60 to 70% DM (Samuelson et al., 2016). In surveys conducted by Asem-Hiablie et al. (2015) and Samuelson et al. (2016), corn-milling byproducts comprise between 10 and 20% DM of the diet. The stocker sector uses winter pastures and native grasses as the primary dietary ingredients and uses supplements to alleviate deficiencies. Corn grain, soy hulls, wheat middlings, cottonseed cubes, and dried distillers’ grains (DDG) are common supplements fed to stocker cattle (Horn et al., 1996; Buttrey et al., 2012; Asem-Hiablie et al., 2015). Similar to the stocker sector, the cow-calf sector primarily grazes forage with supplementation to address deficiencies in the forage. Some supplements fed in the cow-calf sector include protein cubes, cottonseed cubes, distillers' grains, corn gluten, and soy hulls (Asem-Hiablie et al., 2016). Additionally, hay is often fed if standing forage is insufficient for grazing (Asem-Hiablie et al., 2016; Young et al., 2018).

Beef production in the United States is supported by a cow herd which primarily grazing human-inedible forages. Minor supplementation occurs in the cow-calf sector, and of the supplements listed previously (Asem-Hiablie et al., 2015), corn and other cereals grains are human-edible. Most cereal grains are human-edible and most often fed in the feedlot sector (Table 1; Samuelson et al., 2016). When comparing finishing rations in Nebraska, California, and South Korea, corn (human-edible) was the primary feed ingredient in both Nebraska and California (70 and 48% respectively), but byproducts were the primary feed ingredient (51%) in South Korea (CAST, 1999).

Table 1. Human-edible fraction of various feedstuffs.

	CAST, 1999	Wilkinson, 2011	Ertl et al., 201
Cereal grains[1]	0.60 – 0.70	0.80	0.4 – 1.0
Byproducts[2]	0	0.20	0
Soybeans, soybean meal	0.70	0.80	0.50 – 0.93
Silages	0	0	0.19 – 0.45
Peas	n.a.	n.a.	0.70 – 0.90

[1] Cereal grains include barley, corn, oats, wheat, sorghum, triticale, rye.

[2] Byproducts include cereal brans, molasses, corn gluten feed, corn milling byproducts, dried beet pulp

Ertl et al. (2015) defined low, medium, and high estimates of human-edible protein fractions of feedstuffs depending on technology available to process feedstuffs into human-edible products. Silages were considered partially human-edible by Ertl et al. (2015); however, they were considered human-inedible by CAST (1999) and Wilkinson (2011).

Finishing diets in South Korea were estimated to be 12% human-edible compared to 69 and 46% human-edible for Nebraska and California, respectively (CAST, 1999). However, in the United States production of corn-milling byproducts has increased since the early 2000's (Hoffman and Baker, 2010), which may decrease the fraction of human-edible feeds in finishing diets today compared to CAST (1999). When beef cattle diets were compared to swine and poultry diets, Wilkinson (2011) estimated beef cattle diets contained 17 and 28% less human-edible feeds, respectively.

Estimating human-edible protein production from livestock systems becomes slightly more difficult, especially for beef production as the system is not as integrated as pork or poultry production. There is little incentive to vertically integrate beef production because of the long production cycle, variety of genetics and the industry is widely dispersed throughout the United States. In comparison, pork and poultry have a small region where production occurs and their production cycle is shorter which allows for genetic improvements to occur quicker (Ward, 1997). The beef value chain is comprised of 3 sectors; cow-calf, stocker, and feedlot. Estimating human-edible protein for each sector becomes difficult. In the cow-calf sector, outputs are weaned calves (minus retained replacement heifers), cull cows, and cull bulls. For the stocker and feedlot sectors, there is marginal gain in human-edible protein since steers and heifers are not born in these sectors. The beef value chain is the sum of the three sectors.

Furthermore, calculating human-edible protein produced is difficult for each sector of the beef value chain because it cannot be assumed all classes of cattle have the same dressing percentage or carcass to retail conversion. In a study conducted by Bruns et al. (2004), dressing percentage of Angus steers increased from 57.1 to 65.6% when hot carcass weight increased from 208 to 380 kg. Compared to feedlot cattle, cull cows have a lower dressing percentage. Schnell et al (1997) fed cull cows for 0 to 56 d, and reported increased body condition score (4.0 to 6.8, respectively) and dressing percentage (49.5 to 52.7%, respectively), which was lower overall than dressing percentages of feedlot steers reported by Bruns et al. (2004).

To calculate the human-edible portion of beef production for the livestock system, Ertl et al. (2016) used carcass weights and subtracted bones, waste losses between slaughter and consumption, and meat used for pet food production from carcass weight. The remainder was multiplied by percent protein in a beef carcass according to USDA (2016). Additionally, Ertl et al. (2016) accounted for human-edible byproducts (25% of blood, heart, tongue, liver, and kidney). Peters et al. (2014) recognized the three sectors of the beef value chain when calculating feed inputs, but estimated beef produced using a single dressing percentage and carcass to retail conversion. While estimating human-edible protein is a relatively new concept (Ertl et al., 2016; Flachowsky et al., 2017), many have used kg of beef produced or kg of carcass weight as a proxy (Capper, 2011; Stackhouse-Lawson, 2012). However, Capper (2011) and Stackhouse-Lawson (2012) only reported on the beef value chain as a whole and were unable to segregate results by sector. It is important to estimate sector level human-edible protein outputs. Improvements to the value chain can only be made when the shortcomings of the production system are known.

An equation was proposed by Simpfendorfer (1974) for estimating body protein in cattle using empty body weight (EBW). Later, the NASEM (2016) adopted and validated the equation estimated by Simpfendorfer (1974). Using EBW to estimate human-edible protein would alleviate difficulties estimating human-edible protein for each sector, unlike methods used by Peters et al. (2014) and Ertl et al. (2016). Empty body weight includes human-inedible products (hide, blood, feet, mesenteric fat, etc.). Similar to methods proposed by Ertl et al. (2016), body protein should be adjusted following initial body protein equation. Accounting for inedible products in EBW in the initial body protein equation could inflate actual body protein (kg). Additionally, steers, heifers, and cull cows have differing proportions of inedible product in empty body weight (25.0, 24.2, and 22.1%, respectively; Terry et al., 1990, Apple et al., 1999). An assumption must be made that, on average, there are similar amounts of protein in inedible products as there are in edible products, however this methodology proposed is likely more accurate that methodology found previous in literature.

The quadratic nature of the body protein equation would likely result in greater amounts of human-edible protein credited to the cow-calf sector compared to the stocker and feedlot sectors. Additionally, this equation can be applied to all classes of animals, unlike dressing percentage. The body protein equation is quadratic resulting in less protein deposited as cattle continue to gain weight. In agreement with this, Jesse et al. (1976) and Oltjen and Garrett (1988) reported cattle deposit less protein and more body fat for each kilogram of live weight gain. When comparing cattle that were 341, 454, and 545 kg BW, the composition of gain for those cattle were 15.09, 13.20, and 12.30% protein, respectively (Jesse et al., 1976).

Beef cattle are known as the least efficient livestock system when converting feed consumed into kilograms of weight gain or edible product (Godfray et al., 2010; Herrero et al., 2013). Godfray et al. (2010) estimated beef production systems require 4 to 7 kg more cereal grains to produce 1 kg of meat compared to pork and poultry production systems.

Peters et al. (2014) reported beef cattle require the most feed to produce a kg of edible product (14.30 kg feed DM). Pork production was intermediate (2.63 kg feed DM) of beef and poultry production (1.89 kg feed DM; Peters et al., 2014). A bias was introduced when feed comprises human-edible and -inedible ingredients, however the only output considered was edible product. Furthermore, this efficiency ratio is further inflated when diets are not reflective of actual production practices and edible product is inaccurately predicted as discussed previously. Herrero et al. (2013) reported pork production systems to range from 25 to 140 kg DM/kg HeP and poultry production ranged from 15 to 60 kg DM/kg HeP; whereas ruminant meat production was 100 to 2,200 kg DM/kg HeP and ruminant milk production had feed efficiencies ranged from 40 to 400 kg DM/kg HeP. Similar to Peters et al. (2014), Herrero et al. (2013) characterized diets using 4 feed groups (grass, straws, grains, and other) with no attempt to account for human-edible feeds. Additionally, estimates by Herrero et al. (2013) were inflated when feed efficiency was scaled to only human-edible protein produced.

However, pigs and poultry consume the majority of cereal grain fed to livestock, whereas beef production systems primarily graze forages (Wilkinson, 2011; Herrero et al., 2013). Bywater and Baldwin (1983) proposed redefining feed efficiency to consider the ratio of human-edible inputs to human-edible outputs. This efficiency ratio clarifies the role of livestock and the competition for human-edible feeds between livestock production and human consumption. As previously mentioned, beef cattle diets have less human-edible feeds in their diets compared to swine and poultry diets (Wilkinson, 2011); thus, when comparing conversion efficiencies of human-edible products to human-edible feeds, beef cattle may have conversion efficiencies more similar to or greater than swine and poultry.

In a comparison of Austrian livestock production systems, Ertl et al. (2016) reported beef cattle (1.52) have greater human-edible protein conversion efficiency (HePCE; human-edible protein output to human-edible protein input) than swine (0.36) and laying hens (0.63). In the United Kingdom, beef cattle production was more efficient (HePCE ranging from 0.5 to 1.11 depending on type of production system) than pork and poultry production (HePCE of 0.38 and 0.48, respectively; Wilkinson, 2011). In a worldwide assessment of livestock production, Mottet et al. (2017) reported monogastric systems require 0.4 kg more human-edible feed than ruminant production systems to produce 1 kilogram of boneless meat. When considering HePCE, ruminant production systems were superior to monogastric production systems (1.00 vs 0.24, respectively; Mottet et al., 2017). When byproducts replaced 50% of concentrate intake (1.05 kg DM) of beef cattle, the HePCE increases from 0.7 to 1.3 (Flachowsky et al., 2017).

Net protein contribution

Improvement (or reduction) in protein quality when human-edible feeds are converted into meat is assessed with a metric called protein quality ratio (PQR) which uses DIAAS of beef and the feedstuffs fed. HePCE as previously described. It has been documented beef (1.84) has a greater protein quality, and therefore, have a greater PQR than pork (1.74) and poultry (1.43; Ertl et al., 2016). Net protein contribution multiplies PQR by the HePCE metric mentioned previously. When NPC is greater than 1 it indicates the production system is contributing to meeting humanity’s protein requirements; whereas a value less than 1 indicates a production system in competition with society for human-edible feeds.

When incorporating protein quality with conversion efficiencies, beef cattle (NPC of 2.81) become a net contributor of human-edible protein to society, unlike pork (0.64) and poultry (0.52) production were not. Although Ertl et al. (2016) was able to convey a more complete comparison of livestock production, sector level NPC values which would help create strategies improving this metric were not investigated. Because NPC encompasses beef production practices and dietary characteristics, there are likely many drivers and they should be explored.

Enteric methane from beef production

When analyzing a new metric for use in sustainable livestock production, it is easy disregard other impacts. For example, increasing NPC may result in negative environmental costs. Using a decision support tool that balances NPC with enteric methane production allows the end user to create an optimal sustainable solution.

Level of intake, type of carbohydrate consumed, feed processing, and ionophore usage affect enteric methane production (Johnson and Johnson, 1995; Van Nevel and Demeyer, 1996; NASEM, 2016), and these factors may have impacts on NPC as well. Under *ad libitum* consumption, enteric methane production from cattle is approximately 6% of GE when forage is grazed and can range from 2.5 to 4.0% of GE for concentrate-based diets (Johnson and Johnson, 1995; Beauchemin and McGinn, 2005; Hales et al., 2012). Grainger and Beauchemin (2011) identified high starch diets as a management strategy to reduce enteric methane production. As starch increased from 1.98 to 4.14 kg/d in *ad libitum* fed steers, methane production was reduced from 534 g/kg carcass gain to 325 g/kg carcass gain (Mc Geough et al., 2010).

A significant cost associated with the conversion of biomass into edible protein is enteric methane which contributes to GHG emissions (Johnson and Johnson, 1995). Beauchemin et al. (2010) approximated enteric methane contributed to 63% of GHG emissions from the beef production system. Of that, 84% of enteric methane produced by beef production is attributed to the cow-calf phase (Beauchemin et al., 2010). Similarly, in a model of California beef production it was estimated that 65% of methane emissions is attributable to cow-calf production with stocker and feedlots phases making up the remainder (Stackhouse-Lawson et al., 2012).

Opportunities to improve net protein contribution and enteric methane production

Intensifying cow-calf production can improve beef cattle's land use or support an operation when grazing forage is limited (Warner et al., 2011; Sawyer and Wickersham, 2013). Digestion of diets is increased when intake is decreased in cattle (Galyean, 1979 and Zinn and Owens, 1983). Additionally, providing an energy dense diet in limited amounts compared to low-energy diets fed *ad libitum* can reduce gastrointestinal mass (Sainz and Bentley, 1995). Because portal drained viscera and liver contribute 25 to 30% of energy expenditures (Huntington and Reynolds, 1987 and Ferrell, 1988), limit-feeding an energy-dense diet to beef cattle may reduce maintenance energy requirements. Additionally, methane production is related to gross energy (GE) intake (Johnson and Johnson, 1995).

Cattle typically spend less time in the feedlot phase than the cow-calf phase; however, the majority of cereal grain consumed by cattle is primarily in the feedlot phase.

According to Samuelson et al. (2016), grain inclusion in feedlot diets ranges from 50 to 90% of DM. Because HeP fed to cattle is usually in the form of cereal grain, the feedlot phase has potential to compete with humans for HeP. In 2007, 83% of feedlot nutritionists included grain coproducts at 16.5% of the finishing diet (Vasconcelos and Galyean, 2007). Over the past 15 years, corn-milling byproduct production has increased becoming more available to feedlots (Hoffman and Baker, 2010). Currently, 97% of nutritionists surveyed include grain byproducts in finishing diets and those byproducts are the primary protein source (Samuelson et al., 2016). Increasing byproduct inclusion may have the potential to improve NPC of the feedlot (Ertl et al., 2015a; Flachowsky et al., 2017). Additionally, feedlots continue to produce finished cattle at heavier end weights (USDA-ERS, 2018) which may affect a feedlot's NPC.

Technology and efficiency of all sectors in the beef value chain has improved over the last fifty years. It is evident from the rising and/or constant production of beef over the years compared to the size of the cow herd (USDA-ERS, 2019; USDA-NASS, 2019). Implants and ionophores are used in multiple sectors of the beef value chain, while beta-agonists and other feed additives are used in the feedlot sector. According to NASEM (2016), prediction equations for dry matter intake (DMI) have an adjustment factor to reduce DMI (3%) when monensin (an ionophore) is fed, DMI is adjusted upward (6%) when anabolic implants are used. Additionally, monensin improves average daily gain (ADG), feed efficiency and reduces methane production (g/kg HCW) in feedlot cattle (Duffield et al., 2012; Stackhouse-Lawson et al., 2015). Beta-adrenergic agonists (β-AA) are fed during the last days of the feeding period for feedlot cattle. Reduced adipose tissue accretion and increased muscle mass occur when β-AA are fed (Ricks et al., 1984; Johnson et al. 2014), however there is no DMI adjustment for cattle fed β-AA (NASEM, 2016).

Conclusion

Sustainability is a balancing act between societal benefits, environmental concerns, and profitability from beef cattle production. United States beef production contributes 20% of world beef production (USDA-FAS, 2018), making the United States the global leader in beef production. As a major supplier, United States beef production needs accurate modelling of sustainability. Using representative diets and production characteristics is necessary to demonstrate effects of beef production on society, environment, and economic viability of the industry.

Although, enteric methane emissions from beef cattle production continues to be a concern for opponents to beef production, environmental impacts of beef have been reduced over the past 40 years. Implants, feed additives, and β-AA are available to improve performance in cattle and reduce environmental impacts of beef production. Increased usage and availability of corn milling byproducts in the feedlot sector has occurred in since the early 2000's. Beef cattle are considered inefficient in converting feed to live weight gain or carcass weight, Mottet et al. (2017) and Ertl et al. (2016) demonstrated beef cattle are more efficient than nonruminants in converting human-edible proteins in feed to human-edible protein in meat. Net protein contribution was estimated by Ertl et al. (2016) for Austria's livestock systems; however, NPC has not yet been estimated for United States production systems. In addition, NPC should be balanced against other measures of sustainability.

CHAPTER II

ESTIMATION OF HUMAN-EDIBLE PROTEIN CONVERSION EFFICIENCY, NET PROTEIN CONTRIBUTION, AND ENTERIC METHANE PRODUCTION FROM BEEF PRODUCTION IN THE UNITED STATES[1]

Overview

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. Net protein contribution was calculated by multiplying the ratio of human-edible protein (HeP) in beef to the HeP in feedstuffs by the protein quality ratio (PQR). Protein quality ratio 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 2 sets of dietary inputs and 2 sets of production parameters. Dietary inputs represented either inputs used in a previous report estimating HeP (PD) or inputs more representative of conventional beef production systems (CD). Production parameters were either drawn from previous reports (PP) or chosen to characterize current industry standards (CP). The HeP conversion efficiency (HePCE) for CDCP (kg HeP yield/kg HeP

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[1] Reprinted with permission from "Estimation of human-edible protein conversion efficiency, net protein contribution, and enteric methane production from beef production in the United States." by J. R. Baber, J. E. Sawyer, T. A. Wickersham. 2018. *Translational Animal Science*, *2*(4), 439-450. Copyright 2018 by Oxford University Press.

input) was greatest in the cow-calf sector (2,640.83) compared to stocker (5.22) and feedlot (0.34), and other scenarios followed a similar trend. Additionally, the entire production system had a HePCE of 0.99 for CDCP, the PDPP scenario estimated HePCE to be 0.46; other scenarios were intermediate. For the CDCP scenario, 56, 10, and 34% of the HeP was produced in the cow-calf, stocker, and feedlot sectors; PDPP was similar (59, 13, and 28%, respectively). Protein quality ratio 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 kg 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 per kg HeP). 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.

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 and energies consumed and produced, and Ertl et al. (2016a) built on Wilkinson's (2011) work by accounting for quality of human-edible protein (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 predictions equations established by 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 representative 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). Additionally, we use methodology presented by Wilkinson (2011) and Ertl et al. (2015b, 2016a, and 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 body weight (EBW) is a quadratic function where a greater proportion of gain is deposited as fat instead of protein as body weight 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 empty body weight (EBW):

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

Empty body weight was defined as the weight of an animal with the gastrointestinal tract emptied of digesta. Empty BW includes inedible byproducts (IBP) like 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:

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

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, was 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 2). 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., 2016). 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 were summed across production sectors.
Conversion of HeP_f into beef is an important metric to compare. Calculation of the conversion efficiency of HeP (HePCE; Ertl et al., 2016b) was as follows:

Table 2. Human-edible fraction and digestible indispensable amino acid score (DIAAS) of feed ingredient

Item	Human-edible fraction[1], %	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/additives	0	-
Soybean meal	100	96.0
Tallow	0	-

[1] Percent of feed ingredient that is human-edible

$$\mathrm{HePCE} = \frac{\mathrm{HeP_p}}{\mathrm{HeP_f}}$$

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

Assessing protein quality using DIAAS

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:

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

Where: DIAAS = digestible indispensable amino acid score, %

Digestible indispensable amino acids were considered as any of the ten 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 to 3 years. 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). Protein quality ratio 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 consumed in each production sector.

Net protein contribution

Net protein contribution 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 the beef value chain is competing with humans for protein.

Scenario design

Scenarios were arranged as a 2 × 2 factorial with 2 sets of dietary inputs and 2 sets of production parameters. Dietary inputs were either ingredients used in Peters et al. (2014; PD) or current diet (Table 3; CD). Production parameters were from Peters et al. (2014; PP) or parameters characterizing the current industry (Table 4; CP). Thus, scenarios compared were: 1) diets and production parameters by Peters et al. (2014; PDPP), 2) current industry diets and production parameters by Peters et al. (2014; CDPP), 3) diets by Peters et al. (2014) and current industry production parameters (PDCP), and 4) common

Table 3. Composition of diets fed in model scenarios

	Dietary input[1]	
Item	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/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
Soybean meal	6.00	
Distillers' grains with solubles		29.58
Urea		0.72
Molasses		2.79
Mineral/additives		1.49
Tallow		0.62

[1] Peters = diets from Peters et al. (2014); Current = current industry diets

current industry diets and production parameters (CDCP). These four scenarios (PDPP, CDPP, PDCP, and CDCP) were compared based on a 1,000 cow herd.

Production parameters

Production parameters and body weights of scenarios evaluated in this study are presented in Tables 4 and 5, 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 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 yrs 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

Table 4. Production and management parameters for scenarios evaluated

	Dietary Input[1]			
	Peters		Current	
	PDPP[2]	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)[3], %	1.5	1.3	1.5	1.3
Mortality rate (lightweight)[3], %	1.5	2.0	1.5	2.0

[1] Peters: Diets from Peters et al. (2014); Current: current diets fed in the industry

[2] 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

[3] Heavyweight = calves placed weighing more than 272 kg; Lightweight = calves placed weighing less than 272 kg

Table 5. Body weight of each animal class in the production system used in the model

	Dietary input[1]			
	Peters		Current	
Item	PDPP[2]	PDCP	CDPP	CDCP
Body weights, 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

[1] Peters: Diets from Peters et al. (2014); Current: current diets fed in the industry

[2] 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

Table 6. Intake estimates for each stage of production and scenario

	Dietary input[1]			
	Peters		Current	
	PDPP[2]	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

[1] Peters = diets from Peters et al. (2014); Current = current industry diets

[2] 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

a 28-d receiving and transition period). Days on feed for cattle in CP scenarios for both the stocker and feedlot phases were dependent upon gain prediction equations from the 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).

Diet descriptions

Diets and intake levels for each scenario considered in this paper are presented in Tables 3 and 6, 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 non-zero denominator.

During the stocker phase, PD scenarios grazed pasture and were supplemented corn, whereas the CD scenarios grazed winter wheat pasture and 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, dried distillers' grains (DDG), and modified wet corn gluten feed. In the feedlot, PD scenarios were fed a total mixed ration (TMR) 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 4 different diets (7 d each) where roughage decreased from 40% to approximately 8% of DM (CD scenarios; Samuelson et al., 2016).

Enteric methane production

Based on diet consumed and proportion of forage, total enteric methane production (kg) was calculated according to equations from NASEM (2016). The NASEM (2016) categorizes equations for methane production into 3 categories: 1) >40% forage in the diet, 2) 20-40% forage in the diet, and 3) <20% forage in the diet. Thus, equations presented in NASEM (2016) within each category were averaged according percent of forage in the diet. Total enteric methane production was reported per kg HeP to scale environmental effects to human-edible production. Summation of enteric methane production and HeP was used to calculate enteric methane per kg HeP for the entire beef cattle value chain. Equivalents of CO_2 were calculated as methane (kg) 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 the PQR (Table 7). The DIAAS (%) represents the ability of a human-edible feedstuff to meet the protein requirements of a child 0.5 to 3 years of age. Human-edible feedstuffs used in beef cattle diets have relatively low DIAAS (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 soybean meal 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 soybean meal for PD to distillers' grains with solubles for CD based on survey data from Vasconcelos and Galyean (2007) and Samuelson et al. (2016). Soybean meal provides more indispensable amino acids compared to 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 were 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 (DIAAS of beef) was greater than the protein quality consumed by the cattle.

Human-edible protein 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 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). Additionally, 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). Human-edible protein fed in the stocker sector averaged 1,189 kg for CD scenarios and was 10,716 kg 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 HeP) and PDCP (9,653 kg HeP_f) than CDPP (1,356 kg HeP_f) and PDPP (15,380 kg 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 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 7). 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 HeP_p)

Table 7. Estimation of protein quality ratio (PQR), human-edible protein (HeP) conversion efficiency, and net protein contribution of scenarios.[1]

	Dietary input[2]			
	Peters		Current	
Item	PDPP[3]	PDCP	CDPP	CDCP
Cow-calf				
Diet DIAAS[4]	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[5]	3,314.56	2,573.51	3,030.53	2,640.83
NPC[6]	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

[1] Results are estimated for a 1,000 cow herd

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

[3] 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

[4] DIAAS = digestible indispensable amino acid score

[5] HePCE = human-edible protein conversion efficiency

[6] NPC = net protein contribution

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 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 HeP_p for PP and CP, respectively.

Human-edible protein conversion efficiency in the cow-calf sector was 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 body weights (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 versus some other system; rather, that 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 bull 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 worldwide 62% of feedlot diets were human-edible. A possible explanation of this discrepancy is that non-human-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 result 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 consumed. Ertl et al. (2016b) reported a greater HePCE of 1.52 for the Austrian beef production system. Differences in our model compared to 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 was human-edible, respectively). In contrast, Austria's cattle production system (excluding the finishing phase) fed a greater amount (9%) of dietary protein as HeP, which resulted in the lower HePCE. In an extensive production system, like upland suckler beef production in the United Kingdom, HeP was fed in relatively large amounts as well (674 kg concentrate/head) compared to 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 to 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 two 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 estimate the NPC was 0.73 for the system (Ertl et al., 2016b) and these were not contributing to HeP supply.

Net protein contribution 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 a NPC value of 2.81 which is slightly lower than the PD 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 8). 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. Additionally, a cow produces about 55 kg of methane per year (Capper, 2011; Crutzen et al. 1986), 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 (10,085 kg) because 22.8% of calves went directly to the feedlot and the diet was more digestible when compared to 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.

Table 8. Effect of dietary inputs and production parameters on methane production in the beef cattle value chain.[1]

	Dietary input[2]			
	Peters		Current	
Item	PDPP[3]	PDCP	CDPP	CDCP
Cow-calf				
Methane, kg/herd	114,118	128,431	129,201	127,048
Methane, kg/kg of HeP_p[4]	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
CO2 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
CO2 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
CO2 Equivalents/kg of HeP_p	64.60	80.83	77.17	84.38

[1] Results are estimated for a 1,000 cow herd

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

[3] 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

[4] HeP_p: Human-edible protein produced

Methane was expressed per kg 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 kg HeP_p, which agrees with our estimate of 4.53 kg of methane per kg of HeP produced for CDCP in the cow-calf scenario. While the cow-calf sector produced 55% of HeP in the beef value chain, the majority of methane production was also produced in this sector. This resulted in the cow-calf sector having a greater ratio of methane to HeP_p 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 kg of HeP_p) had a slightly higher ratio than all other scenarios (1.76 kg methane per kg of HeP_p). In the feedlot, more HeP (kg) was produced than methane (kg; 0.94 kg methane per kg of HeP_p in CDCP). Across the entire beef value chain, 3.05 kg methane per kg of HeP produced was produced in CDCP, which greater than the estimate by Capper (2011) of 2.76 kg methane per kg of HeP_p for beef production in the United States in 2007. Capper (2012) estimated 2.51 kg of methane per kg of HeP_p was produced for a conventional beef production system in the United States, further supporting our results.

In the entire beef value chain, CO_2-equivalents ranged from 61.60 (PDPP) to 84.38 kg (PDCP). A range of 75 to 170 kg of CO_2-equivalents per kg 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 to 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. The most methane and HeP was produced in the cow-calf sector, indicating that there are tradeoffs 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 conversion efficiency of HeP was low (less than one), the ability of cattle to upcycle protein from low-quality to high-quality allowed for these sectors to have a net protein contribution of greater than one. Based on 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 non-ruminant systems.

CHAPTER III

EVALUATION OF NET PROTEIN CONTRIBUTION, METHANE PRODUCTION, AND NET RETURNS FROM BEEF PRODUCTION AS DURATION OF CONFINEMENT INCREASES IN THE COW-CALF SECTOR

Overview

Intensification of cow-calf production may provide a sustainable solution for meeting increasing beef demand in the face of diminishing resources. However, intensification with its greater reliance on cereal grains potentially decreases the upcycling of human-inedible protein into beef. A previously described model was used to evaluate cow-calf intensification on beef's ability to meet human protein requirements. Four scenarios were compared, based on a 1,000 cow herd: 1) Conventional cow-calf production system (0CON), 2) cows limit-fed in confinement for 4 months after weaning (4CON), 3) cows limit-fed in confinement for 8 months after breeding (8CON), or 4) cows limit-fed in confinement year-round (12CON). Changes were not made to either the stocker or feedlot segments of the beef value chain. Net protein contribution (NPC) was calculated by multiplying the ratio of human-edible protein (HeP) in beef produced to HeP in feed by the protein quality ratio. A NPC >1 indicates that the production system is positively contributing to meeting human requirements, whereas a NPC < 1 indicates the sector or value chain is competing with humans for HeP. Methane was estimated based on proportion of forage in diet and total methane production was reported per kg HeP. In the cow-calf sector, HeP conversion efficiency (HePCE) decreased from 2,640.83 to 0.37 while methane production decreased from 4.53 to 1.82 kg/kg HeP produced as the length

of intensification increased from 0CON to 12CON. Decreased HePCE in resulted in NPC values for cow-calf sector of 8,036.80, 4.93, 2.19, and 1.28 for 0CON, 4CON, 8CON, and 12CON, respectively. Protein quality ratio of the entire beef value chain increased from 3.15 to 3.33, while HePCE decreased from 0.99 to 0.39 as length of intensification increased from 0CON to 12CON. For the beef value chain, NPC was 3.11, 2.30, 1.73 and 1.31 for 0CON, 4CON, 8CON and 12CON, respectively. Across the value chain, confinement of cows for 12 months decreased enteric methane from 3.05 to 1.53 kg/kg HeP (0CON and 12CON, respectfully). Additionally, profitability of the cow-calf operation decreased from $249.34 to 102.16 per cow as intensification increased. Of confinement scenarios, probability of loss to an operation was least for 4CON (4%). Feed costs increased by $260.79 per cow for 0CON when drought conditions existed (0COND). Total methane production was reduced from intensification and none of the scenarios evaluated competed with humans for HeP.

Introduction

Intensification of cow-calf production can involve providing a limited amount of an energy dense diet to cows in drylots for either a portion of the year or year-round. During periods of limited forage availability (i.e. drought), confinement can be a particularly useful tool as nutrient requirements can be met without damaging future forage production and preventing partial or complete herd liquidation. Drought can result in substantial economic loss to ranchers because of increased feed and supplementation costs (Eakin and Conley, 2002) and/or decreased revenues (Ziolkowska, 2016). Additionally, sustainable intensification can help meet the increasing demand for animal protein without increasing land requirements for cow-calf production (Sawyer and Wickersham, 2013).

Upcycling of human-inedible feed protein into high-quality beef potentially decreases with intensification as dependence on human-edible feedstuffs tends to increase when cattle are fed in confinement. Intensified production (i.e. feedlots) had lower human-edible protein conversion efficiency (HePCE) when compared to extensive grazing settings (i.e. conventional cow-calf production), but methane production decreased when cattle were moved from an extensive to intensive production system (Wilkinson and Lee, 2018; Baber et al., 2018). Utilization of byproducts and other less expensive, human-inedible feeds in limit-fed, high-energy diets in intensive systems can mitigate the tradeoff between HePCE and methane production while creating a more economically sustainable operation. When more dried distillers' grains were fed in feedlots, HePCE increased (Flachowsky et al. 2017; Baber et al., 2018); a similar effect was observed when evaluating coproduct usage in dairy production systems (Ertl et al. 2015).

Thus, our objective was to evaluate tradeoffs between human-edible protein consumed and methane produced in the cow-calf sector and the beef value chain as length of confinement increases in cow-calf systems. Additionally, an economic analysis was conducted to compare intensified cow-calf systems to conventional pasture based grazing during periods of adequate or limited forage availability.

Material and methods

Model overview

Our summative model of net protein contribution (NPC) incorporated common production practices in the United States and prediction equations established by NASEM (2016). Calves from the cow-calf sector flowed into the stocker sector and calves from the stocker sector flowed into the feedlot sector. Therefore, the cow-calf sector was representative of an entire production year, and the stocker and feedlot sectors were representative of the time the calves occupied those facilities. Production parameters were consistent with common beef cattle practices combined with the systems approach of Peters et al. (2014). Additionally, we used methodology presented by Wilkinson (2011), Ertl et al. (2015, 2016a, and 2016b), and Baber et al. (2018) to estimate the NPC to the human food supply from various beef cattle production scenarios in the United States. Human-edible protein conversion efficiency, digestible indispensable amino acid score (DIAAS), protein quality ratio (PQR), and NPC were estimated for each sector and the entire system according to methods described in Baber et al. (2018). Protein quality ratio uses the DIAAS of HeP consumed and produced by cattle to capture the improvement (or decline) in protein quality.

To balance environmental effects were societal benefits, total enteric methane production was reported relative to kg HeP. Summation of enteric methane production and HeP was used to calculate enteric methane per kg HeP for the entire beef cattle value chain (Baber et al., 2018). Enteric methane production was based on diet consumed and proportion of forage and was calculated according to equations from NASEM (2016). Equations presented in NASEM (2016) within each category (3 categories based on percent forage of diet) were averaged according percent of forage in the diet. Equivalents of CO_2 were calculated as methane (kg) multiplied by 25 (IPCC, 2007).

Scenario design

Four management scenarios were compared to determine the effect of increasing intensification of cow-calf production on net protein contribution of beef cattle. Scenarios were based on a 1,000 cow herd. Management scenarios considered were: 1) cow-calf production sector grazed pasture continuously for the production year (0CON), 2) cows were confined in drylots and limit-fed from time of weaning until 30 d prior to calving (approximately 120 d; 4CON), 3) cows were confined in drylots and limit-fed from d of weaning until breeding (approximately 240 d; 8CON), and 4) cows were confined in drylots and limit-fed for the entire production year (12CON). When cows were not limit-fed in drylots, cows were grazing pasture and managed under conditions of 0CON. Management scenarios focused only on the cow-calf sector, with stocker and feedlot sectors held constant. Responses were analyzed for cow-calf sector and entire beef value chain.

Production system and parameters

Three subsystems were considered in the beef value chain: cow-calf, stocker, and feedlot sector. Production parameters used in our model were described by Baber et al. (2018). A portion of the heifer calves were retained as replacement heifers, and the remainder along with steer calves were sent to either the stocker sector or feedlot sector. For all scenarios, the production parameters were held constant and all calves flowed into the stocker and feedlot sectors in a similar manner.

Diet descriptions and intakes

Cattle in the cow-calf sector either grazed Bermudagrass pasture (inedible to humans) and supplemented with protein (dry distillers' grains; inedible to humans) or were placed in a drylot and limit-fed a high-energy ration (Table 9). Placing cattle in drylots allows producers to precisely deliver nutrients required by the animal. Pasture and supplement intakes for dry cows, lactating cows, bulls, replacement heifers, and calves were estimated using the NASEM (2016). When cattle were confined, all cattle except

Table 9. Ingredient and nutrient composition of diets fed in the cow-calf sector

	Diet		
Item	GRASS	CON	CONH
Ingredients, % DM basis			
Alfalfa hay			25.59
Bermudagrass, fresh	94.08		
Wheat straw		35.63	
Corn	0.01	28.90	40.13
Distillers' grains	4.71	27.79	26.91
Urea		2.74	
Molasses		3.71	4.56
Mineral	1.20	1.23	2.81
Nutrient composition, %DM basis[1]			
OM	91.43	94.97	94.52
CP	16.62	16.67	16.89
NDF	64.97	38.41	23.11
ME	2.09	2.55	2.70
NE_m, Mcal/kg	1.24	1.65	1.78
NE_g, Mcal/kg	0.67	1.04	1.16

[1] GRASS: pasture based system; CON: diet fed during confinement; CONH: diet fed to replacement heifers during confinement

[2] Estimated using NASEM (2016)

replacement heifers were fed a ration consisting of wheat straw (36%, inedible), corn (29%, source of HeP), dried distillers' grains (DDG; 28%), and supplement (7%). Replacement heifers were fed a separate growing ration consisting primarily of alfalfa hay (26%; inedible), corn (40%), DDG (27%), and supplement (7%). The supplement included in the limit-fed diet and replacement heifer diet contained molasses which was considered a source of HeP.

Total energy requirement of each animal class, intake of each diet, and energy provided by those diets are presented in Table 10. Nursing calves were predicted to consume 1% of BW while in confinement for the 12CON scenario according to research conducted by Jenkins et al. (2015). Nursing calves were predicted to consume less feed DM and feed energy in confinement than on pasture; however, the consumption of milk was not accounted for in our DM or energy calculations. During confinement, dry cows and bulls were fed to meet 80% of NASEM (2016) predicted maintenance requirements (6.40 and 10.42 Mcal NE_m/d, respectively). Cows were limit-fed at 80% maintenance based on previous research demonstrating cows increase maintenance efficiency under these conditions (Freetly and Nienaber, 1998; Trubenbach et al., 2018). Lactating cows were fed to meet 80% of NASEM (2016) predicted maintenance requirements plus the energy to meet lactation requirements (10.41 Mcal NE_m/d). Bred heifers were fed to meet maintenance energy requirements plus energy requirements for 0.50 kg BW gain/d and pregnancy (10.72 Mcal NE_m/d). Dietary energy was not restricted for lactation or bred heifers because research is limited determining the effects of moderate energy restriction in confinement during these stages of production. For all scenarios with confinement, replacement heifers were developed on a stair-step nutrition program. When heifers

Table 10. Dry matter and energy intake of animal classes in production sectors

	Total Energy Requirement[2]	Diet[1]		
		GRASS	CON	CONH
Cow-calf sector intakes, kg DM/d				
Heifer calf		3.33	1.83	
Steer calf		3.47	1.92	
Replacement heifers		6.47		7.06
Bred heifers		8.43	8.40	
Dry cow		10.53	3.88	
Lactating cow		12.85	5.31	
Bull		18.54	6.32	
Cow-calf sector NE intake, Mcal/d				
Heifer calf	5.38	4.13	3.01	
Steer calf	5.46	4.30	3.16	
Replacement heifers	8.25	8.03		10.14
Bred heifers	10.72	10.44	10.72	
Dry cow	8.00	13.05	6.40	
Lactating cow	12.01	15.93	10.41	
Bull	13.02	22.98	10.42	

[1] GRASS: pasture based system; CON: diet fed during confinement; CONH: diet fed to replacement heifers during confinement

[2] Predicted using NASEM (2016)

reached approximately 300 d of age, heifers were initially limit-fed for 41 d (1.7% BW) decreasing their maintenance requirement then fed at a greater rate (3.0% BW) for the remainder of the 90-d period to capture the benefits from the increased metabolic efficiency (Stribling et al., 2018). For the 0CON, replacement heifers were developed on pasture and managed as all other cattle grazing pasture with 4.71% of DMI as a protein supplement on average (dry distillers' grains, a non-HeP source).

Economic analysis

An economic feasibility analysis was completed for each of the four management scenarios (0CON, 4CON, 8CON, and 12CON). In addition, a fifth scenario (0COND) was added to compare the grazing scenario during limited forage availability to the confinement options. Scenarios 4CON, 8CON, and 12CON require capital investment in a mixer wagon and bunks ($6.20 per cow), but creates an alternative for the operation when limited forage is available for grazing. Extra costs for fencing, panels, and feed storage was not considered in this economic evaluation as confinement can occur within an existed pasture or sacrificed lot. Cows under the 0COND scenario were fed *ad libitum* Bermudagrass hay for 4 months of the year, to model an operation under drought conditions.

A stochastic simulation model using empirical distributions of key input variables was used to estimate returns for a cow-calf operation that calves in the spring. Stochastic variables in the model included weaning weights, price of weaned steers and heifers and input prices of feed ingredients. A budget for each system was developed to include these stochastic variables. Stochastic feed prices were linked to intake and days on feed to develop a total feed cost for each system. Costs for labor, fuel and repairs, as well as ration mixing and delivery were calculated from feed intakes and machinery capacity to reflect changes required by scenarios. Additionally, 4CON, 8CON, and 12CON had added fixed costs for a mixer wagon and concrete bunks needed to produce and deliver a TMR. Bunks were accounted for using straight line depreciation and a useful life of 10 years with no salvage value. Straight line depreciation was used for the mixer wagon with a useful life of 15 years and a $2,000 salvage value. Other production costs in the model included mineral supplementation while cattle were on pasture, vet supplies, utilities, and livestock interest. Land costs were estimated from USDA-NASS (2018) where pasture rental rate was $12 per 0.4 hectare and each cow was allotted 4.05 hectares.

Simulated probability distributions of net returns for each system for the 2018-2019 production year were used to determine which production system provided the least risk with greatest chance of profitability. Average net return for each system provides little information on the risk associated with each system. To choose, or to evaluate, the best option among risky alternatives, stochastic efficiency with respect to a negative exponential utility function (SERF) was used to rank these alternatives while accounting for differing levels of risk aversion of the decision maker (Hardaker et al., 2004; Ribera et al., 2004). This simulation was based on an annual enterprise budget; therefore, a negative exponential function was used instead of a power utility function. Certainty equivalence (CE) at differing levels of risk aversion can be used to determine the best alternative for individual producers, and the alternative with the greatest certainty equivalence will be preferred over all others at a given risk aversion coefficient.

Production data from a Brangus cow herd with an average weight of 503 kg were used in this simulation. A previous experiment was conducted to determine the effects of limit-feeding on cow and calf performance (Baber et al., 2016). Weaning weights from Baber et al. (2016) were used to estimate parameters in an empirical distribution of weaning weight. A mean weaning weight of steers (261 kg) and heifers (215 kg) and the percent deviation from the mean of experimental data were used as parameters in the empirical distribution.

Monthly historical cash prices from 1995 to 2017 were obtained from LMIC (2018a, 2018b) for corn, dried distillers' grains (DDG), alfalfa hay, and other hay. Historical price data was used to estimate parameters for prices using multivariate empirical (MVE) distributions. To estimate a stochastic forecasted wheat straw price, the stochastic forecasted hay price was discounted based on a TDN adjustment factor (TDN value of wheat straw was 72% of the TDN value of Bermuda hay). Monthly historical prices were detrended using linear regression, and fractional deviations from trend were calculated from residuals then used to simulate risk about the forecasted monthly mean prices for October 2018. Our model was developed to assume that all feed would be purchased at the start of the feeding period and feed would be delivered monthly in truck loads. Monthly historical price data for urea and molasses were also obtained from USDA reports (USDA-NASS, 2018). These prices were not included in MVE simulated prices mentioned previously due to lack of data and of linear trend in the historical data ($P > 0.85$). Both urea and molasses price distributions were simulated empirically using historical 5 year averages and fractional deviations from the average as the parameters.

Monthly historical prices from 1999 to 2017 were obtained from LMIC (2018c) for steers and heifers at auctions in Texas to estimate parameters for MVE distribution of prices. Steer and heifer prices were detrended using linear regression, and fractional deviations from trend were calculated from residuals then used to simulate risk about the forecasted mean prices for October of 2019, which is based on when calves would be weaned and sold. Multivariate empirical distributions were chosen for estimating ingredient prices and cattle prices to ensure that historical variability and price correlations were reflected in the stochastic forecast prices (Richardson et al., 2000).

Results and discussion

Protein quality was estimated using DIAAS (%) and assigned to each human-edible feed ingredient to estimate the suitability of diets fed to cattle for human consumption. As stated in FAO (2011), DIAAS represents the ability of a human-edible feedstuff to meet the protein requirements of a 0.5 to 3 year old child. Protein quality of the diet (DIAAS) for the cow-calf sector decreased from 36.81 to 32.47 as intensification increased from 0CON to 12CON (Table 11). The decrease in HeP quality in the limit-fed diet was driven by the inclusion of molasses, a poor source of amino acids with a DIAAS of 5.9. Corn, the sole source of HeP in 0CON, has a DIAAS of 36.81. In contrast to cattle diets, beef has a fixed DIAAS of 112, indicating the indispensable amino acid profile of beef is superior to reference protein used for children from 0.5 to 3 years of old. Because the DIAAS of beef is fixed and DIAAS of diets decreased as intensification increased, the PQR of cow-calf sector increased from 3.04 (0CON) to 3.45 (12CON). Protein quality ratio for the beef value chain increased from 3.15 to 3.33 as intensification in the cow-calf sector increased from 0CON to 12CON. For the entire value chain, PQR is calculated as a weighted average based on HeP consumption in each sector. Because HeP consumption in the cow-calf sector increased with increased duration of confinement, the cow-calf PQR exerted

Table 11. Effect of increasing duration of cow-calf confinement on key output variables of net protein contribution (NPC) from beef production

Item	Scenario[1]			
	0CON	4CON	8CON	12CON
Cow-calf				
Diet DIAAS[2]	36.81	32.50	32.45	32.47
PQR[3]	3.04	3.45	3.45	3.45
Total HeP_f, kg/herd[4]	11	20,989	47,220	81,202
Total HeP_p, kg/herd[5]	30,004	30,004	30,004	30,004
HePCE[6]	2,640.83	1.43	0.64	0.37
NPC	8,036.80	4.93	2.19	1.28
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	1,021	1,021	1,021	1,021
Total HeP_p , kg/herd	6,062	6,062	6,062	6,062
HePCE	5.94	5.94	5.94	5.94
NPC	18.07	18.07	18.07	18.07
Feedlot				
Diet DIAAS	35.51	35.51	35.51	35.51
PQR	3.15	3.15	3.15	3.15
Total HeP_f , kg/herd	53,125	53,125	53,125	53,125
Total HeP_p , kg/herd	18,105	18,105	18,105	18,105
HePCE	0.34	0.34	0.34	0.34
NPC	1.07	1.07	1.07	1.07
Beef value chain				
PQR	3.15	3.23	3.29	3.33
HeP_f, kg/herd	54,128	75,135	101,366	135,348
HeP_p, kg/herd	53,437	53,437	53,437	53,437
HePCE	0.99	0.71	0.53	0.39
NPC	3.11	2.30	1.73	1.31

[1] 0CON = conventional pasture grazing system for cow-calf sector; 4CON = cow-calf sector limit-fed in confinement for 4 months; 8CON = cow-calf sector limit-fed in confinement for 8 months; 12CON = cow-calf sector limit-fed in confinement for 12 months

[2] DIAAS = digestible indispensable amino acid score

[3] PQR = protein quality ratio

[4] HeP_f = human-edible protein fed

[5] HeP_p = human-edible protein produced

[6] HePCE = human-edible protein conversion efficiency

greater influence on the beef value chain's PQR. Protein quality is separate of consumption, and while consumption increases due to length of confinement

Incorporating intensification into management practices of cow-calf operations results in a decreased reliance on forage production (Sawyer and Wickersham, 2013). Although this is beneficial for operations when forage availability is limiting, intensification increased human-edible protein fed (HeP_f) from 11 to 81,202 kg for 0CON to 12CON for the 1,000 cow herd, respectively. While consumption of HeP increased from confinement length, it is important to note the quality of HeP_f was reduced from inclusion of molasses (DIAAS of 5.9). The cow-calf sector consumed <0.1, 28, 47, and 60% of the total HeP_f for the value chain for 0CON, 4CON, 8CON, and 12CON. When comparing the cow-calf sector to the feedlot sector, only 12CON consumed more HeP_f (81,202 kg) than the feedlot (53,125 kg). Consequently, the total HeP_f consumed by the beef value chain increased from 54,128 to 135,348 kg when intensification of the cow-calf sector increased from 0CON to 12CON. Total HeP_f represents total amount of HeP consumed by the 1,000 cow herd and all downstream HeP intake by calves produced from the cow herd. Although HeP_f increased, human-edible protein produced (HeP_p) remained constant for both the cow-calf sector and beef value chain (30,004 and 53,437 kg HeP_p, respectively) because gross beef production was not affected by strategy in this model.

Human-edible feed conversion efficiency (HePCE) is the ratio of HeP_p (numerator) to HeP_f (denominator). Because of an increasing denominator and constant numerator, HePCE decreased from 2,640.83 to 0.37 for cow-calf sector when intensification of the cow-calf sector increased from 0CON to 12CON. Both 0CON and 4CON (2,640.83 and 1.43, respectively) were above 1, indicating these scenarios were producing more HeP than were consuming. Mottet et al. (2017) estimated a ratio of 2.00 for HePCE when 441 kg of concentrates (70% human-edible) were fed per cow, which is greater than our 1.43 estimate for 4CON where approximately 456 kg of concentrate was fed per cow, of which about 50% was human-edible. However, when intensification increased to 8CON and 12CON (0.64 and 0.37), HePCE for cow-calf sector decreased below 1. These two scenarios consumed more HeP than the cow-calf sector produced. Flachowsky et al. (2017) reported the beef production system had a HePCE ranging from 0.70 (0% coproduct inclusion in concentrate) to 1.3 (50% coproducts). Diets fed during intensified production of the cow-calf sector in our model contained approximately 30% coproducts (human-inedible) and 30% corn (human-edible), whereas Flachowsky et al. (2017) assumed a 15% concentrate inclusion in the diet. Total confinement (12CON) of the cow-calf production system resulted in a HePCE similar to a common feedlot in the United States (0.34).

The HePCE of the entire beef value chain decreased from 0.99 to 0.39 when intensification of the cow-calf sector increased from 0CON to 12CON. For the value chain, all scenarios consumed more HeP than was produced. A greater HePCE for the beef value chain than the cow-calf sector in 12CON was due to the contributions of the stocker sector, which had a HePCE of 5.94. For all other scenarios, HePCE was greater for the cow-calf sector compared to the beef value chain. According to Wilkinson (2011), cereal beef production in the United Kingdom was similar (0.33) to 12CON in our model whereas lowland suckler beef production was more similar (0.50) to the 8CON scenario.

Although HePCE was below one for scenarios 8CON and 12CON, all scenarios in the cow-calf sector positively contributed to meeting human protein requirements (i.e. NPC > 1) by improving protein quality. For the cow-calf sector, NPC was greatest when cattle were grazing pasture continuously (8,036.80; 0CON), and NPC decreased to 1.28 (12CON) as intensification increased; importantly, this value remained above 1. Ertl et al. (2016b) reported cattle production in Austria had an NPC value of 2.81, intermediate to the scenarios in our model. The 12CON scenario had a similar NPC to that of a United States feedlot (1.07), but was greater than growing-fattening bull production systems (0.73) in Austria (Ertl et al., 2016b).

Furthermore, the entire beef value chain positively contributed to meeting human protein requirements. Net protein contribution for the entire value chain ranged from 3.11 (0CON) to 1.31 (12CON) with approximately a 0.4 decrease for every additional 4 months that cows spent in confined feeding systems. Overall, protein quality was greater in the beef produced than the diets fed offsetting the reductions in HePCE observed as duration of confinement increased. Although not explored in this study, it is possible to maintain a cow-herd on a diet consisting of human-inedible ingredients only during confinement which would improve the HePCE and NPC values reported.

Enteric methane production

Enteric methane production from the cow-calf sector is a major contributor to total methane production from the beef value chain. Estimates of methane production from the cow-calf sector have ranged from 69 to 81% of total methane produced from the beef value chain (Beauchemin et al., 2010; Stackhouse-Lawson et al., 2012; Baber et al., 2018). In our model, if cattle continuously grazed pastureland, 82% of total enteric methane produced by the value chain was derived from the cow-calf sector. As intensification was incorporated into cow-calf management strategies enteric methane production decreased to 66% (12CON; Table 12) of the total. When estimating enteric methane production, the NASEM

(2016) equations utilize intake level as well as diet composition (percentage of forage, fat, starch, etc). Johnson and Johnson (1995) listed diet type and level of intake as two of the main factors that influence enteric methane production. Main differences between 0CON and our limit-fed systems that resulted in enteric methane reductions were decreases in forage percentage consumed in the diet and in reductions in total DMI.

Table 12. Effect of increasing duration of cow-calf confinement on enteric methane production from beef production

	Scenario[1]			
Item	0CON	4CON	8CON	12CON
Cow-calf				
Methane, kg/herd	135,953	114,384	76,568	54,461
Methane, kg/kg HeP[2]	4.53	3.81	2.55	1.82
CO_2 equivalents/kg HeP	127.67	103.30	61.99	46.70
Stocker				
Methane, kg/herd	10,085	10,085	10,085	10,085
Methane/kg HeP	1.89	1.89	1.89	1.89
CO_2 equivalents/kg HeP	47.32	47.32	47.32	47.32
Feedlot				
Methane, kg/herd	16,946	16,946	16,946	16,946
Methane, kg/kg HeP	0.94	0.94	0.94	0.94
CO_2 equivalents/kg HeP	23.55	23.55	23.55	23.55
Beef production system				
Methane, kg/herd	154,079	141,415	103,599	81,492
Methane, kg/kg HeP	3.05	2.32	1.94	1.53
CO_2 Equivalents/kg HeP	84.38	62.06	47.50	38.91

[1] 0CON = conventional pasture grazing system for cow-calf sector; 4CON = cow-calf sector limit-fed in confinement for 4 months; 8CON = cow-calf sector limit-fed in confinement for 8 months; 12CON = cow-calf sector limit-fed in confinement for 12 months

[2] HeP = human-edible protein

To balance environmental costs and societal benefit of beef production, enteric methane was estimated relative to HeP production. Intensification of the cow-calf sector decreased methane production from 4.53 kg enteric methane per kg HeP_p (0CON) to 1.82 kg (12CON). Converting a pasture-based operation (0CON) into a partially confined system (4CON) resulted in a 16% decrease of enteric methane. Further confinement for 8 months and 12 months resulted in 32 and 48% enteric methane reductions for the cow-calf sector compared to 0CON. When cattle were placed in the 12CON scenario, the cow-calf sector produced less enteric methane than 1.89 kg of enteric methane per kg HeP for stocker sector. Ultimately, reduction in enteric methane production by the cow-calf sector while the other two sectors remained constant, reduced enteric methane by the beef value chain by 47%. Enteric methane production decreased from 3.05 to 1.53 kg per kg of HeP_p (0CON and 12CON, respectively) for the entire value chain.

Capper (2012) evaluated grass-fed systems and estimated 4.52 kg of enteric methane was produced per kg HeP_p. Additionally, Pelletier et al. (2010) estimated grass-fed systems in the upper Midwest of the United States and reported 3.84 kg enteric methane were produced per kg HeP_p. As expected, results by both authors (Capper, 2012; Pelletier et al., 2010) were greater than our scenarios because cattle were finished in grass-fed systems. Capper (2011) estimated 2.76 kg of enteric methane was produced per kg HeP_p for the beef value chain, intermediate of our scenarios 0CON (3.05 kg) and 4CON (2.32 kg). In the European Union, enteric methane from beef production was approximately 2.09 kg per kg HeP_p (Nguyen et al., 2010), which was more similar to our 4CON and 8CON scenarios. Lower methane emissions observed by Nguyen et al. (2010) in the European Union was likely because of the amount of barley and soy meal fed resulting in that system being comparable to our intensified scenarios. In agreement with our results, Peters et al. (2010) concluded a more intensive (feedlot-fed) production system results in lower greenhouse gas emissions (approximate reduction of 0.42 kg enteric methane per kg HeP_p).

Economic analysis

Deterministic results

Average gross revenues for scenarios were $761.60 per cow (Table 13). Gross revenues were slightly greater for 0CON and 0COND than the confined scenarios because weaning weights were not equally distributed around the mean in a study examining the effects of confinement (Baber et al., 2016). Feed cost was lowest for 0CON ($16.63 per cow; only DDG was supplemented) and greatest for 12CON ($331.92 per cow). As expected, feed costs increased as length of intensification increased from 4 ($97.83 per cow) to 12 months. Feed costs included mineral costs when cattle were in confinement, but mineral costs were accounted for in other production costs when cattle were grazing pasture. Accordingly, other production costs decreased when intensification increased. During drought producers must secure a source of feed in order to meet cow requirements if production is to be maintained. Hay cost is increased in drought years versus normal forage producing years ($150 vs $85 per 907 kg; Young et al., 2018). Accordingly, the cost of feed per cow for a pasture based cow-calf operation increased from $16.63 for 0CON to $277.42 for 0COND because of the requirement to provide hay under 0COND.

Labor cost was greatest for 4CON ($57.20 per cow) and decreased to $52.14 as intensification increased to 12CON. Drought (0COND; $54.36 per cow) resulted in a similar labor cost to 4CON as a result of feeding hay. Based on our results, confining cattle

Table 13. Enterprise budget per cow for alternative management strategies

	Scenario[1]				
	0CON	0COND	4CON	8CON	12CON
Gross Revenues	759.98	759.98	762.68	762.68	762.68
Costs					
Feed	16.63	277.42	97.83	195.33	331.92
Labor	47.47	54.36	57.20	52.77	52.14
Fuel and lube	17.19	23.12	20.03	25.15	34.33
Repairs and maintenance	13.33	13.90	14.12	15.23	16.79
Interest on loans	15.58	34.23	23.39	28.97	37.77
Other production costs	147.76	147.76	129.83	112.61	95.40
Total variable costs	257.96	550.79	342.39	430.07	568.35
New fixed costs	-	-	6.20	6.20	6.20
Land cost	120.00	120.00	78.90	39.45	0.12
Other fixed costs	85.85	85.85	85.85	85.85	85.85
Total fixed costs	205.85	205.85	170.95	131.50	92.17
Net return	*296.16*	*3.34*	*249.34*	*201.11*	*102.16*

[1] 0CON = conventional pasture based system for cow-calf sector; 0COND = conventional pasture based system supplemented hay during drought in cow-calf sector; 4CON = cow-calf sector limit-fed in confinement for 4 months; 8CON = cow-calf sector limit-fed in confinement for 8 months; 12CON = cow-calf sector limit-fed in confinement for 12 months

in pens in scenarios 8CON and 12CON was less labor intensive than providing hay to cattle in pastures (0COND), but more labor intensive than 0CON ($47.47 per cow). Confinement strategies allow a producer to mix and deliver feed to all cows in one location which is likely near the feed. For grazing systems (0CON and 0COND), cattle require more land which creates more distance when calculating the cost of delivering hay to cattle.

Fuel, lube, repairs, and maintenance costs increased when cow-calf production was intensified. However, scenario 4CON ($20.03 per cow) had slightly lower fuel costs compared to 0COND ($23.12 per cow). These scenarios had to supplement feed for the same number of days, however 4CON confined cows in a smaller area and closer to the feed being mixed and delivered than 0COND.

Interest costs increased as all other variable costs increased. Total variable costs were greatest for 12CON ($568.35 per cow) and lowest for 0CON ($257.96 per cow). Feed costs were a major portion (58%) of total variable costs for 12CON; whereas labor was the greatest single cost item for 0CON. Provision of hay for four months during a drought (0COND) cost $189.25 per cow more than placing cattle in a drylot and providing a limit-fed diet to meet maintenance requirements for four months. Overall, the limit-fed systems lessen the impact of a drought by creating an opportunity to utilize inexpensive feedstuffs and byproducts.

Feed mixer wagon and bunks were new fixed costs incorporated in the cow-calf production enterprise budget when cattle were fed a TMR ($6.20). Land/pasture costs were similar for 0CON and 0COND ($120.00 per cow). As intensification increased, land costs reflected the length of time land was used and/or the amount of land used; thus, land costs decreased per cow from $120.00 for 0CON to $0.12 for 12CON scenario. Net return was greatest for 0CON ($296.16 per cow) and lowest for 0COND ($3.34 per cow). Net return was $249.34 per cow for 4CON and decreased to $102.16 per cow during total confinement (12CON). Grazing was a lower cost source of feed (pasture and supplement costs; $136.63 per cow) than providing feed to a cow in confinement year round ($331.92 per cow), however fertilizer and herbicide costs were not included in this analysis. Thus, an advantage of 4CON compared to 12CON could be the ability of those systems to take advantage of grazing pasture during lactation when the cow's nutrient requirements are the greatest. Although not quantified in this study, confinement scenarios have the ability to collect and spread manure for fertilizer resulting in additional benefits to partial confinement. Additionally, a fixed land base partial confinement system creates the opportunity to increase the number of cows, utilize forages when quality is higher, and utilize feed delivery systems when forage availability is limiting.

Stochastic results

Mean return does not describe risk associated with each scenario evaluated; however, summary statistics (Table 14) describe the distribution of possible outcomes. Standard deviation was lowest for 0CON ($161.39 per cow) followed by 0COND and 4CON ($164.72 and 166.34 per cow, respectively) which is in agreement with ranking of scenarios by the mean. Differences in standard deviation observed were caused by ingredient usage differences and distributions of ingredient prices.

Although the standard deviation observed for each scenario was not substantially different, it is an indicator of the degree of variability in net return. When ranked by variation in outcomes, 0COND ($164.72 per cow) would be preferred over all limit-fed

Table 14. Summary statistics of net return per cow for alternative scenarios

	Scenario				
	0CON	0COND	4CON	8CON	12CON
Mean	296.16	3.34	249.34	201.11	102.16
Standard Deviation	161.39	164.72	166.34	170.21	179.00
Minimum	-5.91	-343.65	-55.26	-140.76	-292.04
Maximum	996.64	691.61	908.07	875.32	798.06

[1] 0CON = conventional pasture based system for cow-calf sector; 0COND = conventional pasture based system supplemented hay during drought in cow-calf sector; 4CON = cow-calf sector limit-fed in confinement for 4 months; 8CON = cow-calf sector limit-fed in confinement for 8 months; 12CON = cow-calf sector limit-fed in confinement for 12 months

systems evaluated. For all scenarios evaluated, part of the distribution of outcomes included negative returns. The maximum predicted loss was $343.65 per cow (0COND) whereas there was a $5.91 and $55.26 maximum loss per cow for 0CON and 4CON, respectively. Although 0CON has greater maximum and minimum net return than confinement scenarios, some years 0CON would become 0COND during drought, creating a riskiness associated with not having an intensification strategy in place.

Probabilities of negative net returns are presented in Figure 1. Risk averse operators tend to minimize the probability of losses (i.e. red bar = net return less than zero). In this case, 0CON would be the preferred scenario (0.4%); however, this option exposes the producer to risk of 0COND unless they are capable of implementing 4CON. Comparing scenarios feasible during a drought, 4CON (3.6%) would be the most preferred scenario. Other scenarios (0COND, 8CON, and 12CON) had a probability of 52.2, 9.6, and 29.2% of a loss for net return. Maximum net return observed was $996.64 per cow (0CON) followed by $908.07 per cow for 4CON. Observations of the minima and maxima of each scenario suggest there is an upside tail on all probability distributions. This tail is likely caused by the distribution of revenues more than variation in feed ingredient prices. Certainty equivalents (CE) is the risk free amount of wealth that brings a producer the same utility as the risky scenario being evaluated, and risk premium is the amount of money required to convince a producer to switch from one scenario to another (Hardaker et al., 2004). Risk premiums (CE of intensified scenarios minus the CE of 0COND) were determined at three levels of risk (risk neutral, moderately risk averse, and extremely risk averse; Table 15). For our analysis, it represents the amount of money that would need to be paid to a producer for them to choose 0COND over one of the limit-fed systems. When

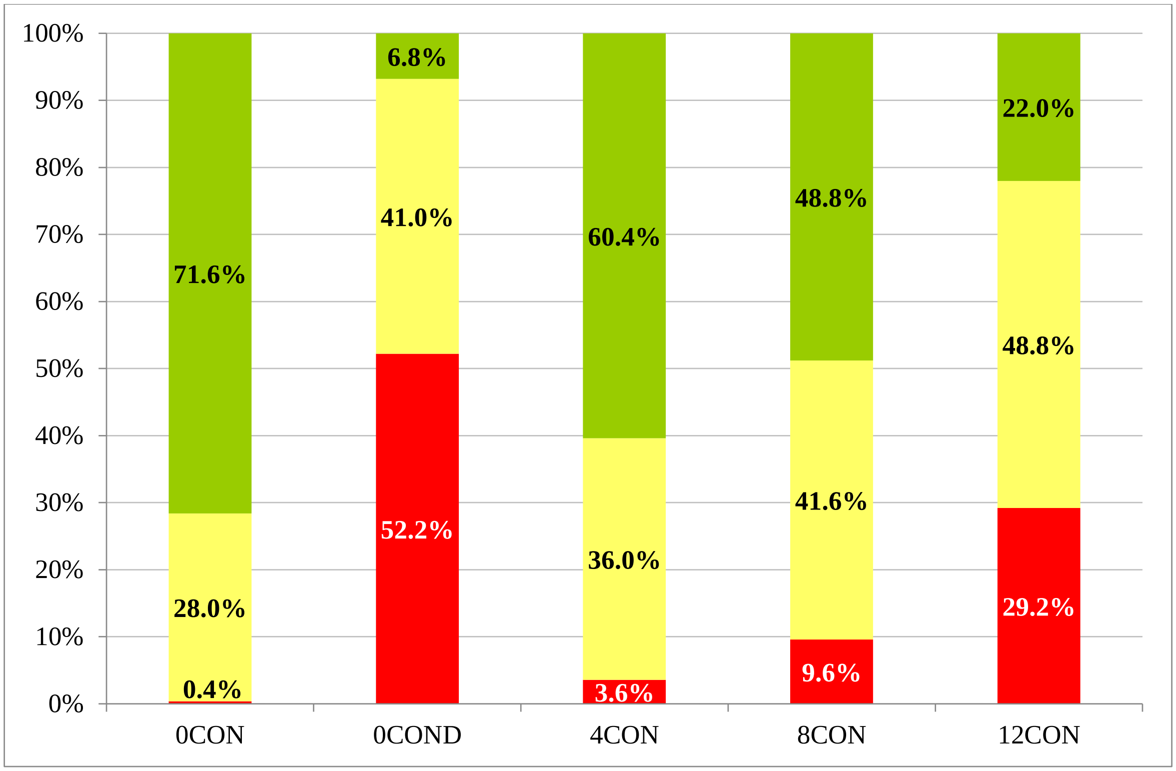

Figure 1. Probability of net return per cow for intensified and conventional cow-calf production. Green bar = net return > $200 per cow; Red bar = net return < $0 per cow; Yellow bar = net return > $0 per cow but< $200 per cow

Table 15. Risk premiums between intensified management strategies and conventional drought mitigation strategy (0COND[1])[2]

	Level of risk aversion		
Production system[2]	Risk neutral	Moderately risk averse	Extremely risk averse
4CON	246.00	245.32	244.59
8CON	197.78	196.03	194.35
12CON	98.83	94.41	90.16

[1] 0COND = conventional pasture based system supplemented hay during drought in cow-calf sector

[2] A positive value indicates a dollar per cow benefit of intensification over hay systems. A negative value indicates a dollar per cow benefit of hay over intensified systems.

[3] 4CON = cow-calf sector limit-fed in confinement for 4 months; 8CON = cow-calf sector limit-fed in confinement for 8 months; 12CON = cow-calf sector limit-fed in confinement for 12 months

a producer is more risk averse, CE associated with net returns of a scenario decreases because the scenario is seen as risky. Comparison to the drought scenario was chosen to simulate how an operation would react when no forage was available for grazing. At any level of risk aversion, the difference in CE represents the value placed on the limit-fed scenario over 0COND. Overall, 4CON had the greatest risk premium, followed by 8CON and 12CON. As risk aversion increased from neutral to extreme, the risk premiums associated with 4CON ($246.00 to 244.59 per cow, respectively) and 8CON ($197.78 to 194.35 per cow, respectively) decreased. The small differences in risk premiums within a scenario indicates producers of all risk aversion level have a similar attitude in these two scenarios. Similarly, the risk premium for 12CON decreased as a producer increased its risk aversion ($98.83 to 90.16 per cow for risk neutral to extremely risk averse, respectively), but the risk premium decreased at a greater rate for 12CON than 4CON and 8CON. The greater discount applied to the risk premium for the 12CON scenario was likely driven by the observation that this scenario had the greatest variation in net returns. Scenario 12CON may be viewed as a risky alternative because of the uncertainty associated with feed prices when cattle are continuously fed in confinement. A negative risk premium would indicate that at that point 0COND would be preferred to the limit-fed system, this was not observed in our analysis.

It is important to recognize that in the current model, the number of cows was held constant; however, increasing the total inventory without incurring excessive utilization is possible for 4CON and 8CON scenarios because there is always a portion of the herd in a drylot. Adding more cattle to the herd would have similar returns per cow, but would increase the enterprise's total net return. Additionally, the limit-fed systems could allow a producer to utilize the drylot for another enterprise while cattle were on pasture, increasing the potential income for the operation.

Conclusions

Sustainable beef cattle production involves minimizing environmental costs while also creating societal benefit and maintaining a profitable business. Choosing one scenario as the most preferred scenario in our model is difficult since these three variables have to be balanced. Although 0CON consumed the least amount of HeP and had the greatest NPC, this scenario also produced the most enteric methane and had increased risk for economic losses during droughts. However, 12CON still had an increased risk of economic losses to the operation, but had lower methane production and contributed positively to meeting human protein requirements since improvement in protein quality occurred. Other intensified scenarios (4CON and 8CON) were intermediate and are viable options for producers during times of drought. Intensified cow-calf management strategies can be incorporated into a sustainable beef value chain while maintaining the ability of the value chain to be a net contributor to human protein requirements. Additionally, these intensified strategies can help decrease the environmental footprint of the value chain, and may confer some advantages to economic sustainability.

CHAPTER IV

NET PROTEIN CONTRIBUTION OF FEEDLOTS FROM 2006 TO 2017

Overview

Feedlot efficiency increases as technologies are adopted and new feed ingredients, generally byproducts, become available and readily incorporated. Byproduct availability increased in response to the renewable fuels standard of 2005, creating a substantial amount of feed best utilized in ruminant diets. Cereal grains, a human-edible feed, have been, to some extent, replaced with byproducts, generally human-inedible feed, as they provide comparable levels of energy. 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. Net protein contribution was assessed for the feedlot industry using lot level production data from 2006 to 2017 for 8 commercial feedlots in the Texas panhandle (n = 6) and Kansas (n = 2). Ingredient and nutrient composition was collected for a representative starter and finisher diet fed for each year from each feedlot. Net protein contribution was calculated by multiplying the ratio of human-edible protein (HeP) in beef produced to HeP in feed by the protein quality ratio (PQR). A NPC >1 indicated that the production system is positively contributing to meeting human protein requirements, whereas a NPC < 1 indicated the sector is competing with humans for HeP. Net protein contribution was regressed on year to evaluate temporal change in NPC, and feedlots were categorized as increasing NPC (INC; slope > 0) or constant NPC (CON; slope = 0) according to significance. Four feedlots were categorized as INC and 4 were CON. A common slope

was estimated for CON and INC over time for PQR (*P* ≥ 0.79). Slopes of INC and CON differed for byproduct and cereal grain inclusion (*P* ≤ 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 CON cattle (*P* < 0.01). Across years, INC produced more HeP (20.9 vs 19.2 kg) 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). Net protein contribution increased 0.027 units per year for INC (*P* < 0.01) and was 0.94 in 2017. Net protein contribution by the feedlot sector improved from 2006 to 2017, utilizing less human-edible feeds to produce more high-quality beef.

Introduction

Beef cattle typically spend less time in the feedlot phase than the cow-calf phase; however, the majority of cereal grain consumed in beef production is in the feedlot phase. According to Samuelson et al. (2016), grain inclusion in feedlot diets ranges from 50 to 90% of DM. Although cereal grains are relatively low in crude protein, over 90% of human-edible protein (HeP) consumed by beef cattle is fed during the feedlot phase (Baber et al., 2018). Since 2000, corn milling byproduct production has increased making these byproducts more available to feedlots (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 net protein contribution (NPC) of the feedlot (Ertl et al., 2015; Flachowsky et al., 2017). Additionally, feedlots continue to finish cattle at heavier end weights (USDA-ERS, 2018) which may affect NPC.

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., 2016; Baber et al., 2018). Net protein contribution assesses a production system's ability to contribute to meeting humanity's protein requirements. 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., 2016; 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.

With increased byproduct inclusion and finished weights of feedlot cattle, we hypothesize feedlots 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

Net protein contribution (NPC) of 8 commercial feedlots (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 through 2017 representing 14 million head finished. Individual feedlots finished 4,333 to 13,604 lots of cattle during this time. Production variables obtained for each individual group (lot) of cattle at each feedlot were cattle in, cattle out, in weight, out weight, beta-agonist use, days on feed, and dry matter intake (DMI) of starter and finisher diets. Mean production values were estimated 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.

Gain in human-edible protein was estimated using the body protein content equation in the NASEM (2016) using the adaptions described in Baber et al. (2018). Human-edible protein gained (HeP_g) was calculated as the difference of human edible protein in beef (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 amount of days each year were used to represent diets for each feedlot within each year. All feedlots in this dataset utilize 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 according to Wilkinson (2011) and Ertl et al. (2016a). Human-edible protein (% 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 was at the lot level, intakes 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 for the feeding period.

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. A DIAAS of 100 (or above) meets (or exceeds) a child's amino acid requirements. A 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 versus the quality of the protein fed using the DIAAS of beef and the diets fed. A PQR above 1 indicates that produced protein was more capable of meeting human dietary requirements than the feedstuffs used for production; whereas a PQR below 1 indicates that the diet had greater protein quality than what was produced. Human-edible protein conversion efficiency (HePCE), the ratio of HeP gained versus fed, PQR, and NPC were calculated according to Ertl et al. (2016a) and Baber et al. (2018).

Statistical analysis

Metrics were calculated per feedlot per year using yearly average lot-level data. 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., Cary, NC). To determine if feedlots were improving NPC over time, a regression line of each feedlot across time was created 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). If the coefficient for feedlot × adjusted year differed from zero (*P* < 0.15), the feedlot was categorized as increasing NPC (**INC**); otherwise, feedlots were categorized as constant NPC (**CON**).

Differences in feedlot attributes and their overall change (difference between year 2006 and year 2017) dependent upon feedlot type were evaluated using PROC MIXED with feedlot type as class variable and adjusted year as a covariate. Regression lines of each feedlot type 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, ESTIMATE statements were used to determined differences between feedlot types within year. 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

Net protein contribution 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 16). For the most recent year evaluated (2017) NPC ranged from 0.47 to 1.15 (Figure 2). 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 feedlot, 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.

Table 16. Summary statistics of net protein contribution (NPC) 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

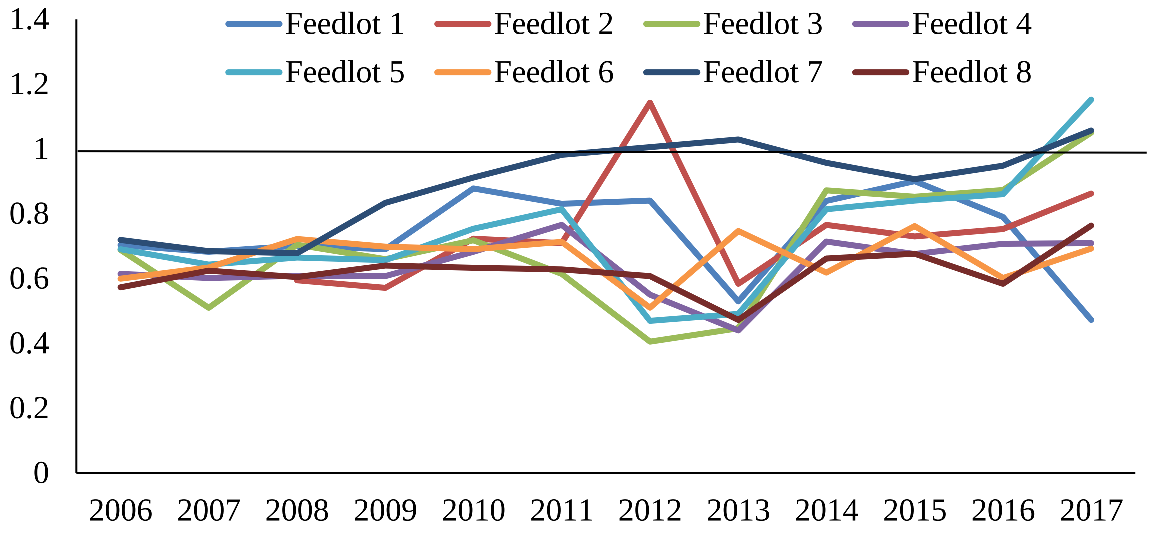

Figure 2. Times series of nine feedlots' net protein contribution (NPC). An NPC above 1 represents a feedlot positively contributing to human protein's requirements. An NPC below 1 represents a feedlot competing with humans for human-edible protein.

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 17); 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 were categorized as CON.

Table 17. Predicted equation of net protein contribution (NPC) regressed over year for each feedlot

	Category	Intercept	Year[1]	*P*-value[2]
Feedlot				
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

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

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

Feedlots were pooled by type (CON or INC), the regression of NPC over time was estimated by type (Figure 3). Feedlots defined as improving NPC averaged a 0.027 unit increase each year. In comparison, CON feedlots had nearly constant NPC, with an estimate of nearly zero improvement (0.004) over time. The difference in slope suggests divergence of NPC over time rather than a constant difference among feedlots, and is consistent with the overall increasing range in NPC described above.

Production and diet characteristics of feedlots were compared to determine potential sources of observed differences in NPC between INC and CON feedlots (Table 18 and 19). There were feedlot type × adjusted year interactions for byproduct inclusion,

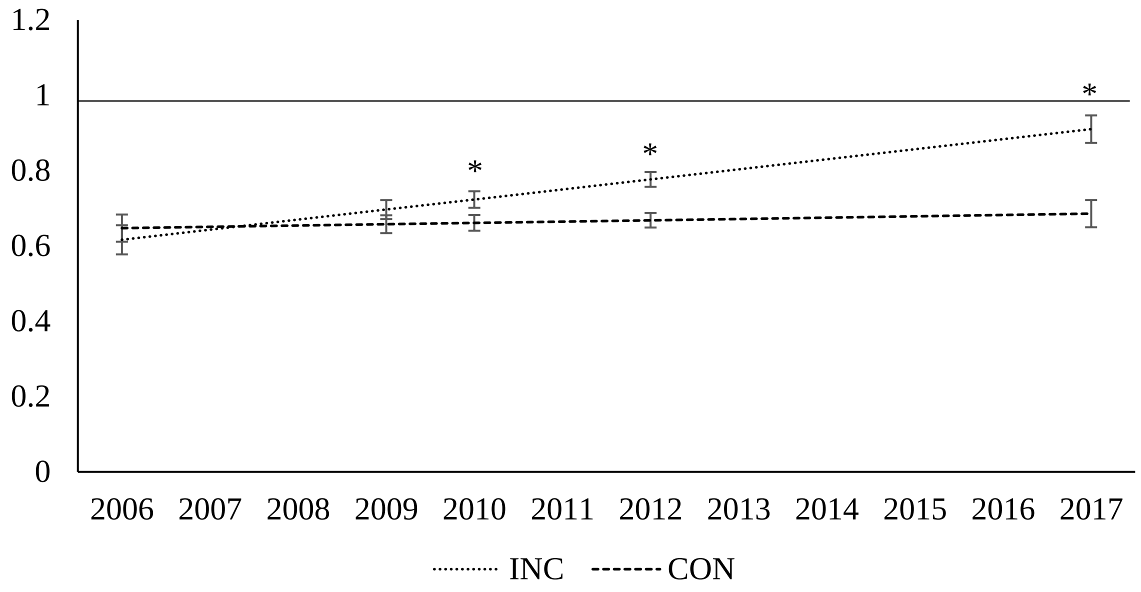

Figure 3. Time series of increasing net protein contribution (NPC) feedlots (INC) and constant (CON) NPC. CON = constant NPC over time; INC = increase in NPC over time. Feedlot type: P < 0.01; Feedlot type × year interaction: P = < 0.01. Estimated line for CON: 0.647 + 0.0035X. Estimated line for INC: 0.616 + 0.0267X; *denotes differences between CON and INC within a year (*P* < 0.05)

Table 18. 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	211.2 ± 7.7	-0.6 ± 1.2	<0.01	<0.01
INC	226.2 ± 8.4	-5.3^a ± 1.3		
HePCE				
CON	0.21 ± 0.01	0.002 ± 0.002	<0.01	<0.01
INC	0.21 ± 0.01	0.008^a ± 0.002		

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

Table 19. Estimates of intercepts and the common year coefficient for feedlot types (CON and INC) for variables impacting net protein contribution

			P-value	
Item	β_0	β_1	β_0	β_1
Feedlot characteristics				
Proximity to byproduct, km[1]				
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			

[1] No interactions were observed between feedlot type and year ($P > 0.10$)

cereal grain inclusion, and HeP fed (HeP$_f$; $P < 0.01$). Both feedlot types were increasing byproduct inclusion each year ($P < 0.05$; Figure 4); 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 ($P > 0.05$), afterwards 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 (168.9 km) compared to INC feedlots (94.3 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.

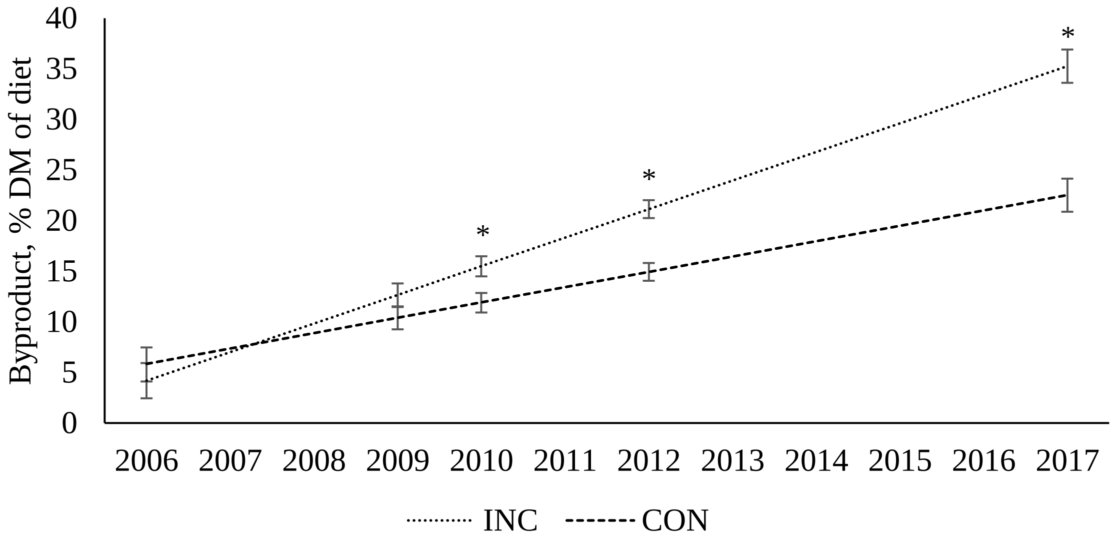

Figure 4. Inclusion of corn milling byproducts in feedlot diets over time. CON = constant NPC over time; INC = increasing NPC over time. Feedlot type: P < 0.01; Feedlot type × year interaction: P = 0.01. Estimated line for CON: 5.85 + 1.52X. Estimated line for INC: 4.18 + 2.82X *denotes differences between CON and INC within a year ($P < 0.05$)

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 to 52.7% inclusion from 2006 to 2017; $P < 0.01$) compared to CON feedlots (76.0 to 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 all years afterwards INC was less than CON feedlots ($P \leq 0.05$; Figure 5). As a result of cereal grain reductions, similar results were observed for HeP_f (Figure 6). Feedlots categorized as INC reduced HeP_f during a feeding period by 2.4 kg per animal each year ($P < 0.01$) whereas CON feedlots did not reduced HeP_f over time ($P = 0.61$). From 2012 to 2017, INC feedlots fed less HeP than CON feedlots ($P \leq 0.03$).

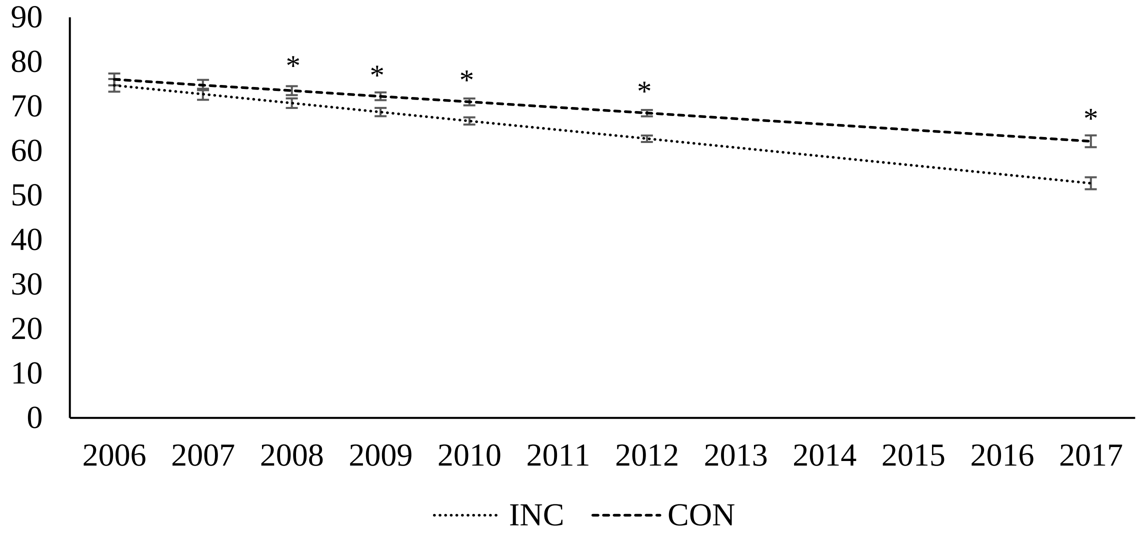

Figure 5. Inclusion of cereal grain in feedlot diets over time. CON = constant NPC over time; INC = increasing NPC over time. Feedlot type: $P < 0.01$; Feedlot type × year interaction: $P = 0.01$. Estimated line for CON: 76.05 – 1.26X. Estimated line for INC: 74.71 – 2.00X *denotes differences between CON and INC within a year ($P < 0.05$)

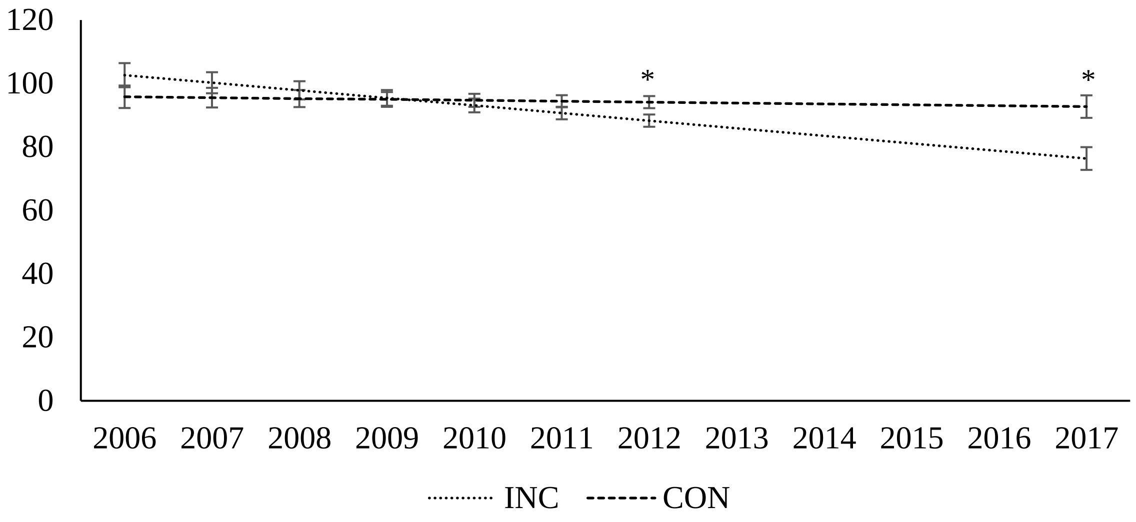

Figure 6. Intake of human-edible protein per animal during a feeding period in feedlots from 2006 to 2017. CON = constant NPC over time; INC = increasing NPC over time. Feedlot type: $P < 0.01$; Feedlot type × year interaction: $P = 0.01$. Estimated line for CON: 95.8 - 0.3X. Estimated line for INC: 102.6 – 2.4X where X is year; *denotes differences between CON and INC within a year ($P < 0.05$)

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 ($P = 0.79$).

Days on feed was greater for INC feedlots compared to CON feedlots (186 vs 173 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 ($P = 070$). 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 body weight (BW) and initial HeP_b were greater for CON than INC (*P* < 0.01), and both feedlot types were increasing BW (1.8 kg BW/year) and HeP_b (0.19 kg HeP_b/year) over time (*P* < 0.01). Additionally, ending BW and HeP_b were greater for CON than INC (*P* < 0.01), but both feedlot types increased by 3.8 kg BW and 0.25 kg HeP_b per year (*P* < 0.01). Accordingly, amount of HeP gained (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 7), 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* ≤ 0.02), but prior to 2010, HePCE was not different between feedlot types (*P* > 0.05).

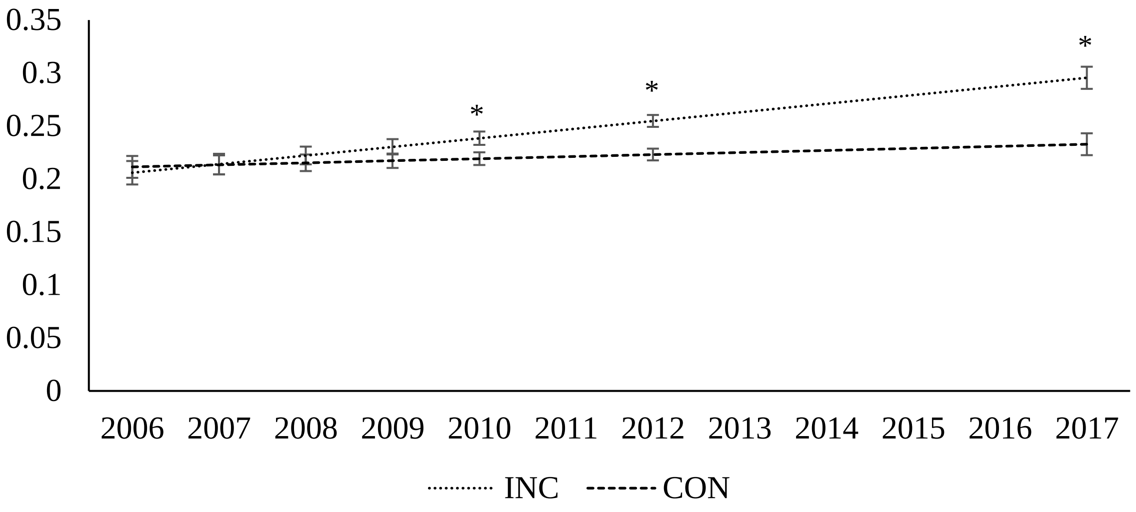

Figure 7. Conversion efficiency of human-edible protein in feedlots from 2006 to 2017. CON = constant NPC over time; INC = increasing NPC over time. Feedlot type: $P < 0.01$; Feedlot type × year interaction: $P = 0.01$. Estimated line for CON: 0.21 + 0.002X. Estimated line for INC: 0.21 + 0.008X where X is year; *denotes differences between CON and INC within a year ($P < 0.05$)

Discussion

We hypothesized NPC from feedlots increased from 2006 to 2017 as the result of increased byproduct utilization and increased finished weight. For half of the feedlots evaluated our hypothesis was correct, NPC was 48% greater in 2017 than 2006 for INC. Notably, in 2017, INC feedlots were approaching 1.0 with an average NPC 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 (0.003 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 range in the feedlot sector's ability to contribute to meeting society's need for high-quality sources of protein. Baber et al. (2018) estimated a 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 Austria, NPC was 0.73 (Ertl et al., 2016a), which is in lower to 2017 estimates of INC feedlots in the United States, but comparable to CON feedlots (0.69) in 2017.

Feedlots with improving NPC (INC) were closer to sources of corn milling byproducts and were able to substitute cereal grains, the primary source of HeP in feedlot diets, with human-inedible feed ingredients to a greater degree than CON. 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 versus 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 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 75 km closer to primary coproduct sources than CON feedlots. Shorter distances reduces transport expense and lowers 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 is driven by the value of dietary protein. 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 is competitive. The feedlot type by year interaction observed for cereal grain was indicative of cereal grain replacement × byproducts. Decreased amounts of cereal grain (% of 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. While byproduct inclusion became different between feedlot types in 2010, cereal grain inclusion was less for INC feedlots than CON beginning in 2008. However, it is evident byproduct inclusion was replacing more of the diet than cereal grain only. Feedlots categorized as INC only reduced cereal grain by 22%, but increased byproduct inclusion by 31% over the 12-year period suggesting that byproducts were also being substituted for roughage and silage (non-human edible ingredients).

Because of the reductions in cereal grain, a human-edible feed ingredient, a feedlot type × year interaction was observed for HeP_f (kg/animal) as well. In 2011, 6 of 8 feedlots adopted a starting diet that contained no cereal grains, 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. Additionally, while 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.

Ingredient inclusion in feedlot diets is based on least cost formulation; therefore, inclusion level of an ingredient changes when price changes relative to prices of comparable 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. Baber et al. (2018) estimated a DIAAS of 35.51 for feedlot diets; however, greater amounts of molasses (DIAAS of 5.9) were included in their diets compared to the diets fed in the present study. Also, flaked wheat grain (DIAAS of 43.1) was included in diets used at 6 of the 8 feedlots during 2013, 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 1 feedlot during each of these years.

Protein quality ratios for CON and INC did not change over time. This was a result of no changes over time for diet DIAAS for either feedlot type, and beef, the product, having 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) was 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. (2016); 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 BW of at both feedlot entry (placement weight) calves and harvest (finished 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 8 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. Human-edible protein gained 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 into the feedlot 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 HeP_g among feedlot types.

Greater HePCE was observed for INC feedlots than CON. This can be attributed to combined effects of reduced HeP_f and increased HeP_g for INC feedlots. Despite increased days on feed for INC feedlots, HeP_f was lower for INC than CON feedlots, indicating that lower diet HeP concentration influenced HeP_f more than days on feed. Over the period analyzed, INC feedlots reduced HeP_f by 14%, and INC and CON feedlots increased HeP_g by 6.3 and 5.7%, respectively, resulting in the feedlot type × year effect observed for HePCE. Human-edible protein conversion efficiency 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 significant from zero. Simultaneous improvements in HeP_f and HeP_g resulted in the improvement of HePCE. Ertl et al. (2015) demonstrated that replacing cereal grains with byproducts increased HePCE in a dairy cattle system which is supported by differences of byproduct inclusion in our study between feedlots. Additionally, Flachowsky et al. (2017) reported that HePCE nearly doubled (0.7 to 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 HeP_f. In the current 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 is 0.21 (Mottet et al., 2017), similar to our estimate of HePCE in 2006 and CON feedlots throughout the time period.

Estimates of NPC for competing proteins pork and poultry are limited to Ertl et al. (2016) which estimated pork and poultry 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), while 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 United States 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.

Compared to poultry and swine production systems, beef production is more complex with multiple segments contributing to NPC of the beef value chain. Supporting cow-calf and stocker segments primarily graze forage and utilize 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 the current study's estimates of NPC for feedlots in 2017 the NPC was approximately 3.5 for INC and NPC was 2.82 for CON. Additionally, when analyzed using the best and worst case scenarios of feedlot NPC observed (1.15 and 0.41), NPC of the beef value chain was 4.60 and 1.51, respectfully. Across a range of feedlot NPC observed, the NPC for the beef supply chain remained greater than 1 indicating that these production systems positively contribute to addressing human protein requirements.

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 utilize these feed ingredients to a greater extent to improve NPC. Although some feedlots in this study were competing with humans for HeP, none of the feedlots had a declining NPC over the time period analyzed and contributions from the cow-calf and stocker segments to NPC ensure the entire beef value chain has an NPC of greater than one. Production efficiency has continued to increase over the past 12 years contributing to the improvement in NPC; however, improvements made in NPC were driven by reductions in HeP_f. Further research designed to quantify the effects of available technologies on NPC and how their potential removal affects sustainability is warranted.

CHAPTER V

EFFECT OF DIET TYPE ON NUTRIENT UTILIZATION AND ENERGY BALANCE IN DRYLOT HEIFERS

Overview

Feeding cattle in intensified settings allows cow-calf producers to decrease their reliance on grazed forage and utilize alternative feedstuffs. Under intensification diet type may alter energy utilization. Fourteen pregnant MARC III heifers (405 ± 44 kg BW) were used in a 180 d experiment to determine effects of diet type on nutrient and energy utilization. Heifers were randomly assigned to 1 of 2 treatments, a forage diet (**FOR**; 2.10 Mcal ME/kg) or a concentrate diet (**CONC**; 2.94 Mcal ME/kg), and individually fed to meet maintenance energy requirements (0.135 Mcal ME/kg BW$^{0.75}$). The CONC diet contained dry-rolled corn, corn stalks, soybean meal, corn silage, dicalcium phosphate, urea, and a premix pellet; FOR contained alfalfa hay, corn silage, dicalcium phosphate and a premix pellet. Measurements of energy intake and digestibility were measured over a 96-h period on d 116, 172 and 235 of gestation. Using portable headbox calorimeters, measurements of O_2, CO_2, and CH_4 gases were collected over a period of 24 h. Data were analyzed in a completely randomized design (CRD) with diet as fixed effect and measurement group as a random block. Dry matter and organic matter digestibility was greater for CONC than FOR (*P* < 0.01). Intake of GE and DE were greater for CONC (*P* < 0.01), but ME intake was not different between treatments (*P* = 0.26). Energy lost as methane (% of GE intake) was not different between treatments (*P* = 0.49). The ratio of ME to DE was greater for CONC (86.8 vs 82.8; *P* = 0.01). Heat production relative to ME

was not different between treatments (*P* = 0.85). Retained energy was 1.2 Mcal/d for CONC and 0.9 Mcal/d for FOR (*P* = 0.73). Greater N consumption was observed for FOR (192.2 g/d) than CONC (134.0 g/d; *P* < 0.01), and retained N was greater for FOR than CONC (*P* < 0.01) on d 116 and 235 of gestation. Feeding concentrate-based rather than forage-based diets increased retained energy, without changing body condition score (*P* = 0.26). However, feeding the CONC-based diets increased energy retention as fat and carbohydrate (*P* = 0.05). Thus, limit-feeding heifers CONC-based diets in a drylot should be used with caution if excessive fat deposition is a concern. The ratio of ME to DE may be dependent on diet and level of intake and is more dynamic than current feeding systems describe.

Introduction

Sustainable cow-calf production is continually challenged by land values and drought which decrease forage availability. Feeding cattle in intensified settings, such as a drylot, allows cow-calf producers to decrease reliance on forage production. Reduced time grazing may reduce energy used for locomotion (NRC, 2000) and when cattle are limit-fed, gastrointestinal tract mass decreases, further reducing maintenance energy requirements (Sainz et al., 1995). Reynolds et al. (1991) reported greater energy retention and metabolizable energy (**ME**) to digestible energy (**DE**) ratio when heifers were fed a 75% concentrate diet compared to a 75% forage diet at equal ME levels. Their results agree with other studies (McAllister et al., 1996; Lovett et al., 2003) which observed greater methane gas losses in forage-based diets compared to concentrate diets fed at equal energy levels. It is recognized that the commonly applied ME:DE ratio (0.82; NASEM,

2016) is not consistent across diet types, but currently there are limited data to support development of a more robust prediction equation for the conversion of DE to ME.

While some have demonstrated decreased dry matter digestibility due to pregnancy in ruminants (Weston, 1988; Linden 2014), others have found no differences as days to parturition decrease (Stanley, 1993) and no differences have been observed between pregnant and nonpregnant heifers (Scheaffer et al., 2001). Weston (1988) reported greater ruminal organic matter (**OM**) digestibility in early and mid-gestation ewes than late gestation ewes consuming medium-quality roughage when intake was held constant which possibly resulted from the decreased ruminal retention time of digesta observed in late gestation ewes. Most of these studies have been conducted with cows or heifers grazing or consuming hay; relatively few have focused on nutrient utilization of limit-fed rations at various stages of gestation in beef heifers.

Our hypothesis was that heifers consuming a more energy dense diet would retain more energy than heifers consuming a forage-based diet when fed to a common target energy intake, and that nutrient utilization from either diet would decrease as gestation progressed. Thus, our objectives were to evaluate the effect of diet type at various days in gestation on nutrient and energy balance.

Materials and methods

All animal use protocols were approved by the Institutional Animal Care and Use Committee at U.S. Meat Animal Research Center.

Fourteen MARC III (1/4 Angus, 1/4 Hereford, 1/4 Red Poll, and 1/4 Pinzgauer) pregnant heifers (405 ± 44 kg of initial BW) were used to determine the effects of diet type on nutrient and energy utilization. Treatments were either a forage- (**FOR**; 2.10 Mcal/kg of

ME) or a concentrate- (**CONC**; 2.94 Mcal/kg of ME) based diet and heifers were fed to meet predicted maintenance energy requirements (0.135 Mcal ME/kg $BW^{0.75}$; Freetly and Nienaber, 1998). Rations were adjusted at the beginning of each trimester to account for fetal growth. Heifers were fed once daily at 0800 h throughout the duration of the experiment. Collection periods to determine nutrient utilization were conducted during the middle of the 2nd trimester, beginning of the 3rd trimester, and middle of the 3rd trimester corresponding to approximately 116, 172, and 235 d of gestation.

Prior to the trial, heifers were adapted to close human contact and then the metabolism barn over a period of 6 wk. During this time, heifers were trained to wear fecal bags and acclimated to headboxes. Throughout the trial, heifers were housed and individually fed in a semi-enclosed barn (open to the south) fitted with Calan-Broadbent electronic headgates (American Calan, InC., Northwood, NH). During collection periods heifers were moved into a metabolism barn with individual stalls (87 × 217 cm). Heifers had *ad libitum* access to water at all times throughout the study. Following the adaptation period, heifers were stratified by BW and randomly assigned to treatments. Forage and CONC diets were mixed in 150 kg batches twice weekly.

Intake and digestibility observations were made over 96 h during the collection period. On d 1 of the collection period, heifers were weighed and body condition scores (**BCS**; scale of 1 to 9; 1, emaciated; 9, obese; average of 2 trained personnel) were collected. Additionally, 24 french Foley catheters with a 75-mL balloon (Bardex, Murray Hill, NJ) were inserted into each heifer's bladder using a stylus. The balloon was inflated using 50 mL of sterile physiological saline. Tygon tubing was connected to the Foley catheter and terminated into a plastic carboy (18 L) that contained 100 mL of 0.36 *M* HCl to prevent volatilization of N. Heifers were fitted with harnesses and fecal bags were used to collect feces over a 24 h period.

Heifers were fed once daily at 0800. Diet samples were collected at h 0, 24, 48, and 72 to correspond with fecal, urine, and orts samples collected at h 24, 48, 72, and 96. Each day, feces were weighed and thoroughly mixed, a sample from each heifer was collected (3% of daily fecal output) and frozen at -20°C. Urine was weighed, a sample was collected (4% of total urine production) and frozen at -20°C each day. Diet samples were composited on equal weight basis across day within collection period, while feedbox orts, fecal and urine samples were composited by heifer across day within collection period. Following the 96 h collection period, urine catheters were removed, heifers were weighed and returned to their home pen.

Indirect calorimetry using portable respiration head boxes (an aluminum frame with dimensions of 0.76 × 0.76 × 1.78 m and covered with 5 mm clear acrylic sheets) was used to measure O_2, CO_2, and CH_4 gases for 24 h during the collection period. Prior to determining gas measurements, at least 3 air turnovers were allowed. A vinyl hood (0.76 × 117 cm opening) on the head box was attached around the heifer’s neck to provide a seal between the head box and heifer. Feed and a water bowl were placed at the bottom of the headbox for each heifer. Gas samples of air going into the box and air exhausted from the box were collected into polyethylene-aluminum-Mylar laminate gas bags. Gas samples were subsequently analyzed for O_2, CO_2, and CH_4 (Nienaber and Maddy, 1985) and heat production was calculated according to Brouwer (1965).

Diet, orts, and fecal samples were dried at 55°C in a forced-air oven for 96 h, allowed to air equilibrate for 24 h, and weighed to determine partial dry matter (DM).

Samples were ground in a Wiley mill (Thomas Scientific, Swedesboro, NJ) to pass a 1-mm screen. Feedbox orts (3-d) and orts collected during indirect calorimetry determination (1-d) were analyzed separately and data was composited as weighted average by number of days of each sample. Diet, orts, and fecal samples were dried at 105°C for 24-h to determine DM. Loss in dry weight during combustion for 8 h at 450°C was used to determine OM. Analysis of NDF and ADF were performed using an Ankom Fiber Analyzer with sodium sulfite omitted and without correction for residual ash (Ankom Technology Corp., Macedon, NY). Direct bomb calorimetry using a Parr 6300 Calorimeter (Parr Instrument Company, Moline, IL) was used to measure gross energy (**GE**) of diet, orts, fecal and urine samples. Diet, orts, fecal, and urine samples were sent to a commercial laboratory (SDK Labs, Hutchinson, KS) for analysis of nitrogen (N). Retained energy was calculated as difference between ME and heat production. Digestibility coefficients were calculated with the following equation: [1-(fecal output of nutrient/intake of nutrient)] × 100.

All data were analyzed using PROC MIXED of SAS 9.4 (SAS Institute Inc., Cary, NC). Data were analyzed as a completely randomized design (**CRD**) with treatment, day, and treatment × day as fixed effects and group and heifer within treatment as random effects. Treatment means were calculated using LSMEANS option, and pdiff function was used to separate treatment means. Retained energy was considered to be different from zero when $P < 0.05$.

Table 20. Formulated and analyzed composition of concentrate (CONC) or forage (FOR) based diets

Item	CONC	FOR
Ingredient, % DM basis		
Alfalfa hay	-	80.75
Corn Stalks	11.00	-
Dry-rolled corn	71.00	-
Soybean meal	5.00	-
Corn silage	7.50	15.00
Dicalcium phosphate	0.75	0.75
Urea	1.25	-
Premix pellet	3.50	3.50
Diet composition, DM basis		
Dry matter, %	81.8	74.3
Organic matter, %	92.0	89.1
Crude protein, %	14.6	15.1
Neutral detergent fiber,%	26.6	48.7
Acid detergent fiber, %	12.5	32.2
ME, Mcal/kg[1]	2.94	2.10
NEm, Mcal/kg[1]	1.98	1.24

[1] Calculated using NASEM (2016).

Results

Diet composition is reported in Table 20. Diets were formulated to be similar in OM and crude protein (**CP**), and fed to achieve similar ME intake. Neutral detergent fiber (**NDF**) was 45.4% greater and acid detergent fiber (**ADF**) was 61.2% greater in the FOR diet than in the CONC diet. These differences were expected based on the dietary constituents.

A treatment × day interaction was observed for body weight (**BW**; $P = 0.04$), but no treatment × day was detected for BCS ($P = 0.16$; Table 21). Body weight increased as gestation progressed for heifers fed the CONC diet, and no differences in BW between treatments were observed. Heifers fed FOR diet did not have different BW on d 116 and 172 of gestation, but BW was greater on d 235 than 116 and 172. Differences between days were observed for BCS ($P < 0.01$), and BCS generally increased as day of gestation increased.

No treatment × day interactions were observed for DM, OM, and NDF intake ($P \geq 0.18$), however there was a treatment × day interaction for ADF intake ($P < 0.01$; Table 22). Intake of DM, OM, and NDF was greater for FOR than CONC ($P < 0.01$). Dry matter and OM intake was greater on d 235 of gestation than d 116 and 172 ($P < 0.01$). No differences between days were observed for NDF intake ($P = 0.11$). Acid detergent fiber intake was less for CONC fed heifers on all days than FOR fed heifers. On days 116 or 172, FOR fed heifers consumed less ADF ($P < 0.05$) than on day 235. A treatment × day interaction was observed for DM and OM digestibility ($P \leq 0.02$), but no interactions were observed for NDF or ADF digestibility ($P \geq 0.14$). Dry matter and OM digestion in CONC fed heifers decreased from d 116 to d 172 then decreased from d 172 to d 235, but were

Table 21. Effect of diet type and stage of gestation on body weight (BW) and body condition score (BCS) in limit-fed pregnant beef heifers fed a concentrate-based diet (CONC) or a forage-based diet (FOR)

	CONC			FOR						
	Day of gestation			Day of gestation				Probability		
Item	116	172	235	116	172	235	SEM[1]	TRT	Day[2]	TRT × day
BW, kg	432^{a}	468^{b}	520^{c}	430^{a}	454^{ab}	498^{c}	9.0	-	-	0.04
BCS[3]	5.8	5.9	6.0	5.8	5.6	6.0	0.07	0.26	<0.01	0.16

[1] Pooled standard error of least squares means (CONC *n* = 7; FOR *n* = 7).

[2] Superscripts a, b, and c denote differences between across day and treatments (**TRT**; $P < 0.05$).

[3] BCS scale from 1 to 9 (1 = emaciated; 9 = obese)

Table 22. Effect of diet type and stage of gestation on nutrient intake and digestibility in limit-fed pregnant beef heifers fed a concentrate-based diet (CONC) or a forage-based diet (FOR)

	CONC			FOR						
	Day of gestation			Day of gestation				Probability[2]		
Item	116	172	235	116	172	235	SEM[1]	TRT	Day	TRT × day
				Intake, $g \cdot kg\ MBW^{-0.75} \cdot d^{-1}$						
Dry matter	54.4	57.3	62.4	79.8	80.5	88.2	1.58	<0.01	<0.01	0.52
Organic matter	50.4	52.3	57.5	70.4	71.9	79.4	1.54	<0.01	<0.01	0.66
Neutral detergent fiber	15.5	16.1	13.9	40.6	39.7	39.7	0.64	<0.01	0.11	0.18
Acid detergent fiber	7.2^{a}	7.9^{a}	6.5^{a}	25.3^{b}	26.4^{b}	27.8^{c}	0.37	-	-	<0.01
				Digestibility, %						
Dry matter	69.2^{a}	63.7^{b}	72.4^{c}	55.6^{d}	55.2^{d}	54.7^{d}	1.57	-	-	0.02
Organic matter	$78.7^{a,c}$	75.2^{b}	79.1^{c}	60.9^{d}	61.1^{d}	59.5^{d}	0.93	-	-	<0.01
Neutral detergent fiber	42.6	40.5	47.8	42.8	44.5	41.7	2.92	0.85	0.60	0.20
Acid detergent fiber[3]	29.8	31.2	30.9	35.2	36.5	38.6	3.74	0.06	0.71	0.88

[1] Pooled standard error of least squares means (CONC *n* = 7; FOR *n* = 7)

[2] Superscripts, a, b, c, and d denote differences across day and treatment (**TRT**; $P < 0.05$)

[3] Pooled standard error of least squares means (CON *n* = 4; FOR *n* = 7)

always greater than FOR fed heifers, for which DM and OM digestion remained constant across day ($P < 0.01$). No differences were noted for NDF digestibility among treatments or day ($P > 0.60$). Acid detergent fiber digestion tended to be greater for FOR than CONC ($P < 0.06$), and was not different among days ($P = 0.71$).

Gross energy intake was greater for FOR than CONC ($P < 0.01$) and GE intake increased from d 116 to d 235 ($P < 0.01$; Table 23). A treatment × day interaction was observed for fecal energy losses expressed as Mcal/d or as a proportion of GE intake ($P \leq 0.02$). Using either expression, fecal energy loss was lower for CONC fed heifers than FOR fed heifers on all days, and the magnitude of this difference was greatest on d 172.

Megacalories of DE intake was greater for FOR than CONC ($P = 0.01$), and was different across day, being greater on day 235 than day 116 or 172 ($P < 0.05$). Furthermore, urinary energy loss (Mcal/d) was greater for FOR than CONC ($P < 0.01$) and was not different across day ($P = 0.36$). However, when urinary energy loss was expressed as a proportion of GE intake, minimal differences in treatment or day were observed ($P \geq 0.11$).

Methane energy loss (Mcal/d) was greater for heifers fed FOR than CONC ($P < 0.01$), and was greatest on d 235 and least for d 116 ($P < 0.01$). However, methane loss as a proportion of GE intake did not differ among diet ($P = 0.49$) or day ($P = 0.87$). No differences between treatments were detected for ME intake (Mcal/d; $P = 0.26$), but when ME was expressed as a proportion of GE intake, CONC had greater ME intake than FOR ($P < 0.01$) as a result of differences in fecal energy losses. Differences among gestation day were observed for ME intake ($P < 0.01$) with ME intake (Mcal/d) not differing for day 116 and 172, but increasing (by design, due to advancing pregnancy) on d 235. The ratio of

Table 23. Effect of diet type and stage of gestation on daily energy partitioning in limit-fed pregnant beef heifers fed a concentrate-based diet (CONC) or a forage-based diet (FOR)

	CONC			FOR						
	Day of gestation			Day of gestation				Probability[2]		
Item	116	172	235	116	172	235	SEM[1]	TRT	Day	TRT × day
Gross energy intake (**GEI**), Mcal	19.3	21.1	25.5	28.5	29.6	36.0	0.76	<0.01	<0.01	0.21
Fecal energy, Mcal	4.6^{a}	6.0^{b}	6.1^{b}	11.9^{c}	12.7^{c}	15.9^{d}	0.39	-	-	<0.01
Fecal energy loss, % of GEI	23.9^{a}	28.5^{b}	24.0^{a}	41.6^{c}	$43.1^{c,d}$	44.2^{d}	1.04	-	-	0.02
Digestible energy intake, Mcal	14.7	15.1	19.4	16.6	16.8	20.1	0.53	0.01	<0.01	0.50
Urinary energy, Mcal	0.9	0.8	0.9	1.2	1.1	1.2	0.09	<0.01	0.36	0.88
Urinary energy loss, % of GEI	4.6	3.6	3.6	4.1	3.8	3.3	0.48	0.37	0.11	0.70
Methane energy, Mcal	1.1	1.3	1.5	1.7	1.8	2.2	0.10	<0.01	<0.01	0.94
Methane energy loss, % of GEI	5.7	5.9	6.0	6.1	6.2	6.0	0.37	0.49	0.87	0.85
Metabolizable energy (**ME**), Mcal	12.8	13.1	16.9	13.7	13.9	16.7	0.49	0.26	<0.01	0.43
Metabolizable energy, % of GEI	65.9	62.0	66.4	48.2	47.0	46.6	1.04	<0.01	0.07	0.08
ME:DE	86.5	86.6	87.3	82.6	82.6	83.4	0.92	<0.01	0.54	0.99
Heat production, Mcal	11.5	13.0	14.8	12.3	13.5	15.7	0.59	0.14	<0.01	0.94
Heat production, % of ME intake	92.6	99.8	87.9	90.9	97.5	94.2	2.88	0.85	0.43	0.73
Retained energy, Mcal	1.3	0.1	2.1	1.4	0.4	1.0	0.77	0.73	0.25	0.65
Retained energy, % of ME intake	7.4	0.2	9.1	9.1	2.5	5.8	5.70	0.87	0.35	0.71

[1] Pooled standard error of least squares means (CONC $n = 7$; FOR $n = 7$).

[2] Superscripts a, b, c, and d denote differences across day and treatments (**TRT**; $P < 0.05$).

ME:DE was 4.5% greater for CONC than FOR ($P < 0.01$), but no differences across day were observed ($P = 0.54$).

No differences among diets were observed for heat production (Mcal/d or as a proportion of ME intake; $P \geq 0.14$). Heat production increased from d 116 to 235 ($P < 0.01$), but when expressed as a proportion of ME intake, heat production across day did not differ ($P = 0.43$). Retained energy (Mcal/d or as a proportion of ME intake) was not different between treatments or across day ($P \geq 0.25$). Notably, RE (Mcal/d) was only statistically different for CON on d 235 ($P = 0.01$), indicating heifers did retain a significant amount of energy.

Nitrogen (**N**) intake was greater for FOR than CONC ($P < 0.01$), and N intake increased from d 116 to d 235 ($P < 0.01$; Table 24). An interaction between treatment and day was observed for fecal N excretion ($P < 0.01$). Fecal N excretion was greater in FOR fed heifers on d 116 and 172 than CONC fed heifers ($P < 0.05$), and treatments did not differ on day 235 ($P = 0.68$). Urinary N excretion was not different between treatments ($P = 0.57$), however there was a day effect ($P < 0.03$). Total N excretion was greater for FOR than CONC across all days ($P < 0.01$). All days differed in total N excretion ($P < 0.01$) with greatest N excretion on day 172 and the least N excretion on day 235. There was a treatment × day interaction for apparent N digested ($P < 0.01$). A greater amount of N was digested for FOR than CONC across day ($P < 0.01$), and day 235 had greater apparent N digested than day 116 and 172 for both treatments ($P < 0.01$). Apparent N digested was greater for FOR fed heifers on all days than CONC fed heifers ($P < 0.05$). Greater N retention occurred on day 235 than 116 or 172 ($P < 0.01$) and was greater for FOR than CONC ($P < 0.01$).

Table 24. Effect of diet type and stage of gestation on nitrogen retention in limit-fed pregnant beef heifers fed a concentrate-based diet (CONC) or a forage-based diet (FOR)

	CONC			FOR						
	Day of gestation			Day of gestation				Probability[2]		
Item	116	172	235	116	172	235	SEM[1]	TRT	Day	TRT × day
N intake, g/d	115.4	129.7	156.8	181.2	184.2	211.3	4.25	<0.01	<0.01	0.25
N excretion, g/d										
Feces	30.4^{a}	42.7^{b}	10.3^{c}	72.6^{d}	80.2^{d}	17.5^{c}	3.70	-	-	<0.01
Urine	96.5	107.9	95.8	95.1	108.7	111.9	7.87	0.57	0.03	0.23
Total[4]	127.2	150.9	106.4	167.4	188.7	129.1	8.42	<0.01	<0.01	0.38
Apparent N digested, g/d	85.0^{a}	87.0^{a}	146.5^{b}	108.6^{c}	103.9^{c}	193.8^{d}	4.93	-	-	0.01
N retained, g/d[7]	-11.9	-21.3	50.2	13.9	-4.4	82.4	8.42	<0.01	<0.01	0.58

[1] Pooled standard error of least squares means (CONC $n = 7$; FOR $n = 7$).

[2] Superscripts a, b, c, and d denote differences across day and treatments (**TRT**; $P < 0.05$).

Table 25. Effect of diet type and stage of gestation on partitioning of protein, fat, and carbohydrate in limit-fed pregnant beef heifers fed a concentrate-based diet (CONC) or a forage-based diet (FOR)

	CONC			FOR						
	Day of gestation			Day of gestation				Probability[2]		
Item	116	172	235	116	172	235	SEM[1]	TRT	Day[2]	TRT × day
Retained energy, Mcal	1.3	0.1	2.1	1.4	0.4	1.0	0.77	0.73	0.25	0.65
Retained energy as protein, Mcal [3]	-0.40	-0.71	1.69	0.45	-0.16	2.75	0.291	<0.01	<0.01	0.59
Retained energy as fat, Mcal[4]	1.69	0.78	0.40	0.50	-1.76	0.79	0.794	0.11	0.04	0.41

[1] Pooled standard error of least squares means (CONC $n = 7$; FOR $n = 7$).

[2] Superscripts a, b, c, and d denote differences between periods within treatment (**TRT**; $P < 0.05$)

[3] Energy retained as protein was calculated assuming a N content of 17% for meat protein and a caloric content of 5.7 Mcal/kg of protein (Kleiber, 1975). Meat protein was estimated using the retained protein values measured in the balance study. Tissue energy retained as protein = N retained × 5.88 g of protein/g of N × 5.7 kcal/g of protein.

[4] Tissue energy retained as fat and carbohydrate = recovered energy – recovered energy as protein.

Retained energy as protein was greater for FOR than CONC ($P < 0.01$) and was different across day ($P < 0.01$; Table 25). However, energy retained as fat and carbohydrate was not different between treatments ($P = 0.10$), but also differed across day ($P = 0.04$).

Discussion

Our study was designed for heifers to consume diets of different ME concentrations at equal ME consumption; therefore, heifers consumed more DM, OM, NDF, and ADF when fed FOR than CONC because of difference in energy density between diets. As designed, there were no treatment differences in Mcal of ME intake, and ME intake increased throughout the study as requirements increased with pregnancy. Intakes in this study were targeted for heifers on each diet to consume equal amounts of ME to meet maintenance energy requirements (Freetly and Nienber, 1998).

Because heifers were fed to meet maintenance energy requirements plus additional energy requirements for pregnancy and growth, intake increased as day of gestation increased. Dry matter intake was increased more during the final collection day (approximately d 235 of gestation) because increased estimated requirements associated with rapid fetal growth during the last trimester of pregnancy (NASEM, 2016). Although Weston (1988) indicated decreases in digestibility near parturition due to increased passage rate, our study did not find differences in DM digestibility as heifers neared parturition. Additionally, in the present study OM, NDF and ADF digestibility did not decrease across day, which does not support the results of Weston (1988). Scheaffer et al. (2001) did not observe differences in ruminal fill in pregnant versus non-pregnant heifers until d 270 of gestation; it is possible that in the current study, gestation had not advanced sufficiently to alter digestion.

Digestibility of CONC was greater than FOR, which was expected because greater amounts of readily fermentable carbohydrates were available in the CONC diets. Similarly, Reynolds et al. (1991) reported greater OM digestibility when heifers were fed limit-fed a 75% concentrate diet compared to a 75% alfalfa diet (80.2 and 66.5%, respectively). In precision-fed dairy heifers, Suarez-Mena et al. (2015) compared various forage to concentrate ratios. As the percent forage in the diet increased from 50 to 75%, OM digestibility decreased from 70.2 to 65.2%, respectively (Suarez-Mena et al., 2015).

Heifers in this study had not reached chemical maturity and were still growing which is indicated by increased BW throughout the trial. Furthermore, the fetus was rapidly growing during the final collection day (d 235 of gestation) which further explains the gain in BW observed among days (Ferrell et al., 1976). Ferrell (1991) reported fetal growth ranging from 261 to 612 g/d during late gestation (d 232 to 272). No differences were detected between dietary treatments for BCS, because heifers were fed to achieve common ME intake, this response suggests the objective was achieved.

Heifers consuming FOR had greater GE and DE intake because the study was designed for treatments to be fed at equal ME_m, and thus GE and DE intake must differ in diets that have different digestibility coefficients. A greater proportion of GE loss as fecal energy was observed in FOR than CONC. Forage-based diets are often less digestible than concentrate-based diets (Poore et al., 1993) because of less fermentable carbohydrates in the diet; this results in fecal energy loss differences consistent with those observed in the current study.

Heifers fed FOR were less efficient in conversion of GE to DE on d 235 compared to d 116. However, this was not evident when heifers were fed CONC-based diets where no difference in the conversion of GE to DE was noted. While no differences in DM or OM digestibility were detected among d 116 and d 235 for diet, the increase in intake (which was, on a mass basis, greater in FOR than CONC fed heifers) may have resulted in changes in fecal energy without detectable differences in fecal mass.

Heifers fed FOR lost 49% more energy as methane than heifers fed CONC. Level of intake, type of carbohydrate consumed, feed processing, and ionophore usage have been reported to affect the amount of enteric methane produced (Johnson and Johnson, 1995; Van Nevel and Demeyer, 1996; NASEM, 2016). Differences in methane production in our study could have resulted from either intake level and/or carbohydrate differences. Blaxter and Clapperton (1965) reported methane production was highly associated with digestibility and level of intake; in the present study, FOR fed heifers both consumed more total OM and more fiber, which might be expected to increase methane losses. Reynolds et al. (1991) fed heifers slightly above maintenance with a concentrate or alfalfa hay diet. In agreement with our results, the forage diet had greater methane energy loss than heifers fed a concentrate diet (Reynolds et al., 1991).

Heifers later in pregnancy (d 235) lost 36 and 29% more energy as methane than heifers early in gestation (d 116) for CON and FOR, respectively. However, no differences between treatments or between days were detected when methane energy loss was expressed as a percentage of GE intake in our study. Johnson and Johnson (1995) concluded that methane production was most related to total GE intake, and in our study total GE intake increased with advancing pregnancy, but methane losses remained proportional to GE intake. Similarly, no differences in methane production as percent of GE intake were seen when limit-fed steers were fed 70% concentrate or 70% forage-based ration (6.4 and 5.9%, respectively; Beauchemin and McGinn, 2006). When heifers were fed a corn-stalk diet near maintenance, Hemphill et al. (2018) reported heifers lost 5.4 to 7.4% of GE intake as methane. Heifers fed near maintenance had 5.5 and 7.1% GE lost as methane for diets that were 75% concentrate or 75% alfalfa hay, respectively (Reynolds et al., 1991). However, when cattle were fed well above maintenance (i.e. ad libitum high-concentrate diets), it was common for methane losses to be close to 3% of GE intake (Archibeque et al., 2007; Hales et al., 2013; 2014; 2017). As greater amounts of readily available carbohydrates or starch are fed to cattle, a shift in VFA production occurs resulting in a greater proportion of propionate (Fulton et al., 1979). Propionate production is an alternative pathway for extra hydrogens in the rumen and therefore competes with methane production. Moss et al. (2000) found a strong negative correlation between propionate and methane. Additionally, Van Kessel and Russell (1996) reported that methanogens lose the ability to utilize hydrogen to produced methane when pH was less than 5.5. Differences in digestibility, pH, and VFA profiles between FOR and CONC are all likely contributing to the differences observed in methane production in our study.

The NASEM (2016) assumes an ME:DE ratio of 0.82 regardless of the diet consumed, but acknowledges that this relationship may vary. Based on a literature review, Galyean et al. (2016) reported that the ME:DE ratio varied from 0.69 to 0.96 in studies where it was directly measured. Our results indicate ME:DE ratio was higher in CONC compared to FOR diets (0.87 and .0.83 respectively). Similarly, ME:DE of 0.81 and 0.88 were observed when heifers were fed a concentrate or alfalfa-based diet, respectively

(Reynolds et al., 1991); these authors also observed greater ME:DE ratios as intake increased. In steers were fed high-concentrate diets, others have reported greater ME:DE ratios ranging from 0.89 to 0.925 (Hales et al., 2014; Crossland et al., 2018). Hemphill et al. (2018) fed a diet similar to our FOR diet near a maintenance level of intake and reported ME:DE ratios from 0.75 to 0.82. The wide range of observed outcomes illustrates the variable relationship between ME and DE, and the need to further define the relationships among diet, level of intake and the ME:DE ratio.

Overall, RE was not different between treatments or between days. Heifers were targeted to be fed at near maintenance, and RE values not different from zero suggest that objective was generally met. However on d 235, heifers fed CONC had RE that was statistically greater than zero. In contrast, in a similar study at the same location, pregnant heifers were in negative energy balance throughout the feeding trial when fed a corn stalk-based diet (Hemphill et al., 2018). Previous research using mid-gestation cows suggests RE is negative approximately 28 d after initiation of feeding a limit-fed high concentrate diet (Baber et al., 2017; Trubenbach, 2014) and can remain negative until d 84 (Freetly and Nienber, 1998), but a negative RE initially (i.e. d 116 of gestation) was not observed in our study. It is important to note that in these reports, diets were often fed at levels substantially below maintenance, in contrast to the current study.

Retained energy was primarily retained as fat and carbohydrate and not as protein during the first two collection days. As the third trimester of gestation began (d 235), heifers retained greater amounts of energy as protein; this is likely attributable to greater fetal growth at this later stage of gestation and the fetal body composition being mostly protein. Heifers fed FOR were potentially mobilizing fat to deposit energy as protein in the form of a fetus.

Nitrogen consumption was 57, 42, and 35% greater for heifers fed FOR throughout the experiment, and was greatest on d 235 for both treatments. Nitrogen intake increased throughout the study to correspond with increasing nitrogen requirements for growth and pregnancy. Additionally, fecal N excretion was 140, 86, and 70% greater for heifers fed FOR. Retained N was greater on d 116 and 235 for FOR than CONC, driven by differences in N consumption. Similarly, the 75% alfalfa diet fed by Reynolds et al. (1991) resulted in greater N consumption than the concentrate diet. However, Reynolds et al. (1991) reported N retention was numerically lower for the 75% alfalfa diet compared to the 75% concentrate.

The type of diet fed during intensified cow-calf production will impact energy utilization. Fecal energy and methane energy losses were greater when heifers were fed a forage-based diet compared to a concentrated-based diet. Energy density, proportion of concentrate in the diet, and level of intake are important to consider when formulating diets designed to achieve maintenance but fed below ad libitum intake levels. The ME to DE ratio differences observed in our study is supportive of a dynamic ratio that is influenced by diet type and intake level unlike the current constant coefficient of 0.82 used in the NASEM (2016). Strategic diet construction can be used to improve efficiency of energy conversion and therefore the sustainability of intensive systems.

CHAPTER VI

CONCLUSIONS

Beef cattle have the unique ability to utilize inedible products and convert those into a high-quality source of protein. Developing models of NPC with industry reflected parameters is pivotal in representing and presenting a sustainable beef value chain to the public. Balancing NPC with enteric methane emissions allows producers to monitor multiple pillars of sustainability at once. Using current diets and current production parameters reflective of the industry (CDCP), we demonstrated the beef value chain has a NPC above one; All sectors and the entire value chain were positive contributing to meet humanity's protein requirements.

Opportunities exist within our industry to optimize NPC with respect to GHG emissions. Increasing the duration of intensified management from zero to 12 months in the cow-calf sector decreased NPC, however enteric methane emissions were reduced. Intensified management year-round resulted in the largest reduction in enteric methane emissions while still positively contributing to meeting human protein requirements. Additionally, profitability decreased when intensification length increased, however all intensified scenarios performed better than no intensification strategy during a drought.

Feedlots have a poor HePCE and NPC compared to other sectors of the value chain, however improvements have been made in feedlot NPC over evaluated time frame. Increased byproduct utilization has reduced human-edible protein inclusion and improved NPC of feedlots. Although some feedlots were in competition with humans for human-edible protein (NPC < 1), when evaluated as a beef value chain, society was benefiting from the beef value chain as a whole (NPC > 1).

Energy utilization is impacted by the type of diet fed. Forage-based diets have greater fecal and methane energy losses (Mcal/d) compared to pregnant heifers fed a concentrate-based diet. When managing cattle in confinement, energy density and concentrate levels in limit-fed diets must be monitored to ensure maintenance is achieved. Differences in ME to DE ratio found in our study is supported by others, and the relationship between ME and DE is a dynamic ratio which is influenced by diet type.

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