Effect of traditional roughage-based or limit-fed, high-energy diets on growth performance and digestion in newly received growing cattle and subsequent implications on feedlot growth performance and carcass characteristics and effect of Enogen corn hybrids or conventional hybrids in diets containing corn coproducts on performance and digestion in newly received growing cattle

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Abstract

Two performance studies and one digestibility trial were conducted to determine the effect of traditional roughage-based diets or limit-fed, high-energy diets on growth performance, behavior, health, and digestion in newly received growing cattle and subsequent implications on feedlot growth performance and carcass characteristics. 40% of diet DM was based on Sweet Bran [proprietary wet corn gluten feed (WCGF); Cargill Animal Nutrition, Blair, NE]. In Exp. 1, 409 crossbred heifers (initial BW = 279 ± 24 kg) were used in a randomized complete block design and assigned to 1 of 2 dietary treatments: 0.99 megacalories of net energy for gain per kilogram of dry matter (Mcal NE_g/kg DM) fed for ad libitum intakes (0.99AL; n = 205) or 1.32 Mcal NE_g/kg DM limit-fed at 85% of 0.99AL intakes (1.32LF85%; n = 204). In Exp. 2, 370 crossbred heifers (initial BW = 225 ± 20 kg) were used in a randomized complete block design and fed the same diets from Exp. 1, but the 1.32LF treatment was limit-fed at 2.2% of body weight (BW) daily on a DM basis (1.32LF2.2). In Exp. 3, eight ruminally-cannulated crossbred Angus heifers (initial BW = 204 ± 11 kg) in a cross-over design were fed diets from Exp. 1 in a 2-period digestibility study. Gain:feed efficiency (G:F) was greater ($P < 0.01$) by 47% and 35% in Exp. 1 and 2 for 1.32LF85% and 1.32LF2.2 heifers compared to 0.99AL heifers, respectively. For 1.32LF85% heifers ADG was greater and DMI was lower in Exp. 1; ADG was lower for 1.32LF2.2 heifers in Exp. 2 than 0.99AL heifers ($P < 0.01$). Rumination time was greater ($P < 0.01$) for 0.99AL heifers compared to 1.32LF85% in Exp. 1 and 1.32LF2.2 heifers in Exp. 2. Activity was greater ($P < 0.01$) for 1.32LF2.2 heifers compared to 0.99AL heifers in Exp. 2. 6.9% more light-sort carcasses than heavy-sort carcasses had livers with large, active abscesses ($P = 0.03$) in Exp. 1. Feedlot morbidity was not different between backgrounding diets in Exp. 1, but morbidity was 15.5% greater for 1.32LF2.2 cattle compared to 0.99AL cattle in Exp. 2. A

significant interaction between backgrounding diet and sort group occurred, because liver scars were greater ($P < 0.04$) for 1.32LF85% carcasses in the heavy-sort group than 1.32LF carcasses in the light-sort group. Light-sort groups had fewer ($P < 0.01$) edible livers than heavy-sort groups, suggesting that greater number of days on feed increases the risk of liver abscess prevalence and condemnation to occur in light-sort cattle. Apparent total-tract DM and OM digestibility was greater for 1.32LF85% diets than for 0.99AL diets in Exp. 3 ($P < 0.01$), but fiber digestibility was not different ($P \geq 0.59$). Limit-fed, high-energy diets fed during the growing phase had little carryover effect on feedlot growth performance or carcass characteristics.

In addition, one performance study and one digestibility trial were conducted to evaluate the effect of feeding corn grain and corn silage from Enogen corn hybrids (EC; Syngenta Seeds, LLC., Downers Grove, IL) or conventional corn hybrids (CON) in diets containing either wet distillers grain (WDG; ICM Biofuels, St. Joseph, MO) or Sweet Bran [proprietary wet corn gluten feed (WCGF); Cargill Animal Nutrition, Blair, NE]. Experimental unit was pen. In Exp. 1, 384 crossbred heifers (initial BW = 264 ± 19.1 kg) were used in a completely randomized design, 81-d receiving and growing study, with a 2 × 2 factorial arrangement of 4 dietary treatments. There were 8 pens per treatment, with 12 heifers stratified by weight to each pen. Experimental diets were formulated to contain 30% WDG or 30% WCGF on a dry matter (DM) basis and provide 1.12 Mcal of NE_g/kg DM. All diets were fed once daily for ad libitum consumption. In Exp. 2, eight ruminally cannulated crossbred heifers (initial BW = 370 ± 42.6 kg) were used concurrently with Exp. 1 to evaluate intake and digestibility of dietary treatments from Exp. 1 in a replicated 4 × 4 Latin square design. Four consecutive, 15-d periods consisted of 10 d for diet adaptation, 4 d of fecal sampling, and 1 d of ruminal sampling; experimental unit

was animal. In Exp. 1, no corn source × coproduct interactions were observed ($P > 0.10$) for performance or fecal starch analysis, with the exception of dry matter intake (DMI; $P < 0.01$) and G:F ($P = 0.01$) at day 14. An effect of coproduct was observed at day 64, with heifers fed WDG having greater ADG than heifers fed WCGF ($P < 0.03$). Effect of coproduct on DMI or gain:feed (G:F) was not significantly different after day 14 ($P > 0.05$). Heifers fed EC had greater ADG at days 28 and 56 ($P < 0.01$) than heifers fed CON, but G:F was not different between corn sources after day 28 ($P > 0.13$). Starch concentration of fecal DM was greater in CON heifers than EC heifers ($P < 0.02$). In Exp. 2, corn source × coproduct interactions were not observed ($P > 0.16$). A main effect of coproduct occurred for molar percentage of isobutyrate ($P < 0.05$), and there was a tendency for greater digestibility of starch in EC diets than CON diets ($P < 0.07$), but neither DM nor fiber digestibility was affected by corn source or coproduct ($P > 0.34$). Results indicate EC when fed with WCGF or WDG did not enhance growth performance of growing cattle, possibly due to similar dietary net energy densities fed in all diets.

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Chapter 1 - Review of Literature

INTRODUCTION

An intrinsic challenge of beef production in the U.S. stocker-backgrounder and feedlot segments is providing cattle adequate nutrition to meet or exceed physiological and metabolic requirements in a cost-effective manner. While faced with ever-evolving economic conditions and often volatile markets, numerous growing programs and nutritional strategies for newly received stocker cattle such as limit feeding have been utilized to help producers attain their operational and production goals. Moreover, limit feeding is well-documented in growing and finishing cattle. However, effects are often confounded by diet type and management preferences. Moreover, the scope of limit feeding strategies varies significantly due to operational goals, preferences, financial resources, and feed products geographically available, but the concept is unchanging. Restricting intake can encourage more efficient utilization of nutrients. Additionally, nutritionists and producers have used this as a strategy in young bovines to encourage early growth, improve feed efficiency, reduce manure output, and improve health detection. However, economically significant nutritional health disorders, namely acidosis and liver abscesses, will be an ongoing concern for cattle fed diets high in rapidly fermentable carbohydrates (Nagaraja et al., 1998). To address this, commercially available corn coproducts such as wet corn gluten feed and wet distillers grains, which have less starch, can be used as an alternative energy source or in combination with traditional concentrates. However, there may be detriments to rumen function and animal health if fiber and other structural carbohydrates are greatly reduced or eliminated altogether. Additionally, the subsequent impacts of previous limit-fed strategies to carcass merit at the abattoir will have important economic consequences for producer sustainability and to consumers purchasing retail end-products. Thus, the primary purpose of this review is to examine the effect of limit feeding in growing cattle.

Newly Received Stocker Cattle

Stress to young cattle caused by transportation, introduction of novel feedstuffs, and changes of environmental conditions pose high risks to animal health, nutrition, and growth (Nagaraja et al., 1998). Adequately accounting for or mitigating these factors in an appropriate manner has enabled producers to improve animal productivity and welfare while optimizing profitability given market constraints.

Effects of transport-induced stress

In the United States, over two-thirds of beef cattle are transported at least once in their lifetime (Van Engen and Coetzee, 2018). This has major implications for animal health (Galyean et al., 1981), stress-load (Grandin, 1997), and feed intake in subsequent feeding programs post-transit (Cole et al., 1988). Transportation is generally considered one of the most stressful events cattle will undergo, although the industry has improved immensely over the past several decades. (Swanson and Morrow-Tesch, 2001a). Unfortunately, there is large variation in the numerous aspects of transport stress induced by shipping, including weather variables, animal type or breed, experience (or training) of personnel and truck drivers, or the condition/age of the cattle. (Swanson and Morrow-Tesch, 2001a).

During transportation cattle are subjected to large variations in ambient temperature, even within trailer compartment. Vehicles must be moving to provide adequate ventilation (Van Engen and Coetzee, 2018). Observational research of temperature and humidity parameters in the summer versus winter and when trucks are stationary or moving reveal greater differences in the wintertime and when they are not moving (Goldhawk et al., 2014). During warmer months, high ambient air temperatures post-transport (> 32.2 °C) impacted and exacerbated physiological hormones and behavior of beef heifers, including elevated cortisol levels post-transit and reduced feed intake (Theurer et al., 2013).

Moreover, transport conditions induced by driver (turning, braking, acceleration, deceleration, and stopping) and driver-experience (Schwartzkopf-Genswein, 2015) will affect animal well-being and stability. Numerous cattle studies and transportation reviews corroborate this and demonstrate physiological changes in several known stress biomarkers. (Van Engen and Coetzee, 2018). Importantly, cattle activity and behavior during transportation is affected by age or previous experience of the animal (Grandin and Shivley, 2015). Cattle activity and behavior during transportation has also been investigated in several countries. Effects of driver, transit-time, stage of journey, and road type on cattle stability were observed in the United Kingdom using 2 drivers with 30-years hauling experience. In this case, yearling *Bos taurus* cattle (age = 316 ± 49 days) stood still during shorter-duration journeys less than or equal to three hours (Cockram and Spence, 2012). Newborn dairy calves (age = 28 ± 6 days) also stood but laid down 12% of the time in a second 3-h journey on minor roads and limited-access motorways (equivalent to an interstate in the United States). Furthermore, the number of events where animals were recorded to lose balance, using video surveillance and accelerometers, was 5 times greater on minor and main roads compared to motorways ($P < 0.05$). Acts of acceleration, braking, cornering, and gear changes occurred prior to events of cattle instability.

Transportation effects also have significant implications in dairy cattle used for beef production. Approximately 3 to 4 million dairy steers are fed in the United States annually (Drouillard, 2018). In 2019, 3.2 million dairy cows represented approximately 50% of U.S. slaughter cows (ERS, 2020). In terms of animal welfare, it has been demonstrated both standing orientations of dairy cattle in the truck, including facing parallel or perpendicular to the direction of travel, and road conditions impacted the level of frequency or vibration transferred to the animals ($P < 0.002$ and $P < 0.0002$, respectively) (Gebresenbet et al., 2011; Schwartzkopf-Genswein, 2015).

Other shipping factors also significantly impact stress-load, such as rest stops or rest stop duration. Countries such as Canada currently limit access without food and water for cattle to no more than 48 hr, with current regulations decreasing this to 36 hr in the early 2020s. (Government of Canada, 2019). Australia limits travel without access to water for cattle over 6 months of age to 48 hr (MLA, 2012). In the United States, federal law requires animals be in transport no longer than 28 consecutive hours without feed, water, and rest (USDA, 1994), however this is generally not enforced (Fike and Spire, 2006). In addition, the livestock transportation industry is currently exempt from electronic logging devices (FMCSA, 2018). In a recent study, Flint et al. (2014) conducted a survey of 129 commercial truck loads of cattle in Ontario, Canada, a majority of which were feeder calves. Their research indicated calves were on the truck for an average of 28 h and off-loaded to rest for about 11 h.

Cortisol is a well-documented corticosteroid and biomarker of stress, and transport raises cortisol levels (Van Engen and Coetzee, 2018). Hair cortisol concentrations increased in concentration ($P < 0.01$) on arrival following transport in young newly-weaned cattle given no rest stops (control = CON) and 15 h rest stops (RS15)(Marti et al., 2017). In this study, each transport group consisted of five Angus or Angus-cross cattle (age = 186 ± 3.67 d) transported 20 h without rest stops (CON), 5 h (RS5), 10 h (RS10), or 15 h (RS15) rest stops. Total numbers of lymphocytes and neutrophils, white blood cells critical for immune function, decreased on-arrival ($P < 0.05$) in CON and RS5 calves compared to RS10 and RS15 calves. In addition to these biomarkers, calf bunk attendance data showed RS5 and RS10 groups were more willing to stand and consume feed at the bunk following transport ($P < 0.05$), according to the authors, possibly due to having less time during the rest period to eat to full satiety. Interestingly, RS5 cattle took an extra hour, compared to RS10 cattle, to begin lying down for a longer duration. Importantly, this study demonstrates the potential effect of rest stops on physiological processes and behavior of cattle following transport.

In another study, Cooke et al. (2013) also evaluated the effects of road transport using 63 young Angus x Hereford cross cattle transported 1,290 km with or without rest stops. Both TRANS (no rest stops) and STOP (two rest stops total, each after 430 km) groups were shrunk more ($P < 0.01$) than the CON group which was not transported. After blood collection and analysis, TRANS cattle plasma cortisol levels on d 0 were elevated ($P \leq 0.04$) compared to the CON and STOP groups. However, in subsequent days there were no differences between treatments in plasma cortisol concentration. Moreover, the authors recorded no significant differences between treatments in cattle feed intake or ADG in the days following transport. While rest stops reduced transport-induced stress on arrival compared to cattle given no rest stops, cattle appeared to be resilient, and there were no negative long-term impacts on health or performance due to transport. This contrasts with (Cernicchiaro et al., 2012), in which subsequent ADG in the feedlot and HCW are suggested to depend upon transport conditions, gender, and body weight classification (light or heavy). Importantly, increasing transport time and distance traveled increased the observed levels of lactate in muscles ($P < 0.05$), leading to muscle fatigue (Chacon et al., 2005). All cattle experienced body shrink during transport, especially from fecal and urinary excretion; this may negatively affect subsequent feed intake, health, and performance particularly in lightweight growing cattle with poor immunocompetency (Cernicchiaro et al., 2012).

Roughages in growing diets

Young growing cattle are often stressed or exposed to new environments and feedstuffs, resulting in increased morbidity or mortality (Rivera et al., 2005). In the growing diet, roughages are important for maintaining overall health and optimal rumen function by supplying dietary fiber, an important structural carbohydrate, along with numerous vitamins and minerals. Notably, many harvested forages are of poor nutritional quality. Moreover, they can be expensive or difficult to store, and conditions during harvest or storage will factor into its nutritional value as a feedstuff. However, an important implication for roughages regardless of specific quality is particle size and length, because they provide ruminal stimulation and scratch factor (SF) (NASEM, 2016).

Commonly, growing diets are initially formulated for increased fiber and decreased energy content to promote overall cattle health and intake, particularly when young cattle have been off feed during and after transport (Lofgreen et al., 1975). In a series of experiments with newly received growing cattle shipped to the Imperial Valley of Southern California (BW = 147.3 ± 35 kg), morbidity was found to typically increase with increasing concentrate (25 to 90%) level in the diet utilizing rolled barley and alfalfa hay. Moreover, in a statistical review of this and several other studies conducted by these authors, (Rivera et al., 2005) showed morbidity increased by 1.35% for every 20% increase in dietary roughage content ($P < 0.003$; $r^2 = 0.356$), thus the increase was small. However, ADG and DMI decreased significantly with increasing roughage ($P < 0.01$; $r^2 = 0.632$ and 0.59, respectively). Furthermore, economic analysis (in 2005 United States dollars) revealed diets with 100% roughage inclusion compared to 40% inclusion resulted in a net profit loss of $29.44 or $5.11 per animal (assuming initial BW is 204 kg, purchase cost was $2.64/kg, transport cost was $0.004/kg, medicine cost was $15.40/calf, and feed cost was \$0.083/kg DM). While costs have generally increased and dollar values are different compared to 2005, these results clearly demonstrate an economic incentive for producers to include greater amounts of concentrate in the diet, with minimal realized impacts by way of increased morbidity rates. Notably, the author stressed that results here were confounded by unknown contributions of protein digestibility, an important factor in determining performance; market prices will also determine specific costs and benefits.

Other studies have evaluated interactions of roughage and concentrate level in growing cattle diets. Early research demonstrated the shift of starch digestion from the rumen to the small intestine with increasing concentrate or grain inclusion (Cole et al., 1976). While total starch availability increases as forage-to-concentrate ratios decrease, post-ruminal efficiency is reduced; additionally, energy conversion from digestible to metabolizable energy most likely is not constant across diets or between feedstuffs (Fuller et al., 2020). Importantly, not all roughages are created equal, in terms of potentially digestible fiber or available NDF. In a trial conducted with 300 growing heifers (initial BW = 260 kg), soybean hulls (SH) was the primary, protein-rich ingredient in limit-fed, forage-free rations (Loest et al., 2001). Additionally, two control diets were provided for treatment comparison, including a roughage (ROUGH) and grain-based diet. Unfortunately, betaine, an alternative to the amino acid, methionine, which serves as a methyl-group donor, did not effectively escape ruminal degradation. However, it was determined with careful management, to avoid bloat issues, that soybean hulls could be included as a primary dietary ingredient (91.6% on a DM basis). While both SH treatments groups (restricted-fed at 1.5 and 2.25% of BW, respectively) underperformed ($P < 0.05$) in ADG and G:F compared to those fed corn-based diets by 29% and 27%, respectively, G:F was similar between SH and ROUGH treatments. Importantly, 38% more ROUGH, the treatment containing 65%

roughage (45% chopped alfalfa hay and 20% chopped prairie hay), was fed compared to SH treatment. Moreover, SH treatments had similar digestibility percentages as ROUGH treatments ($P > 0.05$; 65.5% and 65.2%, respectively). This illustrates the higher degree of fermentable fiber in soybean hulls compared to other roughages, which has been well-documented in previous literature (Hsu et al., 1987).

To reiterate, SH diets contained high amounts of highly digestible fiber. Net energy concentrations in SH treatments were greater than those of roughage and corn-based treatments ($P < 0.05$). Also, treatment net energy values calculated from (Loest et al., 2001) were higher than energy values listed in NRC (1982) and (NRC, 1984), but they acknowledged this discrepancy. NE_m concentrations for cattle fed SH1.5 and SH2.25 (2.16 and 2.11 Mcal/kg, respectively) and NE_g concentrations (1.48 and 1.44 Mcal/kg, respectively) were not significantly different. The authors speculated restricted feeding caused an increase in diet digestibility to occur with higher levels of roughage, due to slower passage rate of digesta and meal-eating behavior. Interestingly, young chickens exhibited meal-eating behavior through limit feeding and showed both improved energy retention and similar body condition compared to ad-lib controls (Nitsan et al., 1984). While differences in the fermentability of fiber in roughage and soybean hull-based treatments illustrates the differences in available NDF, limit feeding in this study did not seem to cause differences in metabolizable energy retention based on performance. Readers are directed to a subsequent section entitled effect of limit feeding on diet digestibility.

Timing of roughage inclusion in limit-fed, receiving cattle diets has also been evaluated. For example, cottonseed hulls and alfalfa hay were increased in pre-fast diets, to simulate conditions encountered during calf marketing and transport (Cole and Hutcheson, 1987). Intakes upon realimentation, or after cattle were reacclimated to feed and water in the days following deprivation, were not impacted by previous roughage level ($P > 0.05$). Also, ruminal volatile fatty acid profiles and dilution rates were unaffected ($P > 0.05$). However, one aspect unexplored in this research was the specific impact limit feeding calves at 1.75% of body weight may have had after recovery. Restricted-fed animals can more efficiently utilize lower energy feeds when intake is restricted and gains are targeted to specific rates in the growing phase (Galyean et al., 1999). This may have promoted overall vigor and reduced visual symptoms of morbidity. These and other aspects of limit feeding are explored in the subsequent section, programming efficient gains in the growing phase.

In summary, there continues to be opportunity for utilizing roughages with different feeding strategies such as limit feeding, particularly in young growing cattle, which often arrive at a backgrounding yard or feedlot deprived of water and energy (Richeson et al., 2019). Timing of dietary energy realimentation is critical post-arrival, because supplied nutrients determine animal health and performance. Thus, properly applied limit feeding protocols may provide young growing cattle a unique opportunity for early growth and improved subsequent health. Many operators perceive health benefits as reasons for higher inclusion of roughages, while others prefer lower roughage inclusion for improved ADG and decreased DMI. Both approaches will directly affect animal efficiency and operational profitability, although the latter may reduce feed costs. Moreover, optimizing dietary roughage inclusion and type is dependent on many factors such as cattle type, age, geographic location of feeding, and available feedstuffs. Researchers have used various types of roughages with unique fermentative qualities in growing cattle diets, but in recent years, corn coproducts have also become widely available.

Corn coproducts in growing diets

Due to high availability and relative low cost, corn coproducts (made for the purpose of feeding, as opposed to byproducts which are secondary or incidental products) are widely used, and they are included in growing cattle diet formulations (Berger and Singh, 2010). Two commonly fed coproducts include wet corn gluten feed (WCGF) and wet distillers grains (WDG) which contain high amounts of readily fermentable fiber, although wet corn gluten feed (WCGF) contains more intact degradable protein. Unlike corn and other cereal grains, corn coproducts such as distillers grains and corn gluten feed are low in starch content, because starch has been removed and converted to sugar or ethanol through either wet or dry milling processes. While corn byproducts have been produced for many years, the need for additional research and development to refine nutritional values and consistency of these products became apparent in recent decades.

A study conducted by Samuelson et al. (2016) surveyed 24 consulting feedlot nutritionists with clients from different regions of the United States, and it indicated 95.8% of respondents use grain byproducts in their receiving diet formulations. Of the total products used corn wet distillers grains and wet corn gluten feed when combined accounted for 83.3%. Furthermore, the authors noted a significant rise in usage of corn wet distillers grain, compared with dried distillers grains since 2007. However, whether the increase was due to preference, availability, or cost could not be ascertained from data collected. Most likely, it is an interaction of all three factors. In general, corn coproducts in receiving and finishing rations are included at less than 50% of total diet DM, but 10 to 20% DM is most common (Samuelson et al., 2016).

In growing cattle diets, coproducts and roughages are often fed in tandem. Moreover, roughages have higher inclusion levels in receiving diets, approximately 30% or greater, compared to finishing diets where roughages account for 6 to 10%, on average, of diet DM

(Samuelson et al., 2016). Reduced inclusion of roughages in finishing diets is primarily due to lower energy density and detrimental effects to finishing gain efficiency and carcass merit. According to a meta-analysis of nine finishing experiments from 1993-2007 with wet distillers grains plus solubles (WDGS), maximal ADG and DMI was found at approximately 30% inclusion of diet DM, with both linear and quadratic responses ($P \leq 0.01$); similar responses for gain:feed were noted for dried distillers grains plus solubles (DDGS) between 30 and 50% of diet DM (Klopfenstein et al., 2008). Research has also demonstrated feeding corn coproducts may depend on roughages in the diet for optimum efficiency and diet digestibility.

Moreover, the increased demand and use of corn coproducts over the past several decades has led to numerous investigations of their effect on performance and health in cattle, particularly with distillers grains (DG) and corn gluten feed (CGF) (Firkins et al., 1985). These authors conducted 8 separate experiments designed to determine optimal combinations and concentrations of three primary corn coproducts, wet distillers grains (WDG), dry corn gluten feed (DCGF), and wet corn gluten feed (WCGF). For brevity, Exp. 1-4 are excluded from this discussion, which utilized sheep; Exp. 5-7 will be discussed, in which cattle were provided ad libitum access to their respective diets. Experiment 5 was conducted to evaluate finishing performance over 108 days by feeding WDG at different levels of dry matter to 132 steers (initial BW= 310 kg). In Exp. 6, 84 Charolais steers (initial BW = 274 kg) were used in a 98-d growing period and fed dried distillers grains (DDG), wet corn gluten feed (WCGF), or dry corn gluten feed (DCGF) diets, respectively. Steers in Exp. 5 had linear increases ($P < 0.08$) in ADG with increasing levels of WDG, and there was no difference in steer DM intakes between diets containing either 50% inclusion of WDG or 72% high moisture corn as the primary ingredient. Regarding Exp. 6, steers fed DDG, WCGF, or DCGF diets outgained ($P < 0.05$) soybean meal

(SBM) controls. Moreover, steers fed the DDG diet had the most optimal gain efficiency ratio, followed by WCGF (0.175 and 0.153, respectively, $P < 0.05$). However, the authors acknowledged differences in efficiency and performance could have been due to large frame size and higher protein requirements of this steer group. At the same time, Exp. 7 was conducted with 132 steers (initial BW = 328 kg). They gained similarly ($P > 0.05$) across diets, however feed efficiency was lowest for steers consuming WCGF-based diets or corn-based diets with SBM or urea, compared to DCGF-based diets ($P < 0.05$). Overall, utilizing an approximate inclusion of 50% WCGF or WDG in cattle diets to replace corn and SBM as the primary dietary ingredients in both growing and finishing diets was the most nutritionally sound strategy and did not negatively affect growth performance or gain efficiency. Moreover, WDG and WCGF are excellent protein and energy sources for cattle.

Following this series of experiments with growing cattle, workers at the University of Missouri, Columbia fed WCGF diets to lambs and growing cattle without the use of SBM or urea; like SBM, WCGF is high in readily degradable protein and readily fermentable fiber (Bowman and Paterson, 1988). Exp. 1 and 2 were conducted with 18 and 10 lambs (avg. BW = 35 and 18 kg, respectively), while in Exp. 3, 5 heifers weighing 225 kg were used, all evaluating differences in digestibility and nitrogen retention of dry, wet, or ensiled corn gluten feed. Interestingly, workers in Exp. 1 fed lambs diets for ad libitum intakes in period 1, but restricted intake to 80% of their period 1 intake in period 2. When ensiled WCGF was limit-fed, it had the greatest ($P < 0.05$) DM digestibility but the lowest nitrogen intake ($P < 0.05$), compared to dry or wet CGF that was not ensiled. Although no statistical comparisons of treatment means across ad-lib or restricted intakes were performed, numeral increases in DM digestibility were noted for all 3 types of CGF when limit-fed. These results are similar to (Firkins et al., 1985), and corn gluten feed can be utilized as the primary dietary ingredient in cattle receiving diets. Furthermore, high-energy diets typically utilizing corn grain or soybean meal and urea could be replaced with any form of CGF at or below 50% of dietary inclusion. Given these data, cattle feeders have numerous, nutritionally-sound options for feeding young growing cattle.

Nonetheless, research has continued with corn coproducts. Unfortunately, major physiological and metabolic disorders such as ruminal acidosis (acute and subacute) (Nagaraja and Titgemeyer, 2007) or liver abnormalities (Rezac et al., 2014) can be caused by diets high in starch if ingredient inclusion is not carefully managed. To determine these effects different intake levels of WCGF were compared; also subsequent implications of feeding WCGF to cattle on performance and rumen health were evaluated. Overall, wet corn gluten feed was demonstrated to help reduce the severity and length of cattle experiencing subacute acidosis due to containing low amounts of starch (Krehbiel et al., 1995). In another performance study, Peter et al. (2000) fed 96 weanling heifers 3 dry-rolled corn-based diets, supplemented with 20% coproduct on a DM-basis to maintain similar crude protein intake levels across treatments. No differences ($P > 0.10$) in DM consumed were found. However, both ADG and gain efficiency improved ($P < 0.01$) for heifers fed dry corn gluten feed and dried distillers grain-supplemented diets. Montgomery et al., 2003 combined increasing amounts of wet corn gluten feed and decreased alfalfa hay to 220 steers (BW = 262 ± 10 kg) and 339 heifers (277 ± 10 kg) in 2 subsequent feeding trials, discovering 40% inclusion of WCGF and 10-20% roughage appeared to be the best combination for performance and efficiency. More recently, branded WCGF products such as Sweet Bran have been introduced and shown to increase growing cattle performance at mid-level inclusion rates around 40% without hampering antibody or immune responses (Spore et al., 2018). They also show promise when adapting feedlot cattle to higher grain diets with less roughage (Huls et al., 2016) and in dairy cattle (Rezac et al., 2012).

Overall, the advent of corn coproducts has dramatically changed ruminant diet formulation by enabling cattle growers and feeders to inexpensively increase energy and protein content of diets fed. High availability of corn coproducts allows producers greater selection of feedstuffs to fit their budget and formulate sound nutritional diets. Thus, corn coproducts can provide balance between animal health, nutrition, and operational profitability when prices are optimal.

Summary

Newly received growing cattle are stressed and prone to sickness, exacerbated by shipping and transportation. After arrival diet management utilizing roughages, grains, and coproducts is critical. While numerous approaches exist to formulate feedstuffs, nutrient requirements applied according to age and status is the fundamental approach. Previously roughages were used almost exclusively to grow cattle, with some grain. Step-up diets may also be utilized to acclimate cattle to dietary changes and novel feedstuffs. However, with corn coproducts, which are high in fermentable fiber but low in starch, digestive upsets are commonly less frequent. A variety of available feedstuffs enable cattle growers to adapt stressed young cattle, often recently weaned and transported long distances, to a nutrient-dense healthy diet for optimized performance and health in a cost-effective way.

Limit Feeding as a Nutritive and Management Strategy for Growing Cattle

Composition of diets fed to newly received stocker cattle profoundly impact feed intake. Cow-calf and stocker operations are often long distances from feed yards; due to increased transportation distances and calves are often deprived of feed and water for extended periods of time. Therefore, adequate nutrient levels in growing diets are essential. Energy and protein intake have lasting effects on health and performance (Cole and Hutcheson, 1990). Moreover, limit feeding has been verified as a sound, effective management strategy for growing cattle prior to the finishing phase, with no adverse effects on either health or performance (Spore et al., 2019).

For example, no digestive issues such as acidosis, bloat, or founder occurred in two separate limit-fed experiments with Angus-Limousin cross cattle ($P > 0.10$); diets consumed were formulated and fed to maintain similar NE_g intake across treatments (Sip and Pritchard, 1991). In Exp. 1, all cattle were limit-fed high moisture, high concentrate diets consisting of mixed hay, rolled corn, and soybean meal for a protein intake of 78 g/kg of $BW^{0.75}$. In Exp. 2, cattle were limit-fed either high moisture ear corn or given ad libitum access to corn containing equal NE_g, and ADG was not different between treatments ($P > 0.10$). In addition, this study highlighted decreased manure output as another important aspect of limit feeding. In a concurrent digestibility trial with 24 Hampshire and Hampshire-cross ram lambs, fecal output was less for animals fed corn silage, producing 342 g/d, whereas limit-fed high moisture corn groups produced only 205 g/d ($P < 0.10$). Furthermore, limit feeding in the background phase had no deleterious subsequent impacts on finishing phase performance; carcass characteristics were similar between backgrounding treatment diets previously offered, and the numbers of days to reach slaughter weight was nearly identical (Sip and Pritchard, 1991; Reinhardt et al., 1998).

Overview of limit-fed strategies

Restricted or programmed-intake feeding, both collectively characterized as limit feeding, have been successfully used in the cattle feeding industry for several decades. Specifically, programmed-intake feeding methodologies see widespread usage in commercial operations at the growing level. In part, this is due to the advent of the net energy equation systems, allowing producers to optimize feed energy intake at a targeted rate of gain (Galyean et al., 1999). While restricted feeding can be used to start young growing cattle on feed, it has not become widespread practice in finishing programs. Over the years concerns for subsequent carcass merit of previously limit-fed cattle include poor rates of gain and reduced carcass merit (Zinn, 1987; Galyean et al., 1999). Moreover, when animal intakes become restricted too greatly or inappropriately, gains are reduced, thus increasing number of feed days required. Finally, increased individual variations of intake with limit feeding, especially within large pens, is concerning. As a result, large commercial feeders and most finishing yards feed for ad libitum intakes.

However, research of energy utilization in various breeds of cattle demonstrates maximum feed intake may not correspond to maximum animal efficiency (i.e. diminishing marginal returns) (Ferrell and Jenkins, 1998a). Additionally, studies utilizing growing cattle demonstrate comparable finishing performance and carcass merit when cattle were previously program-fed. (Loerch, 1990; Sip and Pritchard, 1991) Today, increased regulation and scrutiny to cattle management practices and cost considerations further incentivize application of limit feeding programs. Because feed intake in young growing cattle is often reduced upon arrival, each bite of feed is critical. Limit feeding strategies can afford operators many benefits, namely, improved management and usage of feedstuffs, thereby reducing waste (Zinn, 1987). Early reports also demonstrate greater feed efficiency through reduced feed intake in limit-fed cattle compared to full-fed cattle (Loerch, 1990). It has been demonstrated altering the diet and changing managerial approaches during the backgrounding phase of production can affect subsequent performance in the feedlot, including carcass characteristics (Lancaster et al., 2014). Therefore, numerous studies have investigated the effects of limit-fed diets for growing and finishing cattle.

As eloquently described, effect of previous restrictions on energy utilization is a highly complex, multi-faceted interaction (Drouillard et al., 1991). For example, wheat middlings (WM) contain moderate levels of starch, are highly digestible, and provide ample energy. Moreover, they are 95% similar in feed value to corn in traditional roughage-based diets fed ad libitum, however, this value declined to 83% in limit-fed diets containing increasing levels of WM fed at 2.4% of BW (Kuhl et al., 1998). Also, ADG and feed efficiency declined linearly when WM was increased in the diet ($P < 0.01$). Other diets with varying levels of intake restriction offered different performance results. Moreover, in the first of three growing-phase trials conducted with crossbred Angus steers, treatments were ad libitum, 20% restricted, and 30% restricted intake, with high moisture corn and corn silage (Loerch, 1990). DMI differed by design ($P < 0.01$), with 5.9, 4.7, and 4.1 kg/d DMI, respectively. Conversely, ADG was not different between treatments ($P > 0.05$). This was likely due to increased density of NE_m, NE_g, and crude protein in restricted-intake diets. Although feed efficiency was not statistically different between ad libitum and 20% restricted cattle (6.69 vs 6.09, respectively, $P > 0.05$), 30% restricted treatment group was more efficient by requiring 4.65 kg feed per kg BW gain ($P < 0.01$). Additionally, limit-fed growing cattle were 21% more efficient than cattle with ad libitum access to diets. The growing phase was 85 d in Exp. 1 and 84 d in Exp. 2 and 3. Moreover, previous growing phase treatment did not affect subsequent finishing rate of gain, DMI, feed:gain, or carcass characteristics ($P > 0.05$). However, combined growing and finishing phase ADG tended to be better for high-energy, limit-fed steers than full-fed, corn silage steers ($P = 0.07$).

Unlike the previous study, ADG decreased by 7.4% ($P = 0.04$) when limit feeding high-energy wheat-based diets to steers in a 140 d growing study (Hicks et al., 1990). In this case, limit-fed intakes were adjusted to approximately 85% of ad libitum intakes during the growing phase. ADG for limit-fed heifers tended to be less than for heifers fed for ad libitum intake, but only in the growing phase ($P < 0.08$); limit-fed heifers grew faster in the finishing phase from 57 d through 133 d. Limit-fed heifers consumed 18.1% less feed ($P < 0.01$) during the finishing phase, thus improving overall feed efficiency by 19.8% ($P = 0.06$). Over the entire trial, ADG of both limit-fed and ad libitum treatments were similar, 1.39 and 1.41 kg/day, respectively. Importantly, low growing-phase ADG is not necessarily indicative of finishing performance. Moreover, reduced ADG in the growing phase was likely a function of dietary net energy, diet composition, and intake restriction.

In other studies, decreases in ADG through limit feeding have been noted when restricting intakes of steers by 10 to 20% of ad libitum intakes (Murphy and Loerch, 1994; Reinhardt et al., 1998). While gains decreased linearly with increasing feed restriction in both growing and finishing periods ($P < 0.005$), feed efficiency was similar between all treatments in Exp. 1 (Murphy and Loerch, 1994). While days on feed increased for limit-fed groups by 14 to 28 d, total feed fed was reduced by 3% and 9.7% for 90% and 80% of ad libitum treatment groups, respectively ($P < 0.005$). However, when steers were fed to increase gains incrementally in stages, days on feed were not different ($P > 0.10$) between ad libitum and limit-fed treatments (Loerch and Fluharty, 1998); this was attributed to compensatory gain. Readers are directed to subsequent impacts on feedlot performance for more information and data regarding compensatory gains in young limit-fed cattle.

Importantly, ADG is not always decreased due to limit feeding, but this likely depends on length and severity of restriction duration. For instance, Hereford steers fed for 12 or 24 weeks to achieve 0.45 or 0.9 kg/d, respectively, gained faster ($P < 0.05$) in a subsequent full-fed period of 28 d following restriction, compared to the treatment group fed ad libitum during both periods (Hironaka and Kozub, 1973). In addition, steers previously limit-fed to attain 0.91, 1.13, or 1.36 kg/d, respectively, during period 1 of growth from 272 kg to 372 kg were able to over-compensate and numerically out-gain ad libitum cattle during period 2 of feeding when all cattle were full-fed from 372 kg to 535 kg (Loerch and Fluharty, 1998). However, ADG was not statistically different between treatments ($P > 0.10$).

Similar ADG and net energy consumption can be achieved with limit feeding when high-energy diets are fed, compared to contemporaries fed lower energy diets for ad libitum intakes. Results show all-concentrate, limit-fed (CL) steers gained 0.73 kg/d, and high fiber, ad-lib (FA) steers gained 0.76 kg/d in a growing period from 237 to 327 kg of BW (Sainz et al., 1995). High fiber diets contained 96.1% alfalfa and oat straw on an as-fed basis. In this study, CL cattle had greater gain efficiency primarily due to lower ME intake of FA ($P < 0.05$). Efficiency of ME utilization, expressed in kilograms of empty body weight (EBW) gain per megacalorie (Mcal) of metabolizable energy (ME) intake, was greater in concentrate, limit-fed treatments (48 kg EBW gain/Mcal) than high fiber, ad-lib treatments (39 kg EBW gain/Mcal). Thus, high-energy diets, even when restricted, allowed limit-fed cattle to gain more efficiently with less feed compared to cattle fed high fiber diets for ad libitum intakes.

These results demonstrate ADG using limit feeding strategies employed in growing cattle depends upon diet and level of intake restriction. However, limit feeding young growing cattle did not reduce finishing gain efficiency compared to full-fed in most cases. In certain aspects, effects of limit feeding are highly dependent on diet composition, namely starch or fiber content, net energy of diets, interactions of dietary feedstuffs, and level or duration of restriction applied. The next section will address limit feeding through the lens of programming efficient gains in growing cattle.

Programming efficient gains in the growing phase

Programming efficient gains accomplished through limit feeding is a sound method for efficiently growing cattle and is widely used in many growing operations. Importantly, net energy for maintenance and gain equations allow precise determination of predicted nutrient requirements for specific rates of gain (Galyean et al., 1999). Yet the difficulty in deriving equations to accurately forecast or target rate of gain is repeatedly substantiated by the literature, due to physiological and energetic complexities of the animal and array of production systems (Ferrell and Oltjen, 2008). Reviewing energy history, the California Net Energy System (CNES) was pioneered in the late 1960s by Dr. Glenn Lofgreen and others, becoming a cornerstone for future net energy systems and defining energy values of feedstuffs. CNES separated net energy values into two groups, for maintenance and for gain. Although body weight and modeled growth curves are still used to predict energy needs in many livestock species, many energetic, model, and statistical enhancements have been made to the original net energy system, while maintaining its original integrity and functionality (Galyean et al., 2016). Overall, little has changed since the 1990s.

Under limit-fed conditions, net energy equations from the 1976 and 1984 National Research Council tended to underpredict efficiency of gains. For example, when predicted to gain 0.91, 1.13, and 1.36 kg/d, limit-fed steers in two experiments conducted by Loerch and Fluharty (1998) gained 1.03, 1.22, and 1.40 kg/d, respectively. This under-predicting of gains by the equations also continues through both feeding periods in Exp. 2. Cattle were programmed to gain 1.13 and 1.24 kg/d in periods 1 and 2, respectively, but realized gains were 1.35 and 1.61 kg/d. This was presumed to be caused by lower maintenance energy requirements and greater efficiency under restricted-intake conditions. It may also be attributed to differences in ruminal gut fill. Nonetheless, programming rates of gain for cattle in a specific environment allowed for more enhanced gain efficiency than initially predicted.

Limit feeding for programmed rates of gain has also caused an overestimation of nutrient requirements in growing and finishing cattle (Hicks et al., 1990). These authors utilized 96 crossbred steers, finding both high-programmed (1.50 kg/d) and low-programmed (1.35 kg/d) treatment groups did not fully realize predicted rates of gain. High-programmed cattle gained 1.25 kg/day, while low programmed cattle gained 1.17 kg/day. These two limit-fed groups often did not consume the entirety of their daily feed allotment, thus cattle were not constantly limit-fed. It is likely the equations in this case did not fully allow for variations in feed intake, or the cattle could not physiologically consume the ration due to greater nutrient and energy density. This illustrates the inherent challenge in predetermining how cattle will gain and accordingly feeding for their specific energy needs.

In contrast to the previous studies, program feeding has also accurately targeted ADG. Two experiments that utilized crossbred, medium-frame cattle (234 and 295 kg, Exp. 1 and 2 respectively) performed as expected. To evaluate different allocations of bunk space at 15, 30, 45, or 60 cm per animal on energy intake under limit-fed condition, Exp. 1, rate of gain was programmed for 1.45 kg/d. (Zinn, 1989). Interestingly, bunk space allocation did not affect growing performance in steers fed diets high in steam-flaked corn ($P > 0.20$), and predicted gains were within 5% of actual gains (1.45 versus 1.51 kg/d, respectively). Similar results occurred in Exp. 2, where predicted gains were only 1.6% below actual gains (1.22 and 1.20 kg/d, respectively). These results indicate adequate prediction by the 1984 NRC equations. However, it is questionable whether these results are truly indicative of limit-fed conditions.

In Sainz et al., (1995), increased feed intake accounted for 60% of the increased EBW gain for the concentrate limit-fed cattle (CL-CA), while feed intake of full-fed, high-roughage groups (FA-CA) accounted for 104% of increased EBW. The magnitude of EBW gain efficiency was higher for CL-CA treatment (0.175, $P < 0.05$) relative to FA-CA treatment (0.147, $P < 0.05$). Interestingly, cattle limit-fed in the finishing phase, as opposed to ad libitum, had higher GI tract contents ($P < 0.05$) on an EBW basis, however the authors could not elucidate an explanation for this unexpected occurrence. Limit-fed cattle weights used in performance and efficiency calculations reflect physiological and metabolic changes due to treatment in the animal with a higher degree of accuracy (Watson et al., 2013), but gut fill could not explain increased performance of the limit-fed steers, because empty body weight gains accounted for growth rate differences more so than live weight gain (57% and 54%, respectively).

Coleman et al. (1995) also observed differences in gastrointestinal tract fill between steers program-fed high grain diets at restricted intakes and steers full-fed forage-based diets containing sorghum silage. During a 145-d growing trial, both treatments were provided for approximately equal NE_g intakes. DM intakes were different by design ($P < 0.01$), but grain-fed steers outgained silage-fed steers (0.76 vs. 0.58 kg/day, $P < 0.01$). Steers limit-fed grain in the growing phase consumed less DM compared to the ad-lib, silage treatment group, and Mcal NE_g/kg BW gain was lower for the limit-fed group ($P < 0.05$). Nonetheless, grain-fed steers outgained silage-fed steers, likely because overall NE_g consumption per day was higher for the limit-fed, grain treatment group ($P < 0.01$). Also, greater growing-phase performance by grain-fed steers, the authors elucidate, was due to 10 kg less gut fill, on average, and lower DMI than silage-fed steers (4.89 and 6.62 kg/day, respectively). In the finishing phase, all steers were placed on a high-grain diets for 45 d, 75 d, or 105 d, and carcass merit was examined upon completion. Steers previously limit-fed grain-based diets in the growing phase were heavier when slaughtered at 45 d, 75 d, and 105 d, respectively ($P < 0.05$). As a result, limit feeding appears to alter both eating behavior and energy efficiency in the growing phase, affecting subsequent performance.

Meal-eating behavior has been observed in limit-fed chickens (Nitsan et al., 1984), along with other species of birds and reptiles. In Exp. 1, young chickens were assigned to ad libitum (T100/V100), 75% (T75/V75), or 50% (T50/V50) restricted intake feeding treatments. All treatments were evaluated for effects of voluntary or tube-fed protocols on energy retention and lean-fat deposition. Results showed limit-fed chickens with tubes improved energy retention by up to 56% in T50 treated birds. In addition, variation coefficients for final body weight increased with increasing feed restriction in groups allowed voluntary access to feed. In a commercial cattle grower or feedlot setting where cattle are often fed in large groups or pens, meal-eating behavior has been observed. Thus, limit feeding can create large intake variations (Montgomery et al., 2003). Due to potential for intake variation, bunk space is an important consideration for limit-fed protocols, however, few recommendations have been made in growing cattle. Zinn, (1989) recommended limit-fed cattle need ample bunk space to prevent detrimental effects on performance; 15 cm per steer appeared adequate, because greater allocations did not improve performance. Much bunk space allocation work has been conducted in dairy cattle. Recently, limit-fed dairy heifers show improved ADG and reduced intake variability with 0.4 m of bunk space per heifer compared to 0.28 m of bunk space (Greter et al., 2013). Ultimately, experimental results show limit-fed cattle may have different growth patterns and improved efficiency when programmed for specific rates of gain and net energy consumption.

Effect of limit feeding corn coproducts in growing diets

Corn coproducts such as WCGF have shown significant value in limit-fed growing cattle programs in recent years. Limit-fed diets containing branded WCGF (Sweet Bran) programmed to specific rates of gain have shown no negative impact on receiving cattle health; additionally, increasing prevalence of metabolic disorders due to increased dietary energy from corn coproducts is not evident (Spore et al., 2018; Spore et al., 2019). Even though perceived benefits of roughages in growing cattle diets encourages diet formulation accordingly, the real performance-health tradeoff with less energy-dense diets may not be worthwhile (Richeson et al., 2019). Remarkably, indications point to higher energy diets with fibrous byproducts as a significant alternative to the status quo of feeding diets primarily based on roughages in receiving rations.

In limit-fed growing diets, effects of wet corn gluten feed (WCGF) as the energy source, and alfalfa hay (AH) as the roughage/fiber source were evaluated on growing steer performance (Montgomery et al., 2003). Furthermore, growing performance seemed to improve by limit feeding WCGF with increased AH, compared to diets based on steam-flaked corn. By replacing steam-flaked corn with AH, linear increases occurred in DM intake, but ADG was lower, and overall gain efficiency was suppressed ($P < 0.01$). Optimal ADG and G:F were achieved through limit feeding these diets with a roughage inclusion between 10 and 20% when WCGF was 40% of diet DM. In this case, WCGF appeared to increase in feeding value due to roughage inclusion, but effect of limit feeding was confounded with diet.

Although the authors in the previous study determined greater overall value from limit feeding specified ranges of WCGF and roughage, less desirable performance has also occurred with diets containing corn coproducts. For example, growing cattle limit-fed diets containing dried distillers grains plus solubles (DDGS) had less desirable ADG and G:F ($P < 0.01$) compared to corn-based diets groups, and lower DMI ($P < 0.01$) (Felix et al., 2011). All cattle were limit-fed to gain either 0.9 or 1.4 kg/d. Moreover, corn-based diets consisted of 65% dry rolled corn, whereas DDGS diets consisted of 65% DDGS. Results depicting lower performance of DDGS-based diets was unexpected, but BW gains for these treatments were on target. Corn-based diet gains, on the other hand, exceeded predicted targets (NRC, 2000). Overall, several dietary factors, including excess nitrogen due to high crude protein (27%), high fat content, or high dietary sulfur over the recommended tolerable maximum of 0.4% may have contributed to low steer performance on DDGS diets. Moreover, rapid consumption of diets, which were delivered once per day, due to limit feeding may have contributed to decreased growth performance because of lowered rumen pH. Thus, overall nutrient utilization and performance on the DDGS-diets may have declined.

Although performance through limit feeding DDGS in the previous trial demonstrated challenges through complex nutritive factors inherent for all ruminant nutritionists, researchers, and growing cattle producers, the limit-fed strategy still holds promise. A 55-d limit feeding trial with 354 growing heifers from the southeastern United States demonstrated the benefits of limit feeding when coupled with the branded WCGF product, Sweet Bran (Spore et al., 2019).

Importantly, higher-energy diets can be effectively substituted and fed once daily in place of lower energy, higher roughage-based rations by limit feeding diets to achieve targeted energy intake. In this trial, 4 diets were fed with increasing net energy for gain (NE_g) from 0.99 up to 1.32 Mcal NE_g/kg DM. Moreover, each treatment intake was restricted to a percentage of the ad libitum intakes, with 0.99 treatment allowed ad libitum access. 1.32 treatment cattle were restricted to 85% of ad libitum intakes. Morbidity and mortality were not different between treatments ($P < 0.82$), even though the total number of treated animals and those that died was indicative of highly stressed, auction market-sourced cattle. In addition, by study design ADG was similar across treatments ($P \geq 0.33$). For high-energy, limit-fed cattle, G:F was 22% more efficient, compared to cattle fed low-energy diets ad libitum. However, once again, effect of limit feeding was diet-dependent.

Overall, greater gain efficiency and no adverse health implications when limit feeding higher energy diets to newly received growing cattle can be achieved. Although products vary in nutrient composition, inclusion of corn coproducts due to high fermentability and low starch opens many opportunities for feeding growing cattle. Often, compromised immune health and poor management can detrimentally impact growing performance. However, consistent gains through limit feeding can be achieved. At times limit-fed protocols may not be incorporated due to concerns for ADG and performance for newly received stocker cattle, but these concerns may not be realized. Importantly, effect of limit feeding on diet digestibility will be discussed in the next section.

Effect of limit feeding on diet digestibility

Limit feeding has numerous implications on diet digestibility in highly-stressed, young growing cattle. Namely, level of intake affects energy or protein utilization due to ruminal passage rate. In addition, animals on restricted diets demonstrate rapid meal-eating behavior, often consuming a diet in just a few hours, as opposed to ad libitum feeding. This increases risks of digestive upsets and other metabolic maladies. Due to different combinations and various types of carbohydrates in the feedstuffs provided, proper nutritional balance helps to reasonably avoid such issues. Uniquely cattle can convert structural carbohydrates (fiber) to high-quality protein and energy, which allows numerous physiological processes and critical organs to function (Van Soest, 2018).

By the mid-twentieth century, numerous metabolism studies showed forages and cereal grains have different digestibility characteristics in the ruminant; however, no evaluation of digestibility due to limit feeding had been conducted. Moreover, structural carbohydrates are more efficiently digested in the ruminant than hind-gut fermenters and other non-ruminants, but quantifying these differences was costly and ineffective. Due to alterations in chemical analyses and refined methodologies, researchers' ability to determine digestibility improved immensely, especially through the neutral detergent fiber (NDF) system. Prior to using NDF evaluations, total digestible nutrients (TDN) and digestible energy (DE) were primarily used, but results often minimized differences in forage digestibility at various levels of intake. For instance, forages harvested at various stages of maturity affected plant nutrient digestibility ($P < 0.01$), but diet digestibility of subsequent rumen or duodenal samples were similar ($P > 0.20$) (Andersen et al., 1959). Furthermore, digestibility of chopped compared to long-stem forage were similar. However, finely ground forages were speculated to have increased passage rate, therefore reducing overall nutrient digestion opportunity. From previous experiments conducted, differences in retention time of nutrients were also apparent, suggesting concentrates had a greater TDN value than forages. Finally, DE declined with forage maturity or later harvest times.

Fiber digestibility is also affected by animal body size, which may be a function of DMI (Udén and Van Soest, 1982). This would have important implications for cattle being limit-fed. In this study, rabbits had the greatest mean cell wall indigestibility (CWID), whereas horses were intermediate, but horses had the highest reported coefficient of variation (28.3). CWID for heifers averaged 49.6%. Furthermore, metabolic fecal output for all species as a percentage of DMI was similar. When not compared across species all animals utilized in this evaluation were relatively efficient, which is remarkable, but cattle and smaller ruminants had slower passages rates and increased ruminal retention for fiber components, thus allowing progression of digestion (fermentation) to reach a greater level.

Contrarily, non-structural carbohydrates are quickly degraded by microbes in the rumen before reaching the lower gastrointestinal tract. Yet, a review of starch showed intestinally-degraded starch was 42% more valuable than ruminally-degraded starch (Owens et al., 1986). However, about 70% of total starch degrades before reaching the small intestine and is converted into volatile fatty acids (VFA) (Owens et al., 1986; Ramos et al., 2009). Thus, optimizing ruminal fermentation of both starch and fiber would undoubtedly have immense benefits for cattle.

Moreover, different intakes of diets high in starch affects the ruminants' efficiency of digestion. Work conducted by Galyean et al. (1979) involved feeding 285 kg crossbred steers a whole corn-based diet at 84% of diet DM, 4.8% cottonseed hulls, 4.8%, and 4.42% soybean seeds. Levels of intake were either maintenance (NE_m) or twice maintenance (2x-NE_m). Total tract dry matter digestion was 7% lower at 2x-NE_m than NE_m ($P < 0.05$), and ruminal dry matter digestion similarly decreased. Moreover, liquid passage rate or percentage of fecal starch content increased from 3% per hour or 10.3% at NE_m to 5.3% per hour or 35.2% at 2x-NE_m ($P < 0.05$).

Markedly, increasing DM intake decreased overall digestion of carbohydrates and increased passage rate.

Dynamic ruminal fermentation through microbial attack of digesta converts carbohydrates into volatile fatty acids (VFA) (Varga and Kolver, 1997). Unfortunately, variations of DM intake dramatically impact microbial populations, subsequently altering VFA production and pH within the rumen. Acetate is the predominant VFA in ruminants such as cattle, but increasing dietary starch generally causes acetate proportions to decrease while increasing propionate; however, acetate concentrations are usually still greater (Bergman, 1990). Also, variations in DM intake through once or twice-daily limit feeding can alter energy retention, utilization, and animal performance (Soto-Navarro et al., 2000). When nine ruminally-cannulated steers (344 ± 26 kg) were limit-fed a corn-based diet at 90% of their ad-libitum intakes (measured in a previous 2-wk adaptation period), acetate:propionate ratios were greater for animals fed twice per day than those fed once per day ($P < 0.05$). Steers fed twice per day also tended to have higher rumen pH than those fed once per day ($P = 0.10$). In the rumen, fibrolytic bacteria are primarily responsible for acetate production while starch-digesting bacteria produce propionate (Sanchez et al., 2014), and the former bacteria thrive at pH levels closer to neutral. Increasing feeding frequency to twice daily in limit-fed animals appears to decrease rumen volatility by encouraging growth of fiber-digesting microbe species. In turn, pH increases, but starch-digesting microbe activity decreases.

In addition, significant interactions of feeding frequency and fluctuation of intake were found between the constant-fed and the fluctuation-fed groups when fed once per day (Soto-Navarro et al., 2000). Feed intake of fluctuating-intake treatment groups was alternated every second day between 90% and 110% of a predetermined constant-level intake; this constant intake was fed to respective constant-intake treatment groups to serve as controls across once daily or twice-fed daily groups. There was a significant interaction with liquid passage rate ($P < 0.05$). For groups fed twice daily with prescribed fluctuating daily intake, passage rate increased, but it decreased when fluctuating groups were fed once daily. However, ruminal liquid volumes were similar across groups ($P > 0.10$). Associated with increasing passage rate in the former group, total tract digestion of organic matter, nitrogen, and starch all decreased ($P < 0.05$). Therefore, multiple limited feedings (resembling meal-eating behavior) may decrease diet digestibility due to increased passage rate. This shows the importance of consistent intakes when limit feeding cattle to ensure optimal digestive health and utilization of dietary energy; limit feeding once daily may be superior to limit feeding twice daily in terms of diet digestibility.

In limit-fed cattle rations are consumed quickly and more rapidly digested, leading ruminal microbes to more rapidly convert energy substrates to volatile fatty acids (VFA). Feeding corn-based diets decreased the acetate-to-propionate ratio in steers (BW = 400 ± 12 kg) fed for both ad libitum and limited intake cattle (Murphy et al., 1994). Moreover, a significant interaction of intake level and corn processing method occurred, such that starch digestion decreased in limit-fed (at 70% of ad libitum intakes) whole-corn steers ($P < 0.03$), but limit-fed cattle had slower passage rate compared to those fed for ad libitum intakes ($P < 0.03$).

In contrast, passage rate in other limit-fed cattle was not affected (Montgomery et al., 2004). However, diets fed in this study contained approximately 40% wet corn gluten feed, which contains less starch and more fermentable fiber. Although higher molar proportions of propionate were found in both limit-fed and ad libitum groups fed steam-flaked corn, limit-fed groups had decreased molar proportions of propionate independent of diet ($P < 0.01$). In contrast to (Soto-Navarro et al., 2000), restricting intake compared to ad libitum feeding in this study decreased total-tract digestion of organic matter, along with neutral detergent fiber digestibility and ruminal VFA concentration in 12 cannulated Jersey steers (BW = 534 kg). Diets were offered once daily. Increased ruminal volatility may have caused decreased digestibility, due to rapid DMI of limit-fed diets, but rate of DMI was not measured beyond visual observation. In addition, rapid feed ingestion and decreased chewing due to less dietary roughage may have also decreased overall digestion. Finally, both pH and ruminal ammonia were significantly affected by intake level and hour ($P < 0.03$). Limit-fed cattle experienced more fluctuation through the day and decreased ruminal ammonia at 0 and 4 h after feeding, compared to cattle fed ad libitum. Overall, results of digestibility parameters between cattle fed ad libitum and limit-fed are likely diet-dependent, but limit feeding appears to alter diet digestibility somewhat through changes in eating patterns, ruminal pH, and ruminal ammonia concentrations.

In addition, growing cattle often receive diets high or exclusively forage-based, or they may be grazed on pasture. Chewing behavior of restricted-intake, forage-fed cattle directly impacts diet digestibility and passage rate (Dias et al., 2011). Both dry matter intake and organic matter digestibility were highly correlated to the rate at which feed particles progress through the gastrointestinal tract; increasing roughage DMI decreased passage rate ($r = -0.868$). Moreover, chewing rates and time spent chewing increased for cattle consuming oat grass hay at less restricted levels or ad libitum, compared to more-restricted levels ($P < 0.02$). In theory, restricting intake of forage-based diets could improve overall digestibility by increasing retention time. Mean particle retention time, measured in hours, decreased ($P < 0.01$) from heavily restricted (1.5% of BW) to less restricted and ad libitum intakes (2.0/2.5/AL). In addition to particle size, palatability may also influence rates of intake, thus affecting overall mastication and diet digestibility.

Palatability is an important consideration for cattle fed in confined feeding because it can impact intake, therefore overall energy consumption; confined cattle often receive high-energy diets to improve growth performance. Moreover, digestibility appears to increase when cattle are fed high-energy diets at restricted intakes. For instance, steers had 10% greater ($P < 0.01$) percent dry matter, organic matter, and ADF digestibility when fed a high-energy diet containing corn, distillers' grains, and wheat straw at 80% of calculated NE_m levels, compared to the 120% level (Trubenbach et al., 2019). Digestibility was similar across low-energy diet intakes ($P > 0.05$). In addition, digestibility increased ($P < 0.01$) with decreasing (more-restricted) intakes in steers fed a diet containing 40% Sweet Bran, a branded wet corn gluten feed (Spore et al., 2019). In this case, total-tract dry matter digestibility was improved ($P < 0.01$) by 12% in limit-fed, high-energy diets, while fiber digestibility was not significantly different. Furthermore, liquid passage rate decreased as intakes were restricted ($P < 0.01$); by design NE_g increased from ad libitum to 85% of ad libitum intakes. Generally, increasing energy in limit-fed diets improves digestibility because more energy is available; passage rates decreased with high-energy, low-starch limit-fed diets thus improving utilization of some dietary components.

By increasing energy concentration yet decreasing starch in limit-fed diets, energy was more efficiently utilized. As a result, retention of digesta in the gastrointestinal tract generally increased. However, passage rate greatly depends upon particle size and carbohydrate (energy) form, whether structural (i.e. fiber) or nonstructural (i.e. starch). In the case of forages, limit feeding may cause chewing rates and total time spent masticating to increase, thus improving energy retention and digestibility but at the expense of increased DMI and reduced performance. While shifts in ruminal VFA production and pH were likely caused by changes in dietary energy source, rapid intake due to limit feeding diets high in starch may destabilize and decrease energy metabolism in the rumen. In the final analysis, limit feeding once daily appears to improve overall total-tract diet digestibility; decreased passage rate may also shift the site and extent of digestion away from the hindgut to the rumen.

Effect of limit feeding on visceral organ mass

The effect of limit feeding different levels of dietary energy, protein concentration, and energy source on visceral organ mass (VOM) has been investigated in the literature. Research indicates previous level or plane of nutrition has major implications in determining metabolic requirements of ruminants. However, accurate assessment of such differences is confounded because of comparisons made with vast ranges of body weight, age, or type and length of nutritional restrictions applied in a treatment (Ferrell et al., 1986). However, whole-body carcass analysis of 48 crossbred lambs similar in weight and age revealed lambs previously fed at higher nutritional levels had greater liver, intestine, and stomach weights than lambs fed at lower levels ($P < 0.05$). Additionally, correlations (coefficients of determination) for fasting heat production to liver, kidney, small intestine, and stomach weights were high ($r^2 = 0.69$, 0.68, 0.82, and 0.68, respectively). As body weight changed, organ weights also changed, indicating a relationship between VOM and rate of gain. Importantly, these data illustrate the impact plane of nutrition has on VOM.

In addition, research shows that limit-fed animals have smaller VOM and lower maintenance energy requirements compared to animals fed ad libitum. Thus, effect of ad libitum and maintenance-level energy intake restrictions on organ composition in 32 crossbred wether lambs of similar age and weight was evaluated (Burrin et al., 1992). While not explicitly clear, protein amount per unit of DNA, a proxy measure for estimating changes in organ DNA content, suggested altering energy intake levels decreased cell size or mass, but not cell number, the latter which would indicate DNA-level modifications. Most organ protein-to-DNA ratios were smaller in restricted animals compared to ad-lib controls ($P < 0.05$). In addition, liver tissue accretion rates of valine, an essential amino acid, were greater in restricted lambs ($P < 0.05$). Changes in liver tissue accretion indicates that plane of nutrition affects VOM. Many organs including the liver, ileum, and jejunum in animals fed for ad libitum intakes expressed lower DNA concentrations compared to those with intakes restricted to maintenance. ($P < 0.05$) In this analysis, both protein and ribonucleic acid mass (RNA), measured in mg per kg of empty body weight, were higher in ruminal tissues in lambs fed for ad libitum intakes ($P < 0.05$). Additionally, significant interactions of day and intake level occurred in duodenal and jejunal tissues; lambs fed for ad libitum intakes had greater mass of protein and RNA ($P < 0.05$). Overall, DNA mass was not affected by intake restriction in the small intestine or liver ($P > 0.05$). Perhaps greater dilution of DNA, but not change in DNA mass, seen in the liver and small intestine in animals fed for ad libitum intakes is a function of greater DMI, thus energy intake. This is an important finding, because it demonstrates total cell size, determined by protein and RNA changes, was impacted by intake restriction, becoming smaller. However, total cell number was unaffected, as evidenced by lack of DNA mass changes.

Importantly, age at which intake was previously applied may be a confounding factor. While effect of age on VOM in limit-fed animals was not investigated in the previous study, it can be significant on a molecular or DNA-level. For example, changes in cellular DNA and total cell count were evident in poorly-fed rats from birth to weaning, with lasting impacts after reaching full maturity (Winick and Noble, 1966). While such impacts may affect cattle differently, molecular changes due to restricted intake at different ages, or when restrictions are lengthy or extreme, are possible.

Nonetheless, limit feeding decreases organ mass, but other factors also contribute to the magnitude or extent of VOM change. For example, due to limit feeding Fluharty and McClure (1997) found lambs had smaller rumens, reticulums, and large intestines ($P < 0.05$). Liver weights were also lower. In this study, there were no interactions for intake level and protein concentration ($P = 0.41$), and final weight was not significantly different for any slaughter group ($P > 0.05$). Moreover, breed differences can cause changes in VOM, where Bos taurus-influenced cattle generally have larger VOM than Bos indicus-influenced cattle under both limit-fed and ad libitum feeding treatments (Ferrell and Jenkins, 1998a).

In addition to breed, dietary protein level may affect VOM in limit-fed animals (Fluharty and McClure, 1997). Increasing protein requirements to 125% of NRC recommendations increased liver and kidney weights in lambs slaughtered at intermediate weights, approximately 36.3 kg ($P < 0.01$). Alternatively, restricting feed intake level to 85% of ad libitum reduced rumen, reticulum, omasum weights ($P < 0.05$). In terms of final lamb performance when limit-fed, liver weights were lower for restricted-intake lambs ($P < 0.01$). Moreover, significant reductions in rumen, reticulum, and large intestine weights also occurred ($P < 0.05$). Regarding increased protein concentrations at 125% of normal, lambs had larger livers ($P < 0.01$). Furthermore, increased small intestine mass was observed ($P < 0.05$). Thus, effect of protein intake are similar to energy, but energy appears to be the primary cause for decreased VOM in limit-fed animals.

Importantly, the previous studies conducted with lambs utilized the same dietary composition across energy intake levels. Alternatively, Coleman et al. (1995) limit-fed cattle grain-based diets (G) consisting of ground shelled corn, compared to ad libitum sorghum silage-based diets (S). Consequently, the grain-based diet contained twice as much dietary NE_g. Initially grain-fed cattle in the growing phase were limit-fed to attain similar rates of shrunk ADG as ad libitum cattle; however, EB gains throughout the trial reflect increased rates in grain-fed cattle over silage-fed cattle (.633 vs. .382 kg/d, respectively; $P < 0.01$). As a result of the increased plane of nutrition during the growing phase, carcass results upon termination on d 145 show grain-fed cattle had numerically larger livers, with minor differences in all other organs across treatments. However, these differences are most likely due to large differences in body weight, confounded by diets effects. As finishing days on feed increased through 105 d, all numerical differences disappeared. Interestingly, diet effect on visceral organ size was not statistically significant upon regression analysis ($P > 0.10$). As a result, liver growth was likely a function of overall intake of net energy for gain. On the contrary, energy-restricted cattle were determined to have larger livers as a percentage of carcass weight than control steers with ad libitum energy access ($P < 0.05$) (Drouillard et al., 1991). Additionally, because less digestible feeds require more energy to breakdown, lower-quality roughages require greater energy expenditure by the gastrointestinal tract organs to digest, compared to grain. Thus, fasting heat production is greater in animals consuming forage-based diets (Coleman et al., 1995). Overall, differences in diet digestibility between grain and silage-based diets or overall energy-intake could have led to differences in organ size.

Dietary treatment and energy intake restrictions during the growing phase size of visceral organs was different, but not after the finishing phase (McCurdy et al., 2010). 46 steers (initial BW = 216 kg) were assigned to 1 of 3 growing treatments, including wheat pasture grazing, silage, or program-fed high concentrate. After a 112 d growing phase, all treatments were finished on a high-concentrate diet ad libitum until 1.27 cm of backfat was reached. Steers grazing wheat pasture during the growing phase consumed a greater amount of protein, compared to other treatments; both liver and kidney mass was greater in this treatment group (*P* < 0.01). Additionally, retained energy was different between steers on wheat pasture and program-fed steers (*P* < 0.05), but metabolizable energy intake did not differ between treatments (*P* = 0.50). In addition, program-fed steers had greater mesenteric and omental fat than wheat pasture or silage-fed steers (*P* < 0.05). Upon completing the finishing phase, total visceral tissue mass was not different between treatments (*P* > 0.10). Thus, net energy for gain in the diet affected differences in liver and kidney mass in these steers in the growing phase, but differences diminished subsequently with finishing.

Limit feeding in the growing phase does decrease visceral organ mass. Subsequent decreases were also evident in energy expenditure by the liver and other energy-costly organs in the finishing phase, resulting in increased organ efficiency. Across diets, energy costs of visceral organs are high. Importantly, limit feeding appears to cause changes in cell size, not cell number; thus, DNA changes attributed to limit feeding are minimal or non-existent. Importantly, complex interactions of limit feeding with other factors, including dietary energy and physiological characteristics of the animal such as age and breed will also determine energy utilization, leading to changes in visceral organ mass.

Summary

In essence, limit feeding strategies can be useful for growing cattle. Protocols vary but seek to target net energy (NE) intake based on NE equations, body weight, or ad libitum consumption to achieve specific rates of gain. Intake variation and meal-eating behavior associated with limit feeding has confined its use to primarily grower or backgrounding yards. Moreover, limit feeding is not used in finishing cattle primarily due to decreased energy intake and potentially detrimental effects to carcass quality. By targeting intake at restricted levels during the growing phase however, gains are more efficiently realized, often without reductions in growing ADG, but specific performance depends on diet composition and level of restriction. Across diets manure output is decreased in limit-fed animals. Moreover, limit feeding diets low in starch or high in fiber can decrease passage rate of digesta through the gastrointestinal tract and increase total-tract digestion. However, greater ruminal volatility due to meal-eating behavior from limit feeding may subsequently increase passage rate. This could result in depressed animal performance, especially if used in finishing cattle. Finally, previously limit-fed growing animals had reduced visceral organ mass due to smaller tissue cell size from moderate intake restrictions, and gain efficiency generally is improved.

Measuring Health and Behavior of Limit-fed Growing Cattle

Visual, performance, and digestibility parameters are affected by limit feeding protocols in growing cattle. However, effect of limit feeding can also be explored on a quantitative level utilizing newly developed technologies; assuredly these technologies will continue to develop and progress producers' ability to measure cattle health parameters such as rumination and activity level. Currently, investigations using advanced accelerometers to measure how rumination and activity is affected by limit feeding remain largely unconducted in growing cattle.

However, changes in rumination time (RT) and activity (A) due to limit feeding strategies will likely have behavioral and metabolic implications for growing cattle. Specific reasons may be intake related, or they may be due to dietary, genetic, or environmental differences. Environment plays a key role in health status of highly stressed growing cattle, and programs now exist to evaluate climatic and weather-related impacts on cattle performance and health throughout the United States (Mader et al., 2010). By quantitatively measuring rumination and activity, a sophisticated understanding of the complex ruminant microbiome previously evaluated only using visual techniques can be unveiled (Richeson et al., 2018).

Health detection and observation strategies

Visual inspection or observation of livestock as a tool for determining animal health status has been practiced albeit with varying criteria, experience, and success for millennia. Clearly, visual assessments can be subjective or potentially unreliable. Animal behavior as both subject and science has risen to the forefront in recent decades as an important way to diagnose, treat, or prevent illness (Weary et al., 2009). For example, behavioral indicators which are signs of animal health status may decrease in times of discomfort or illness. Activities such as play or environment learning may decrease when animals are sick (Marek et al., 2001). During illness visual observations shows negative behaviors usually increase, such frequent or increased lying or depressed feed intake (Sowell et al., 1999). Preclinical health changes can be difficult or impossible to predict or detect, and flighty or temperamental animals' natural predator-prey responses mask symptoms which may otherwise be observed, as in domesticated livestock or pets (Weary et al., 2009). Animal science researchers have begun to explore the concept of animal behavior as not only an indicator but also as "adaptive responses" to ailments. According to recent research, animals can experience emotions (Grandin and Shivley, 2015). Perhaps these emotions ought to see evaluation without personification, but animals certainly have unique ways of expression and communication which continue to be evaluated. To quantify behavioral or subclinical health indicators using advanced technology will assuredly enable better animal husbandry and management.

As previously stated, to reveal important subtle clues elucidating animal health, often before becoming visible, is of paramount importance. Recent research from the University of Kentucky illustrates electronic monitoring technologies can objectively and consistently differentiate between animals visually-identified as healthy or sick (Smith et al., 2015). Two separate studies during the late fall of 2011 and 2012 evaluated 311 steers fitted with custom triaxial accelerometer ear tags to evaluate device efficacy in detecting activity differences between animals visually identified to be health or sick. Results demonstrated tags performed, and activity between groups were different by 25%. Similar patterns were observed in both studies ($P \leq 0.05$). Other similar technologies have been successfully employed with site of attachment around the neck via a collar (Tomczak et al., 2019) or on the metatarsus of the foot (Pillen et al., 2016). Application of accelerometers to the commercial feedlot industry is limited, primarily due to high entry costs, but the benefits may outweigh the costs (Pillen et al., 2016), particularly to identify sick cattle at the subclinical level. Furthermore, costs will decrease with improved access and greater use of such technologies.

Quantitatively measuring rumination behavior and activity

Behavioral and health studies evaluating time spent ruminating and in various activities is well-documented in the dairy industry (Beauchemin, 2018). In beef cattle, evaluations are becoming more readily available, but few data for growing cattle can be found, and quantitative analysis on the effect of limit feeding is not well-defined. Moreover, in northeastern Italy, numerous backgrounding and finishing operations grow cattle from low weights to finishing weights in special indoor facilities with either soft or slatted floors unlike backgrounding yards in the United States; in the U.S., young growing cattle are outdoors in dry lots or on native pasture (Marchesini et al., 2018). These authors utilized 108 (group 1) and 106 (group 2) yearling Charolais bulls of French-origin (initial BW = 453 and 429 kg, respectively) in 2 periods each 70 d in length. All cattle were fitted with a collar accelerometer (Allflex Livestock Intelligence, Madison, WI). Overall, linear regression analyses revealed moderate correlation coefficients between rumination time and a homogeneity index with 3 different rates of low, medium, or high ADG. For instance, low average daily gain cattle were determined to have significantly lower average rumination time and range of rumination ($P < 0.05$), but the authors do not specify the weight of low ADG. Period 1 and period 2 ADG was 1.56 and 1.28 kg/d, respectively. In addition, a 9% decrease in rumination minutes in this trial allowed subsequent prediction of either lameness or bovine respiratory disease (BRD) as early as 6 days prior to clinical signs, but both were virtually indistinguishable from the other. Clearly this could be problematic. Additionally, for data interpretation to occur, a baseline behavior for each animal had to be established, which can take up to 14 days. After data "equilibration," comparisons can be made against previously recorded activity and rumination levels when animals were also confirmed to be healthy. To this end, visual health assessment remained critical. While this research demonstrates the power of this technology to objectively assess cattle health and behavior through rumination and activity time, it requires meticulous analysis and careful monitoring. Furthermore, sensors must individually equilibrate for several days to the individual animal for reliable data to be collected and interpreted.

In growing cattle, rugged electronic measuring devices also showcase promising results with tulathromycin via metaphylactic administration compared to vaccination with a modified-live vaccine (Munoz et al., 2020). In this growing trial, activity was reduced from d 9 through d 32 in young bulls and steers diagnosed with bovine respiratory disease (BRD) ($P = 0.04$). Rumination time declined during the evening and nighttime hours but was increased ($P < 0.05$) for BRD cattle treated with a tulathromycin. Moreover, these technologies have been recently evaluated in feedlot cattle. To measure and quantify rumination time researchers utilized sensory accelerometers attached to the outer ear or around the neck on a collar. Data was both collected and analyzed in total minutes per day. In this experiment, 51 individually-fed feedlot steers (BW = 385 ± 3.6 kg) were evaluated for rumination characteristics when given 5% or 10% short (5SG/10SG) or long-grind (5LS) cornstalk treatments (Gentry et al., 2016). Contrary to expectation, when roughage inclusion decreased DMI increased; 5SG treatment cattle had the lowest DMI ($P = 0.03$). However, the magnitude change in roughage between treatments was small; it may have been caused by palatability differences or random chance. In addition, rumination time (RT) was not affected by DMI ($P = 0.46$). After d 112 of the study, significant treatment-by-day interactions occurred, however the authors were unable to attribute a cause for this interaction ($P < 0.01$). Results also indicated larger particle sizes of corn stalk appeared to increase time cattle spent ruminating each day. The authors acknowledge within day fluctuations in DM intake or meal-eating behavior could impact RT. Markedly, the information collected from this data demonstrates changes in RT caused by roughage (corn stalks) inclusion and particle size. Unfortunately, information regarding activity was not directly provided in this study. Another feeding trial was conducted to quantify effects of corn stalks as the roughage source on rumination time and ruminal pH in finishing steers (Jennings et al., 2020). While increasing roughage inclusion increased DMI ($P \leq 0.05$) and decreased both ADG and G:F ($P \leq 0.05$), rumination time increased ($P \leq 0.01$). Generally, pH increased with increasing roughage in the diet ($P < 0.09$). These results show increasing roughages in the diet, but not necessarily DMI which depends on diet composition, causes rumination time in cattle to increase.

Summary

Assessing health and behavior of animals and livestock species is performed through visual assessment. Reliability and timeliness depend on skill-level and knowledge of the observer, making evaluations subjective. Quantitative analysis requires advanced technologies, but usage in both beef and dairy cattle breeds demonstrate ability to detect various illnesses with a high degree of accuracy, although precision is lacking. In addition, use of these technologies has not been fully evaluated in limit-fed protocols. However, diets with opposing compositions of roughages and concentrates reflect in rumination time values.

Limit Feeding Effects on Feedlot Performance and Carcass Merit

Undoubtedly, previous stocker-backgrounding cattle management ensures more efficient, less stressful transitions to the feedlot for finishing (Swanson and Morrow-Tesch, 2001b). While limit feeding is utilized in grower yards, its utility and application in finishing cattle is low. The primary goal in finishing cattle is to maximize gains and minimize days on feed; ad libitum feeding is predominant, but variants such as slick bunk management and multiple daily feedings are also often utilized in finishing strategies. In addition, predicting nutrient requirements or future intakes of cattle, especially those of unknown histories, can be difficult. Cattle in the feed yard arrive through a wide variety of marketing sources, being subject to numerous stressors and pathogens (Step et al., 2008). Certainly, refinement of performance and net-energy prediction equations (Galyean et al., 2011) and the implementation of user-friendly data management programs (Richards and Lalman, 2017) has greatly improved finishing phase productivity and efficiency.

Finishing phase performance can be affected by limit feeding protocols. In fact, restricting energy intake below ad libitum consumption can improve metabolic efficiency by reducing visceral organ mass and potentially increasing diet digestibility (Loerch and Fluharty, 1998). Importantly, energy utilization and rates of gain follow curvilinear patterns above maintenance levels in cattle, thus rates decline at greater intake levels (Ferrell and Jenkins, 1998b). Nevertheless, limit feeding remains underutilized in commercial feedlot settings due to practical concerns for meal-eating behavior, increased variability in animal DMI, inadequate bunk space, depressed rates of gain, and reduced carcass merit. However, previously limit-fed cattle may consume more and gain more efficiently during the finishing phase (Loerch, 1990). Subsequent compensatory gain in the finishing phase has occurred following intake restriction practices due to less dietary energy (Carroll et al., 1963). While finishing ADG can decrease due to previous restrictions (Murphy and Loerch, 1994), gain efficiency may increase, particularly if the previous energy restriction period is long (Drouillard et al., 1991). Furthermore, greater energy and protein density can be provided in a diet to allow for similar gains in restricted growing cattle (Loerch, 1990) and in the finishing phase (Hicks et al., 1990). In addition, effect of energy source in limit-fed strategies is often a cofounding factor. These factors and subsequent impacts of limit feeding in the growing phase on feedlot performance and carcass merit will be discussed.

Subsequent impacts on feedlot performance

Young growing cattle previously subjected to modest energy restrictions respond favorably in the finishing phase (Drouillard et al., 1991). In this experiment with 164 steers, increasing restriction length resulted in greater gain efficiency for finishing ($P < 0.03$). As ADG declined during the growing phase for energy-restricted steers, finishing phase gain efficiency increased significantly ($P < 0.01$). No efficiency improvements were observed for protein-restricted steers ($P = 0.41$). However, if protein was restricted too severely, both performance and health declined precipitously. Cattle receiving heavy protein malnourishment did not exhibit compensatory gain post-restriction on the finishing phase diet provided for ad libitum intakes. Severe and mild protein-restricted treatment groups had similar finishing phase performance as control cattle receiving no previous restrictions but required more days on feed to finish ($P < 0.01$). Performance measures observed were individually analyzed through multiple linear regression analysis. Results suggest energy metabolism and dietary protein have an associative relationship in the rumen. Markedly, limiting energy intake during early growth improved subsequent steer efficiency in the finishing phase.

Improved finishing phase performance due to limit feeding in the backgrounding phase was also seen in two experiments evaluating 5 feeding protocols with varying levels of intake restrictions or no intake restriction in growing cattle (Knoblich et al., 1997). No differences were observed in either Exp. 1 or 2 in overall ADG or days on feed ($P > 0.05$). However, DMI was lower for restricted cattle ($P < 0.01$). A longer duration of ad libitum feeding in Exp. 2 compared to Exp. 1 likely resulted in performance similarities observed, diminishing the effects of previous restrictions. Also, compensatory gains were not realized in exp 2. Loerch and Fluharty (1998) demonstrated if cattle are given a minimum of 100 days of ad libitum access to diets following limit-fed protocols, overall steer performance will not be impacted. By restricting intakes, 109 kg less feed was used to attain market weight, compared to groups fed for ad libitum intakes in both growing and finishing periods ($P < 0.09$). Reduced overall feed use by restricting intakes in the growing phase for moderate to long durations of 100 to 150 days can improve subsequent finishing efficiency and energy utilization.

Often, previous backgrounding effects on subsequent feedlot performance are cofounded by many factors and are difficult to interpret across experiments and locations. To address this, a meta-analysis conducted by Lancaster et al. (2014) evaluated over 50 different experiments from 1970 to 2014 to determine the impact of previous nutrition strategies on finishing performance. Differences evaluated included levels of dietary starch, stocker-phase rate of gain, and feeding strategies broadly classified as either calf-fed (i.e., ad-lib high grain diets from weaning to slaughter) or yearling-fed (e.g., limit feeding high concentrate diets, fiber diets, or grazing) production systems. Overall, there was no difference between medium or high dietary starch levels across 9 experiments from the backgrounding phase on final ADG ($P = 0.78$), DMI, or G:F ($P = 0.62$) in the finishing phase. While starch in the diet must be managed carefully, subsequent impacts on finishing performance from starch inclusion in the growing phase from this report seem minimal at best. Thus, lengthy finishing periods can minimize previous effects of stocker or backgrounding strategies.

However, effect of limit feeding and diet interactions in the backgrounding phase can persist into the finishing phase. Moreover, high concentrate diets limit-fed (CL) compared to high fiber diets fed for ad libitum intakes (FA) showed improved performance in the subsequent finishing phase. (Sainz et al., 1995). During the finishing phase, previously limit-fed cattle were either allowed ad libitum access to a high-grain diet (CL-CA) or restricted to 70% of ad libitum intakes (CL-CL). Previously limit-fed cattle on the high-grain growing diet gained more efficiently than ad-lib controls ($P < 0.05$). Both CL-CA and FA-CA treatment groups were fed for 112 days during the growing phase, yet the CL-CA treatment group required 22 fewer days in the finishing phase to reach market weight (481 kg) compared to FA-CA treatment group. For the previously mentioned treatments, there was no difference between DMI in the finishing phase ($P > 0.05$). However, CL-CA treatment group had subsequently higher rates of gain than FA-CL cattle (1.92 and 1.76 kg/d, respectively), thus more efficient gain ($P < 0.05$). As a result, limit feeding a high-grain diet in the growing phase appeared to improve subsequent performance of these cattle when allowed ad-lib access to a high-grain diet in the finishing phase.

However, after a finishing period for cattle with ad libitum access to high-energy diets, a typical finishing scenario, not all studies conducted to compare previous intake levels and dietary energy sources from the growing phase result improved efficiency or fewer days on feed. For example, there were no differences observed for finishing phase daily DMI ($P > 0.46$) or G:F ($P > 0.75$) across limit-fed concentrate, ad-lib concentrate, or ad-lib roughage-based diets, all fed in the growing phase of Exp. 1 (Schoonmaker et al., 2003). Moreover, all cattle were given ad libitum access to a high-grain diet from 218 d on feed until final slaughter. As a result, 16 additional days, on average, from last implant (140 d on feed) to slaughter were required for cattle previously limit-fed for programmed rates of gain at 0.8 or 1.2 kg/d, compared to cattle fed ad libitum, regardless of diet energy source. For the entire trial, cattle limit-fed during the growing phase required 17 to 44 additional feed days to finish. In Exp.1, cattle were fed to reach a similar backfat thickness of 1.27 cm ($P > 0.83$) and weight ($P > 0.57$) irrespective of treatment, while in Exp. 2 all cattle were fed for 273 d; carcass characteristics and performance was evaluated upon slaughter. Importantly, the 73 cattle (BW = 170.5 ± 5.5 kg) used in exp 1. were individually fed in an enclosed feeding barn, while an outdoor feedlot typical of a commercial or industry setting was utilized in Exp. 2 with 216 steers (135.4 ± 4.4 kg). Furthermore, all cattle were, on average, 119 d of age. The young age of cattle used in these trials may result in different subsequent effects on performance from intake restrictions in older growing cattle. While, in general, limit feeding in the growing phase increased total days on feed compared to ad-lib feeding, G:F efficiency for cattle limit-fed high-energy diets during the growing phase improved by 34.4% over cattle consuming high-roughage diets fed for ad libitum intakes ($P < 0.01$). Overall, cattle limit-fed, high-energy diets during the growing phase, but subsequently allowed ad libitum access to a high-energy diet for finishing consumed less DM than cattle given ad libitum access to diets from growing through finishing ($P < 0.01$) by up to 263.2 kg DM.

In a series of experiments at Kansas State University, performance of growing cattle with dietary intake restrictions subsequently improved ADG during the finishing phase ($P < 0.02$) even though growing phase performance was similar ($P > 0.74$) (Montgomery et al., 2002). In another trial, ADG was not impacted by previous limit-fed treatment ($P > 0.05$) but increasing wet corn gluten feed (WCGF) in the diet decreased DMI linearly ($P < 0.01$) within 2 h of feeding (Montgomery et al., 2003). A similar case occurs in a performance study utilizing 144 Angus-cross steers (Felix et al., 2011). 4 treatments included limit-fed, dried distillers grains plus solubles (DDGS) or dry rolled corn (DRC) based diets, each program-fed for either 0.9 or 1.4 kg/d. Final growing BW were not different ($P > 0.66$), but cattle programmed for 0.9 kg/d rate of gain in the growing phase, those with the greater intake restrictions, took subsequently longer to finish, requiring 12 additional days on feed compared to those restricted at similar levels on corn-based diets. In addition, DDGS-based treatments showed lower gain efficiencies in the growing phase than corn-based controls. Again, growing phase energy intake level significantly affected subsequent feedlot performance ($P < 0.03$). Cattle programmed to gain 0.9 kg/d in the growing phase, on average, gained 14% faster than those with less intake restriction. In this study, there was no control group to evaluate limit-fed intake levels to ad libitum intakes from the growing phase on subsequent performance. However, all cattle were given ad libitum access to a common DRC finishing diet until similar end-target BW was attained within each small, medium, or large weight block. Perhaps in this study intake restrictions lasted too long; if limit-fed protocols were halted earlier, fewer finishing days may have been required.

Overall, feeding high-energy diets after a subsequent period of targeted growth through limit feeding by using less DM and incurring compensatory gain upon feedlot entry may allow for similar or improved subsequent performance compared to cattle previously fed high-roughage diets ad libitum. To take advantage of limit feeding benefits, multiple (limited) daily feedings has been suggested and applied in many feedlot settings. In turn, concerns for increased variability in feed intake are addressed by giving animals multiple opportunities to eat, while stimulating activity and improving feed bunk management.

Subsequent impacts on carcass merit

Importantly, a moderate-to-heavy, well-marbled, yet relatively trim beef carcass is highly desirable and preferred in the industry. Subsequent impacts of nutrition from previous diet and restriction level may impact numerous economically important carcass traits, such as longissimus muscle size and marbling. Specifically, intramuscular fat deposition is of high economic importance and a driving factor for profitability in beef production. While subcutaneous, or seam fat is generally not desirable (Smith and Crouse, 1984), marbling drives quality grade and consumer eating experience by enhancing meat tenderness, juiciness, and flavor depending on final cooking temperature (Olson et al., 2019). In recent years marbling has also become center in research of backgrounded cattle feeding strategies. Early research indicated a possibility to alter how and particularly where fat is deposited (Smith and Crouse, 1984). An important implication of fat cell hyperplasia, meaning an increase in cell number, was articulated by Schoonmaker et al. (2004), stating it is affected more by the source from which energy came. On the other hand, fat cell hypertrophy, an increase of individual cell size, is affected most by energy amount. Stated another way, lipogenic cell size may be impacted by energy intake level. As a result, animal nutrition and feeding strategies prior to slaughter, or perhaps in early growth stages of an animal prior to feedlot entry may affect marbling fat development (Krehbiel, 2012) and other lipogenic depots due to diet energy source from the backgrounding or receiving phase (Schoonmaker et al., 2004). However, intramuscular fat deposition is complex. Furthermore, numerous evaluations use different numbers of cattle, cattle of varying breeds, diverse lengths/intensity of intake restrictions, and numerous dietary compositions. In this section, subsequent impacts of limit feeding growing cattle on carcass merit will be further examined.

When DMI is heavily restricted in the growing phase, subsequent marbling deposition may be reduced (Murphy and Loerch, 1994). In Exp. 1 marbling, ether extract, and carcass fat each decreased linearly ($P < 0.02$) with increasing intake restriction in steers (initial BW = 280 ± 13 kg) provided 90% or 80% of ad libitum control intakes of an all-concentrate, high-energy diet for 140 d. The diet consisted of 85% whole-shelled corn. Results in Exp. 2 were similar. However, there were no differences in marbling between ad-lib controls or limit-fed cattle. Additionally, no other differences in carcass characteristics, including carcass weight, dressing percentage, percent kidney-pelvic-heart fat, backfat, or yield grade were detected between ad libitum controls or limit-fed treatment groups in this trial.

A group from the University of California at Davis (Sainz et al., 1995) conducted a trial to evaluate the carcass quality impacts of limit feeding at different stages of growth in 135 medium-framed, British-bred steers. In this study the high concentrate diet consisted of 43.3% rolled wheat, 21.7% rolled corn, and 10% alfalfa, while the low concentrate diet consisted of 0% wheat, 0% corn, and 64.0% alfalfa. During the growing phase (237 to 327 kg) intakes of calves receiving the high concentrate diet (CL) were restricted to match live weight gains of ad-lib calves fed the low concentrate diet (FA). To determine carcass merit, carcass evaluations were performed at initial (control), intermediate, post-growing phase, and post-finishing phase intervals on cattle from each treatment group (15 calves/treatment). Intermediate slaughter results reveal FA steers had the least overall carcass and back fat, and they displayed the lowest marbling scores ($P < 0.05$). CL steers showed intermediate levels of carcass fat, backfat, and marbling. Demonstrating the most marbling at post-growing phase slaughter was the CA treatment group. During the finishing phase of the trial (327 to 481 kg), all cattle were either limit-fed at 70% intake of CA controls, or they were allowed ad libitum access to the high concentrate diet. Results indicate cattle limit-fed on the high concentrate diet in the growing phase but allowed ad libitum access in the finishing phase (CL-CA) tended ($P < 0.10$) to have less backfat than the FA-CA treatment group. Marbling scores were not different between either treatment group ($P > 0.05$). Finally, CL-CA cattle had larger ($P < 0.05$) ribeye areas than FA-CA cattle (68.7 cm^2 and 60.0 cm^2, respectively). In review of this data, previously limit-fed steers finished with ad libitum access to a high concentrate diet appear to have no less ability to deposit intramuscular fat following growth restriction, compared to cattle fed a low concentrate (high fiber) diet ad libitum in the growing phase. Yet, muscle development (ribeye area) is not impaired by intake restrictions earlier in the growing stage. This is similar to the findings of Murphy and Loerch (1994) where ribeye area was unaffected by previous intake restriction status. They also found decreased differences in marbling scores for previously limit-fed cattle finished with ad-lib access to a high concentrate diet. Thus, limit feeding cattle early in growth does not negatively affect ribeye area when finished on an ad-lib, high concentrate diet, but marbling differences are decreased during subsequent finishing.

Schoonmaker et al. (2004) similarly demonstrates no marbling differences following a finishing phase period in which all treatments were fed a common high concentrate diet ($P > 0.10$). All three treatments groups, including ad-lib, high concentrate (ALC), ad-lib, high fiber (ALF), and limit-fed, high concentrate (LFC) were subjected to a 153 d growing period. Following this period, 8 steers per treatment were slaughtered, while the rest of the steers were evaluated for carcass characteristics utilizing ultrasound technology. Post-growing phase slaughter results reveal ALC and ALF treatment groups have similarly greater marbling scores ($P > 0.05$) at 153 d, while LFC cattle have significantly lower scores ($P < 0.05$). ALC cattle had the most longissimus muscle fat ($P < 0.01$). In addition, both ultrasound and slaughter indicate

ALC cattle have the largest longissimus muscle areas ($P < 0.05$), and ALC cattle exhibit greater subcutaneous fat, compared to ALF and LFC groups ($P < 0.05$). During the finishing phase (154 d to 334 d) treatment groups were fed a high concentrate diet ad libitum. Interestingly, all ribeye area differences disappear ($P = 0.38$). Marbling scores follows a similar pattern ($P = 0.21$), with a numerical increase in marbling score over ALC and ALF cattle, however LFC cattle demonstrate a significant increase in longissimus fat composition ($P < 0.10$). Notably, there were no differences in yield grade or KPH following either growing or finishing phases.

These results indicate growing phase feeding regimen may impact subsequent carcass merit, in terms of intramuscular and subcutaneous fat deposition, although it is evident a long finishing period prior to slaughter will diminish prior treatment differences.

Effects of limit feeding and diet composition on liver abscess prevalence

In beef cattle, the liver is responsible for numerous metabolic and energetic processes, including protein metabolism, urea synthesis, regulation of glucose, and blood detoxification (McBride and Kelly, 1990). Combined with the gastrointestinal tract, these organs account for nearly a quarter of all energy utilization (Ferrell, 1988). Moreover, liver abscesses constitute a major source of animal welfare, performance, and economic loss during the finishing phase, particularly on subsequent carcass merit in the form of liver abnormalities causing condemnation or rejection. Approximately 18.1% of beef carcasses possess liver abnormalities during processing, with other reports ranging up to 32% (Nagaraja and Chengappa, 1998). From 2004 to 2008, 26.9 million heifers and steers were finished in the United States; with approximately \$3.25 lost for each rejected liver, in 2010 dollars, lost annual economic value for the beef industry is an estimated \$15,873,456 (Brown and Lawrence, 2010).

Importantly, scoring liver abscesses in carcasses at the packer allows for better understanding of the health and economic impact. In an economics analysis of two databases containing 76,191 beef carcasses from 61 different feedlots and 214 separate carcass harvesting dates, Brown and Lawrence (2010) utilized a liver scoring system adapted from the Eli Lilly Liver Check system (Elanco, Greenfield, IN) to describe various severities of liver damage. “0” represents normal, edible livers; “A-” represents a liver with 1 or 2 small abscesses or in active scares; “A” represents 1 to 2 large abscesses, or multiple small abscesses; “A+” represents multiple large abscesses; A+AD represents livers which have adhered to the gastrointestinal tract, diaphragm, or both, and A+OP represents any liver with ruptured or open abscesses, including livers diagnosed with cirrhosis, distoma (liver flukes), or telangiectasis (Brown and Lawrence, 2010; Elanco, 2020). Carcasses scored as either A-, A, A+, A+AD, A+OP, cirrhosis, distoma, and telangiectasis had smaller longissimus muscle area and reduced HCW ($P < 0.05$) compared to carcasses with normal livers (Brown and Lawrence, 2010).

In ruminants *Fusobacterium necrophorum* is primarily responsible for causing liver abscesses, and *Actinomyces pyogenes* is usually secondary (Nagaraja and Chengappa, 1998). These anaerobic bacteria are well-documented, and are commonly found throughout the animal gastrointestinal tract (Langworth, 1977). Unfortunately, feeding high-energy diets has been implicated albeit at varying degrees of severity and prevalence in the literature for allowing these microorganisms to grow and thrive. Moreover, animals with rumen epithelial damage from acidosis induced by rapid diet changes to high-energy rations could allow entry to and invasion of the liver via blood circulation (Nagaraja and Chengappa, 1998; Owens et al., 1998). Montgomery et al. (2002) found when limit feeding high-energy diets with wet corn gluten feed, which is low in starch, to 736 cattle in two experiments, no treatment group had greater than

4.2% incidence of liver abscesses. In a subsequent trial with 217 finishing cattle, liver abscess rate incidence was low and not different between groups fed different amounts of WCGF and alfalfa hay ($P > 0.05$) (Montgomery et al., 2003). Carcasses from limit-fed, all-concentrate diets (high in starch) fed to growing cattle tended ($P = 0.08$) to have greater liver abscesses on the rail (Loerch, 1990), but Hironaka and Kozub (1973) reported no such findings in carcass data for growing cattle fed all-concentrate diets at two programmed rates of gain, then finished on the same ration ad libitum.

In contrast to the previous study, steers on all-concentrate diets in Exp. 1 had greater total condemned livers than steers fed silage-based diets for growing, then finished on a high-concentrate diet in Exp. 2 (Murphy and Loerch, 1994). While no condemned livers were reported in Exp. 2, 80% restricted intake cattle had the highest reported percentage of condemned livers at 25%. However, the effect of intake restriction in this case seems ambiguous, because 90% intake-restricted cattle were reported to have an 8.3% condemnation rate, while 16.3% of livers in the group fed for ad libitum intakes were condemned. Statistical evaluation was not provided for livers condemned in this study, but evidence would suggest limit feeding did not impact liver condemnation rate, but rather diet composition; moreover, diets high in starch significantly increased occurrence of liver condemnation.

Currently, tylosin, an antimicrobial feed additive, is commonly included in cattle diets, and it has been proven effective to reduce, although not eliminate, liver abscesses (Cazer et al., 2020). One study reported feedlot cattle previously fed tylosin had fewer liver abscesses (12.6%), compared to 18.4% of cattle not previously fed tylosin (Nagaraja et al., 1999). Inclusion rates of tylosin fed in diets ranges so each animal receives between 60 and 90 mg/animal daily, but major liver abscesses were reduced from 56% to 19% through the inclusion of 70 mg/animal daily of tylosin in the feed (Brown et al., 1975). Although 68.6% of cattle from a large audit of commercial packing plants in Kansas and Texas reportedly had normal livers, 24.1% had rumenitis lesions, further suggesting continued opportunity and potential to address liver abscesses when feeding high-energy diets (Rezac et al., 2014).

In addition, with increased regulation of antibiotic usage in cattle since the passage of the veterinary feed directive (VFD) in 2017, research has been ongoing to determine alternatives methods for controlling liver abscesses, including vaccines or essential oils (Amachawadi and Nagaraja, 2016). Recent research with vaccines in feedlot cattle have proven vaccines are limited to ineffective at reducing liver abscess prevalence (Checkley et al., 2005). Currently, providing adequate roughage inclusion in the diet for ruminal scratch factor and motility is the best preventative measure to address liver abscesses in cattle fed high-energy diets (Reinhardt and Hubbert, 2015). Research conducted at the University of Guelph, Ontario, Canada indicates several blood biomarkers such as aspartate aminotransferase (AST) enzyme is elevated in blood from liver abscessed cattle compared to cattle with no abscesses ($P < 0.02$) (Macdonald et al., 2017). Moreover, significantly depressed levels of blood cholesterol ($P < 0.05$) and albumin ($P < 0.02$) were indicated in cattle with liver abscesses. AST enzymes are commonly found in high concentrations in the liver, heart, and skeletal muscle tissue in many species; when damage occurs in these tissues, tissues release AST into blood circulation (Washington and Van Hoosier, 2012). These factors could create further opportunity for investigating implications of backgrounding phase dietary treatments on cattle prior to the finishing phase.

Diet compositions with high starch concentrates and low roughage increase liver abscesses and condemnation rate compared to low starch and high-roughage. Therefore, limit feeding might impact overall incidence rates in unique feeding protocols, however few studies document the effect; those that do show variable or minimal impacts. Moreover, changes in ruminal pH due to diet composition, causing ruminal volatility, lesions and shifts in microbial populations have a significant impact on liver abscess prevalence. Thus, utilizing feeding protocols to promote overall health and minimize digestive upsets causing acidosis and ruminal epithelium tissue damage would aid in mitigating liver abscesses in growing and finishing cattle.

Summary

Subsequent impacts of limit feeding during the backgrounding phase prior to feedlot entry depend on previous diet composition. Nonetheless, restricting intake during previous growth stages appears to improve finishing phase efficiency in some cases, and cattle may experience compensatory gain; however, increased performance may be due to differences in ruminal gut fill. While days on feed may be increased when cattle are limit-fed, this can be addressed by shortening limit-fed durations. Furthermore, increasing the number of finishing days decreases diet or treatment-created differences in economically important traits such as loineye muscle area and intramuscular fat deposition. Carcass fat in many locations (except intramuscular loin fat) is less desirable, thus restricting intake in earlier phases of production may reduce deposition of these fatty deposits during the finishing phase. Liver abscesses continue to be a major source of lost revenue in the beef industry, and effective methods for mitigation are currently limited. Diets high in starch which cause increased ruminal volatility are primarily implicated for increased incidence of liver abscesses, but evidence suggests low-starch, high-fiber energy sources, adequate roughage inclusion, and conscientious feeding protocols in the growing and finishing phases are most effective in reducing severity and total number of liver abscess cases in beef cattle.

Limit Feeding: An Economic Perspective

Limit feeding has been established as a sound method for growing cattle. Yet, an important consideration is the economic value of limit feeding compared to traditional ad libitum feeding in the stocker-backgrounder phase. Namely, value comes through producer profitability. Simply defined, profitability is total income minus total costs. For beef operations, profitability is impacted by many intrinsic and extrinsic factors, briefly summarized in six broad resource categories to include human, capital, markets, forage, cattle, and environment (Field, 2018). Importantly, these combined factors will determine whether limit feeding is an economically sound strategy to apply for a specific growing operation compared to traditional ad libitum feeding. Moreover, applying the strategy depends on perceived benefits over costs and total industry rate of adoption (Hissong, 2021); when a survey of growing cattle producers was conducted, results indicated those who limit-fed were more likely to continue limit feeding. However, producers who received a bachelor's degree or sold 50% or more of their cattle through auction market avenues were more likely to feed for ad libitum intakes. Furthermore, the previous economic analysis of limit feeding demonstrated that socioeconomic factors did not influence producers surveyed whether to use a certain feeding strategy. In other words, producers were most likely to choose a strategy based on effectiveness. Perhaps producers prefer performance data and results to determine if a strategy is beneficial to adopt for their specific operation and production setting. Ultimately, effectiveness of limit feeding beef cattle in the growing phase will determine its future use or application in the industry.

CONCLUSION

Use of limit feeding strategies in growing cattle effectively and efficiently utilize diets of various compositional structures. Limit feeding enables young, stressed cattle to gain at targeted rates while balancing health and performance. As intake increases, rate of gain does not linearly increase. Roughages in growing diets provide fiber and protein, while corn coproducts provide alternative sources of fermentable fiber, decreased starch, and ample protein to the diet. In limit feeding scenarios these products can provide a baseline for solid performance at reduced intakes when fed in conjunction with lesser amounts of roughages. These strategies provide alternative ways to grow cattle prior to finishing. Digestibility can also be improved through reduced passage rate and lower metabolic requirements due to reduced organ mass, particularly the liver and gastrointestinal tract. Subsequently, cattle can experience rapid gains and improved efficiency during the finishing phase compared to cattle grown using traditional ad libitum feeding methods, but days on feed may be increased if restrictions are too severe. Carcasses of previously limit-fed cattle with similar finishing weights are not less adequate than those grown with ad libitum intakes, however dietary net energy will alter rate of growth. Liver abscessing attributed to limit feeding is variable but may increase significantly with concentrate diets compared to forage diets. As a result, diet composition greatly affects liver abscess prevalence.

EXPERIMENT OBJECTIVES

In the following experiments, the primary objective was first to determine the effect of limit feeding in the growing phase on overall growth performance, health, and behavior, then analyze subsequent effects of previous treatment on finishing performance and carcass merit. Moreover, growing trials conducted to evaluate effect of limit feeding often do not maintain cattle separation through the finishing phase based on growing phase treatment. If separation is maintained, cattle typically remain at the original research setting. Commercial feed yards may not be utilized in these research experiments due to difficulties in communicating necessary arrangements with the feed yard, and significant economic challenges exist for pen space to accommodate studies conducted with limited cattle numbers. Thus, previous intake management on subsequent feedlot performance and carcass merit could not always be determined in a manner commonly practiced in the industry. Objective two was to determine effect of limit feeding diets with corn coproducts high in fermentable fiber on liver abscess prevalence compared traditional forage-based diets fed for ad libitum intakes during the backgrounding phase. Finally, currently published literature does not evaluate the effect of limit feeding nor fully elucidate effect of limit-fed high-energy diets on either rumination time or activity in growing cattle. Thus, objective three was to determine effects of dietary intake and energy restriction on rumination and activity levels. The final objective was to determine the effect of Enogen corn hybrids or conventional hybrids fed as dry-rolled corn and silage in conjunction with wet distillers grain or wet corn gluten feed (Sweet Bran) on growing cattle performance.

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Chapter 2 - Effect of traditional roughage-based or limit-fed, high-energy diets on growth performance and digestion in newly received growing cattle and subsequent implications on feedlot growth performance and carcass characteristics

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ABSTRACT

Objective: The objective was to determine the effect of traditional roughage-based or limit-fed, high-energy diets on growth performance, behavior, health, and digestion in newly received growing cattle and subsequent implications on feedlot growth performance and carcass characteristics.

Materials and Methods: In Exp. 1, 409 crossbred heifers (initial BW = 279 ± 24 kg) were used in a randomized complete block design and assigned to 1 of 2 dietary treatments: 0.99 Mcal of NE_g/kg DM fed for ad libitum intakes (0.99AL; n = 205) or 1.32 Mcal NE_g/kg DM limit-fed at 85% of 0.99AL intakes (1.32LF85%; n = 204). Both diets contained 40% of DM as Sweet Bran (Cargill Animal Nutrition, Blair, NE). Treatment integrity was maintained through the finishing phase where cattle were fed a common diet. In Exp. 2, 370 crossbred heifers (initial BW = 225 ± 20 kg) were used in a randomized complete block design and fed the same diets from Exp. 1, except the 1.32LF treatment was limit-fed at 2.2% of BW daily on a DM basis (1.32LF2.2). In Exp. 3, eight ruminally-cannulated crossbred Angus heifers (initial BW = 204 ± 11 kg) in a cross-over design were fed diets from Exp. 1 in a 2-period digestibility study.

Results and Discussion: G:F was greater ($P < 0.01$) by 47% and 35% in Exp. 1 and 2, respectively, for 1.32LF heifers compared to 0.99AL heifers. Rumination time was greater for 0.99AL heifers than for 1.32LF85% heifers in Exp. 1 and 1.32LF2.2 heifers in Exp. 2 ($P < 0.01$). Activity was greater for 1.32LF2.2 heifers than for 0.99AL heifers in Exp. 2. 6.9% more light-sort carcasses than heavy-sort carcasses had livers with large, active abscesses ($P = 0.03$) in Exp. 1. Feedlot morbidity was 15.5% greater for 1.32LF2.2 cattle compared to 0.99AL cattle in Exp. 2. Light-sort groups had fewer ($P < 0.01$) edible livers than heavy-sort groups, suggesting that

greater number of days on feed increases the risk of liver abscess prevalence and condemnation to occur in light-sort cattle. Apparent total-tract DM and OM digestibility was greater for 1.32LF85% diets than for 0.99AL diets in Exp. 3 ($P < 0.01$).

Implications and Applications: Limit-fed, high-energy diets fed during the growing phase had little carryover effect on feedlot growth performance or carcass characteristics, and increased frequency of liver abscesses due to growing phase diet strategy was not apparent.

Key words: limit feeding, ad libitum, liver abscesses, coproduct, ruminal health

INTRODUCTION

Transport of young growing cattle to grower or feed yards leads to periods of feed and water deprivation, reducing subsequent feed intake and performance for several days following realimentation (Cole et al., 1988a). Use of roughages in traditional growing programs promote dry matter intake and minimize metabolic upsets (Lofgreen et al., 1975). However, greater intake of roughages come at the expense of decreased feed conversion and elevated feed costs, resulting in unrecoverable economic losses (Richeson et al., 2019). By the same token, increasing energy density or modifying energy sources in the diet, namely via non-structural carbohydrates, increases the risk for digestive disorders including acidosis and liver abscesses (Owens et al., 1998).

Limit feeding, a well-documented nutritional strategy for growing cattle, offers attractive opportunities in some situations for enhanced growth performance by improving feed efficiency and health detection, decreasing cost of gain, and easing transitions to finishing diets (Galyean et al., 1999). Research suggests animals limit-fed high concentrate diets during the growing phase followed by a finishing period with ad libitum intakes can achieve gains equal to animals receiving high-roughage diets offered for ad libitum intakes only, without negative effects to either feedlot performance or carcass merit; however, liver abscesses increased in limit-fed cattle (Loerch, 1990; Murphy and Loerch, 1994). Limit-fed animals have been shown to experience compensatory gains following a period of energy restriction (Drouillard et al., 1991). As a result, limit-fed growing strategies prior to the finishing phase may alter deposition of intramuscular fat, a significant factor determining final carcass value and quality (Krehbiel, 2012). Corn coproducts have been utilized in limit-fed growing diets (Montgomery et al., 2003; Felix et al., 2011). In recent studies, limit-fed diets containing highly fermentable fiber in comparison to roughage-based diets had no deleterious impacts on health during the growing phase (Spore et al., 2019).

The objectives of these three experiments were to compare the effect of two distinct growing diet strategies, ad libitum high-roughage vs. limit-fed high-energy, with diets based on Sweet Bran (branded wet corn gluten feed; Cargill Animal Nutrition, Blair, NE) on growing performance, behavior, digestibility, and subsequent feedlot performance and carcass characteristics, particularly liver abscess prevalence. Our hypothesis was that feedlot performance would be better for cattle previously limit-fed, high-energy diets compared to cattle previously fed roughage-based diets for ad libitum intake.

MATERIALS AND METHODS

All procedures involving the use of animals were approved by the Kansas State University Institutional Animal Care and Use Committee (IACUC #4181 and 4182).

Experiment 1

Growing Phase Cattle Management. Four hundred nine weaned, crossbred heifers (BW = 279 ± 24 kg) were purchased at auction markets in Texas and New Mexico, assembled at two different farms approximately 145 km southwest of Amarillo, Texas, then shipped 917 km to the Kansas State University Beef Stocker Unit on May 28, 2019. Heifers were used in a randomized complete block design, and pen was the experimental unit. On arrival, cattle were individually weighed, visually assessed for physical injuries or disease, and assigned a visual number ear tag. Prior to assignment to experimental pen cattle had access to long-stem hay and water via automatic waterers overnight (Lil' Spring 3000; Miraco Livestock Water Systems, Grinnell, IA). The following day (d 0) all cattle were individually weighed, given a pen assignment ear tag, and an electronic identification tag. Additionally, all cattle received a modified live vaccine (Bovishield Gold 4; Zoetis, Parsippany, NJ) to protect against IBR, BVD-I, BVD-II, and PI3. Due to extensive vaccination history no other vaccines were administered. Heifers were allocated by d -1 BW using a serpentine method to 1 of 16 treatment blocks with 2 pens per block. Each block contained 2 treatment pens with 13 or 14 heifers per pen to ensure both pens within each block were balanced for weight. Pens were soil-surfaced and of equal size (9.1 x 15.2 m), and concrete bunks were 9.1 m in length attached to a 3.6-m concrete apron.

Two experimental dietary treatments were formulated and assigned (Table 2.1): 0.99 Mcal of NE_g/kg DM fed for ad libitum intakes (0.99AL) or 1.32 Mcal NE_g/kg DM limit-fed at 85% of 0.99AL intakes (1.32LF85%). Both diets contained 40% Sweet Bran (Cargill Animal Nutrition, Blair, NE) on a DM basis. Cattle were fed once daily at 0700 h using a Roto-Mix feed wagon (model 414-14B, Dodge City, KS). Bunks were visually assessed, and estimated orts were recorded each morning at 0600 h. Daily orts for 0.99AL pens were visually targeted at 9 kg. On a weekly-basis orts were collected from each bunk and weighed on a small portable scale (model iGB; Ishida, Kyoto, Japan) to assess 0.99AL consumption, and returned to the bunk. Feed offered to 1.32LF85% pens within block were targeted at 85% of the adjacent 0.99AL pen. Limit-fed pens always consumed their daily allotment, requiring 3 to 4 h to reach an empty bunk. Moreover, a scale (Rice Lake Weighing Systems, Rice Lake, WI) was used to collect pen weights on a weekly basis from d 14 to 84. Individual weights were also collected on d 0 and d 84. Final performance data was calculated using pen weights over 2-wk intervals from d 0 to 84. To measure shrunk final BW, pens 1 through 16 were withheld access to feed on d 83. Shrunk pen weights were measured on the following day (d 84) prior to feeding. On d 84, pens 17 through 32 were withheld access to feed, and shrunk pen weights were measured prior to feeding on d 85.

All animals were observed twice daily for signs of lameness or morbidity, including depression, nasal or ocular discharge, and anorexia. Any animals displaying these symptoms were promptly removed from their pen for further observation or treatment, if necessary. Rectal temperature was measured, and a clinical illness score (CIS) was determined chute-side. A CIS of 1 indicated a normal, healthy animal; 2, slightly ill with mild depression or gauntness; 3, moderately ill with severe depression, labored breathing, and nasal or ocular discharge; 4, severely ill, near death, and showing minimal response to human approach. Heifers pulled from their pen exhibiting a rectal temperature above 40°C and assigned CIS greater than or equal to 2 were treated with the proper antibiotic as per facility protocol and were returned to their home pen. Upon third pull or acquirement of other physical injuries animals were considered chronic and removed from the study.

Moreover, trained technicians from the Cattle Performance Enhancement Company (CPEC, Oakley, KS) ultrasounded each heifer at the top backfat line and over the ribs to estimate backfat thickness and intramuscular fat deposition. Muscle depth was estimated by the CPEC software program from the bottom backfat line to the top of the mirror image of the rib bones at the bottom of the image, in MM. Feed samples were collected weekly and frozen at – 20°C. At the conclusion of the study, feed samples were thawed, mixed, subsampled, and frozen for further nutrient analysis.

Rumination and Activity. All heifers were outfitted with a 3-axial sensory accelerometer ear tag (Allflex Livestock Intelligence, Madison, WI). Tags continuously recorded rumination and activity in 2 h time increments throughout the study (min/d). Rumination measures, on average, total time in minutes per day spent masticating and ruminating. Activity measures, on average, total time in minutes per day of all other movement (not including mastication and rumination). An equilibration period was applied prior to d 10, thus data prior to d 10 was not analyzed. Due to antenna reception issues, all d 23 data, and d 24 to d 34 for 3 pens were removed from the analysis. All data were collected after d 34.

Finishing Phase and Carcass Evaluation. To prepare for and facilitate shipping to the feed yard (Pratt Feeders, Pratt, KS) for the finishing phase, all cattle received 1 of 4 color-coded tags based on growing phase dietary treatment (0.99AL or 1.32LF85%) and sort group was determined by d 84 pen weights (light-sort or heavy-sort). 16 pens (8 per treatment) were designated light-sort (BW = 354 ± 19 kg), and 16 pens (8 per treatment) were designated heavy-sort (BW = 393 ± 17 kg). Cattle continued to be fed their respective treatment diets until shipping.

On d 90 and d 91, all cattle were shipped in their respective treatment sort groups 303 km to a feed yard (Pratt Feeders, Pratt, KS) and grouped in 4 pens (approximately 100 cattle/pen) according to backgrounding dietary treatment and sort group. All animals were processed and fed according to standard feedlot protocols for the duration of the finishing period. Step-up diets were fed to all cattle, and three different formulations were fed. Formulation 1 contained steam-flaked wheat and was fed from day 7 through day 60 of the finishing phase. Formulation 2 contained no steam-flaked wheat and was fed from day 61 through day 132 (10/21/2019). Formulation 3 was fed starting at day 133 (1/1/2020) through the end of the finishing phase. Feed samples were collected approximately once per month during the finishing phase and frozen at – 20 °C for nutrient analysis. Cattle were marketed and transported by backgrounding treatment and sort-group pen 122 km to a commercial abattoir (National Beef, Dodge City, KS) on January 14, 2020 (heavy-sort) and February 4, 2020 (light-sort). Finishing growth performance data was calculated by using individual shrunk weights (in-weight) collected on d 84 of the growing phase for beginning body weight. Any cattle that died during the finishing phase were excluded from the analyses. Ending live weight (out-weight) was calculated by dividing hot carcass weight (HCW) by average dressing percentage. Carcass characteristics and liver scores according to Brown and Lawrence, 2010 were obtained by trained personnel from the Beef Carcass Research Center at West Texas A&M University in Canyon, TX.

Nutrient Analysis. All growing phase feed samples were delivered frozen to a commercial laboratory (SDK Labs, Hutchinson, KS) for further nutrient analysis. Finishing phase feed samples (excluding fat) for finishing step-up diets 3, 4, and 5 in Formulation 1, and diet 5 of Formulation 2 and 3 were delivered fresh to a commercial laboratory (SDK Labs). Dry samples ground to pass through a 1-mm screen were obtained following analysis. All other finishing phase feed nutrient analyses (Table 2.6) were obtained by Pratt Feeders, and nutrient analyses are from a commercial laboratory (Midwest PMS, Firestone, CO).

Experiment 2

Growing Phase Cattle Management. Three hundred seventy crossbred heifers (n = 370; initial BW = 225 ± 20 kg) were purchased and assembled at an auction facility in Dickson, TN and shipped 1,067 km to the Kansas State University Beef Stocker Unit on 4 trucks, each representing one block, on March 11, 2020, March 12, 2020, March 17, 2020, and March 19, 2020. Experimental design was a randomized complete block, and experimental unit was pen. On arrival (d -1) cattle were individually weighed, assigned a visual number ear tag, and any pre-assigned ear tags or markings were recorded. Additionally, all cattle were ear-notched to test for persistently infected (PI) BVD individuals. For 3 loads, notch samples were placed on ice and taken to the Kansas State Veterinary Diagnostics Laboratory (Manhattan, KS) for analysis. For one load, BVD-PI status was tested using SNAP BVDV Antigen test kits (IDEXX Laboratories, Westbrook, ME). Only one animal tested positive for BVD-PI, and it was excluded from the experiment. Cattle had ad libitum access to long-stem prairie hay and water via automatic waterers (Lil' Spring 3000; Miraco Livestock Water Systems, Grinnell, IA) prior to allocation to experimental pens on d 0.

Twenty-four hours after arrival, (d 0), cattle were individually weighed and received visual and electronic identification (EID) ear tags. Cattle received a 7-way clostridial vaccine, Caliber 7 (Boehringer Ingelheim Animal Health, Duluth, GA) and Titanium 5 (Elanco Animal Health, Greenfield, IN), a modified-live vaccine for protecting against infectious bovine rhinotracheitis (IBR), bovine viral diarrhea types 1 and 2 (BVD-I, BVD-II) and parainfluenza (PI3). Additionally, cattle received Nuplura PH (Elanco Animal Health, Greenfield, IN) for protection against *Mannheimia haemolytica*, and tulathromycin (Draxxin; Zoetis, Parsippany, NJ), a macrolide antibiotic. Upon completion of processing, heifers were assigned to 1 of 2 dietary treatments based on d -1 BW, with 4 pens per block, and 16, 18.2 m × 30.4 m soil-surfaced pens. Twenty to twenty-five heifers were allocated to each treatment pen. Additionally, cattle were revaccinated on d 14 using Titanium 5.

The two experimental treatment diets (Table 2.1) were identical to Exp. 1, except the 1.32LF treatment (1.32LF2.2) was limit-fed at 2.2% of BW on a DM basis. Diets were formulated to contain 40% Sweet Bran (Cargill Animal Nutrition, Blair, NE) on a DM basis. During the final 14 d of the study, all cattle were offered a gastrointestinal tract fill equilibration diet (Table 2.3) formulated to contain 1.17 Mcal NE_g/kg DM limit-fed at 2.5% of BW daily. Animals were fed once daily at 0700 h using the same mixing wagon as Exp. 1. Bunks were visually observed, and orts estimated at 0630 h. 0.99AL treatment orts were targeted at 9 kg. A pen scale (same as Exp. 1) was used to record weekly pen body weights, adjust feed offerings, and to calculate pen performance. Individual weights were measured on arrival, at revaccination, and at the conclusion of the study. Feed samples were collected weekly and frozen at – 20°C. At the conclusion of the study, feed samples were thawed, mixed, subsampled, and frozen for further nutrient analysis.

A health monitoring protocol and scoring system similar to Exp. 1 was used, but the antibiotics administered were different. At first morbidity animals exhibiting a rectal temperature ≥ 40°C and a CIS ≥ 2 were treated with a florfenicol and flunixin meglumine combination (Resflor Gold; Merck Animal Health, Madison, NJ). At second morbidity animals received an enrofloxacin (Baytril 100; Bayer Livestock, Shawnee, KS). Upon the third pull animals were considered chronic, received an oxytetracycline (Biomycin 200; Boehringer Ingelheim Animal Health, Duluth, GA), and removed from the study.

Rumination and Activity. Each heifer was outfitted with a 3-axial accelerometer ear tag (same as Exp. 1) on d 0 of the experiment (Allflex Livestock Intelligence, Madison, WI). Due to computer collection issues, only data after d 50 was included in the analysis. Tags were removed prior to the 14-d gastrointestinal tract-fill equilibration period at the conclusion of the trial.

Finishing Phase and Carcass Evaluation. Prior to shipment for finishing, cattle were sorted into a heavy-sort or light-sort based on final individual weights measured on day 98 or 105, depending on block. Sort group weight thresholds were established for each experimental treatment group (0.99AL: BW = 362.8 kg; 1.32LF2.2: BW = 358.3 kg) to obtain an approximately equal number of cattle in each of 4 groups Cattle were loaded into trucks to maintain backgrounding treatment and sort group integrity and shipped 303 km to a commercial feed yard (Pratt Feeders, Pratt, KS). Upon arrival at the feedlot, cattle were sorted into 4 pens (approximately 100 heifers/pen) according to backgrounding treatment/sort group. All cattle were processed and fed following standard feedlot protocols for the duration of the finishing period. Cattle were marketed and transported by backgrounding treatment/sort group pen 122 km to a commercial abattoir (National Beef, Dodge City, KS) on November 17, 2020 (heavy-sort) and January 12, 2021 (light-sort), and carcass characteristics were collected. Finishing growth performance was calculated by using individual shrunk weights collected after the gastrointestinal tract fill equilibration period at the end of the growing phase as beginning body weight (in-weight). Ending live weight (out-weight) was calculated by dividing hot carcass weight (HCW) by average dressing percentage collected at the abattoir. Cattle that died during the finishing phase were excluded from the analyses. Three heifers were removed from carcass data analyses due to inability to identify original treatment pen during the backgrounding phase; one heifer was removed due to incorrect feedlot pen placement.

Nutrient Analysis. All growing phase feed samples were delivered frozen to a commercial laboratory (SDK Labs, Hutchinson, KS) for further nutrient analysis. Dry samples ground to pass through a 1-mm screen were obtained following analysis.

Experiment 3 – Intake and Digestibility Study

Cattle Management. Eight ruminally cannulated crossbred Angus heifers (BW = 204 ± 11 kg) were used in a cross-over design with two consecutive 15-d periods. Experimental unit was animal within period. Due to cannula issues, data for one heifer were removed on d 15 of period one. Experimental diets were the same as Exp. 1 (Table 2.1). When feed was mixed for Exp. 1, feed was removed from the beginning of the wagonload for Exp. 2, thus, separate feed samples were obtained for further nutrient analysis.

Eight, soil-surfaced 6.1 m × 12.2 m pens were constructed in a large outdoor holding facility. Each pen had access to a manually filled water tank, and cattle were fed once daily at 1000 h. Each 15-d period included 10 d for diet adaption, 4 d for fecal sampling, and 1 d for ruminal sampling. All cattle were offered the 0.99AL treatment diet for 7 d prior to study initiation to acclimate and determine ad libitum DM intakes. 0.99AL orts were targeted at 1.8 kg/d during diet adaption and sampling. Cattle receiving the 1.32LF diet (1.32LF85%) were restricted to 85% of their own reference 0.99AL DM intake determined prior to study initiation. Indwelling rumen pH boli (smaXtec, Graz, Austria) inserted through the ruminal cannula continuously monitored pH throughout the study in 10 min intervals.

On d 4 to 14, 10 g of chromic oxide (Cr_2O_3) marker was top dressed and hand mixed into each TMR to calculate apparent total-tract diet digestibility of DM, OM, NDF, ADF, and starch. Feed samples were collected on d 10 to 14. Orts were collected on d 11 to 14 for each animal.

Fecal samples were collected from the rectum of each animal on d 11 to 14 at 8-hr intervals after feeding. Fecal sampling time advanced by 2 h each day, so each 2-h interval after feeding was represented. Immediately following collection, all samples were frozen at -20°C. Following study completion all feed, fecal, and ort samples were thawed, mixed, subsampled, and refrozen by animal within period.

On d 15 of each period, four locations in the rumen were sampled prior to feeding, and at 2, 4, 6, 8, 12, 18, and 24 h after feeding to determine ruminal VFA profile and ammonia concentration. Approximately 100 mL of ruminal fluid were immediately strained through eight layers of cheesecloth. One mL of strained ruminal fluid was pipetted into four, 2-mL microcentrifuge tubes each containing 250 μL of 25% (wt/vol) *m*-phosphoric acid, then frozen at -20°C. Following collection of 0 h samples, 3 g of Co-EDTA dissolved into 200 mL of distilled water was dosed through the ruminal cannula. At 2, 4, 6, 8, 12, 18, and 24 h sampling times, 15 mL of ruminal fluid was pipetted into 20-mL scintillation vials to measure Co concentration and estimate liquid passage rate and ruminal liquid volume. After collection all ruminal fluid samples were frozen at -20°C.

Laboratory Analysis and Calculations. Composited feed samples were delivered frozen to a commercial laboratory (SDK Laboratories, Hutchinson, KS), and dry sample aliquots, ground to pass through a 1-mm screen, were obtained following analysis. To prepare ruminal fluid samples for Co analysis, 5 mL were transferred from scintillation vials to centrifuge tubes and centrifuged at 25,000 × g, for 25 min at 4°C. Supernatant was pipetted into another test tube and refrigerated at 4°C for immediate analysis or frozen at -20°C for future analysis by atomic absorption spectrophotometry (Perkin Elmer AAnalyst 100; PerkinElmer, Waltham, MA). If necessary to remain within the linear range of the assay, samples were diluted with ultrapure water.

To prepare acidified ruminal fluid samples for analysis of VFA concentration, samples were centrifuged at 17,000 × g for 30 min at 4°C. Supernatant was pipetted into 2-mL gas chromatograph (GC) vials and frozen at -20°C for future analysis. Analysis was conducted by gas chromatography. To prepare acidified ruminal fluid samples for analysis of ammonia concentration, samples were centrifuged at 17,000 × g at 4°C for 30 min conducted following procedures of Broderick and Kang (1980).

To calculate apparent total-tract diet digestibility, wet fecal samples and dried, ground ort samples were analyzed for Cr by atomic absorption spectrophotometry (Perkin Elmer AAnalyst 100; PerkinElmer, Waltham, MA), following sample preparation as described by Williams et al., 1962. Fecal output (g/d) was estimated by dividing Cr intake (g/d) by Cr concentration in the feces (g Cr/g fecal DM). Apparent total-tract DM, OM, NDF, ADF, and starch digestibility were calculated as: 1 – (fecal output/intake) × 100%.

Net Energy Calculations

In Exp. 1 and 2, performance data were used to calculate net energy for maintenance and gain using equations from Galyean (2021) based on NRC (1996) nutrient requirements. Initial BW in both experiments was pencil shrunk 4% shrink to account for differences in gastrointestinal tract fill when cattle were offered ad libitum access to hay. Ending BW was not shrunk in Exp. 1, because it was measured following a 1 d fast. In Exp. 3, ending BW was not shrunk because it was measured following 14 d of gastrointestinal tract fill equilibration.

Statistical Analyses

In Exp. 1, growing phase growth performance, net energy calculations, behavior (rumination and activity) data were analyzed using the MIXED procedure in SAS (v9.4, SAS Institute Inc., Cary, NC). Dietary treatment and block were included as fixed effects in the model. Pen was the experimental unit. Behavior data were analyzed with dietary treatment, block, day, and dietary treatment × day interaction included as fixed effects in the model, using day as the repeated measure and pen as the subject. The covariance structure was autoregressive for rumination, and spatial power for activity, as determined by better-fit characteristics of the model using Akaike information criterion (AIC) and Bayesian information criterion (BIC) statistics. In addition, a behavior data set which was averaged over d 10 to d 83 were analyzed with dietary treatment, block, hour, and treatment × hour interaction included as fixed effects in the model. The MIXED procedure in SAS was used to analyze finishing phase growth performance and carcass data with the fixed effects of backgrounding diet, sort group, and backgrounding diet × sort group interaction. Block and backgrounding diet × pen (from the growing phase) interaction were included as random effects. To calculate finishing phase morbidity and mortality, liver characteristics, and USDA quality grades, backgrounding diet, sort group, and backgrounding diet × sort group interaction were included as fixed effects, and block was included as a random effect.

In Exp. 2, the MIXED procedure in SAS was used to analyze all data. For growing phase growth performance and behavior data, diet and block were included as fixed effects in the model. For behavior, the model also included fixed effects of day and diet × day interaction, with day as the repeated measure and pen as the subject. Covariance structure was compound symmetry for rumination data (based on AIC and BIC better-fit statistics), whereas autoregressive was selected for activity data. For finishing phase growth performance and carcass data, backgrounding diet, sort group, and backgrounding diet × sort group interaction were included as fixed effects, and block and backgrounding treatment × pen (from the growing phase) were included as random effects. To calculate finishing phase morbidity and mortality and USDA quality grades, backgrounding diet, sort group, and backgrounding diet × sort group interaction were included as fixed effects, and block was included as a random effect.

In Exp. 3, all data were analyzed in the MIXED procedure of SAS, with animal within period as the experimental unit. For ruminal pH collected by smaxTec boli, hour served as the repeated measure, with dietary treatment, period, hour, and treatment × hour interaction included as fixed effects in the model; animal and day were included as random effects. Experimental unit was animal, with subject animal × period × day. The covariance structure selected was spatial power, as determined by better-fit characteristics of the model using AIC and BIC statistics. For ruminal VFA and ammonia, fixed effects were treatment, period, hour, and treatment × hour interaction; animal was included as a random effect. The repeated measure was hour, with subject being animal × period, and the covariance structure selected was compound symmetry or spatial power according to the dependent variable being analyzed, as determined by better-fit characteristics of the model using AIC and BIC statistics. Liquid passage rate was estimated by regressing the natural logarithm of cobalt concentration for samples collected from 2 to 18 h after Co-EDTA dosing against time for each animal in each period using the NONLINEAR procedure in SAS. Liquid passage rate was determined as the negative slope from the regression, and ruminal liquid volume was calculated by dividing the original Co concentration dosed at 0 h after feeding by the constant, *e*, raised to the power of the y-intercept of the regression. Liquid passage rate, ruminal liquid volume, and nutrient intakes and digestibilities were analyzed with treatment and period as fixed effects in the model, and animal was included as a random effect. For all experiments and data analyses, significance was declared at $P \leq 0.05$, and tendencies at $P \leq 0.10$.

RESULTS AND DISCUSSION

Experiment 1

Growing Phase Growth Performance and Health. Composition of experimental diets and nutrient analyses are presented in Table 2.1. Results of growing performance, ultrasound, and behavior parameters are presented in Table 2.2. The better efficiency for 1.32LF85% than for 0.99AL was the result of 15% greater ($P < 0.01$) ADG and 22% lower ($P < 0.01$) DMI. Overall, G:F was 47% greater for 1.32LF85% treatment cattle than for 0.99AL cattle ($P < 0.01$). In this experiment, 0.99AL groups had less muscle depth and less backfat compared to 1.32LF85% groups, based on ultrasound scanning ($P < 0.01$), but this was expected in light of the differences in ADG. The heifers we used were healthy and exhibited few clinical signs of morbidity, therefore, data is not shown. According to necropsy reports, mortality cases were associated with bovine respiratory disease, liver disease, or bloat.

Growing performance was better for 1.32LF85% cattle than 0.99AL cattle in this experiment. These findings concur with a previous growing study evaluating four dietary energy concentrations with progressively restricted intake for a programmed rate of gain of 1 kg/d in heifers, in which a 22% greater G:F was observed for cattle receiving diets containing 1.32 Mcal NE_g/kg DM than for those consuming diets with 0.99 Mcal NE_g/kg DM (Spore et al., 2019). In that study, however, ADG was not different among treatments, which reflected that the intakes were programmed to yield similar ADG. In contrast to Spore et al. (2019), greater ADG in our trial was possibly due to greater net energy (NE) intake. While 1.32LF85% cattle had 13% greater intake of dietary NE_g than 0.99AL contemporaries, by design (1.32/0.99 × 0.85 > 1), NE density calculated from animal performance were much lower than what was formulated in the diets. The 0.99AL diet yielded 0.68 Mcal NE_g/kg DM based on cattle performance, and the 1.32LF85% diet yielded 1.01 Mcal NE_g/kg DM. Possible reasons for lower NE values based on performance compared to diet formulation include poor pen conditions and heat stress, due to the experiment being conducted during a hot, wet summer. Thus, some energy may have been shifted away from growth.

Hicks et al. (1990) observed a 19.8% efficiency improvement in cattle limit-fed finishing diets, yet a direct comparison to our work is problematic, because our study used two distinct energy-intake regimens, thus widening differences in G:F. In another limit feeding trial, Knoblich et al. (1997) examined 5 different growing-finishing systems of identical dietary composition using crossbred steers initially limit-fed high-energy diets at 1.13 kg DM/d, then subsequently offered 1.36 kg DM/d and, finally, ad libitum access until slaughter. In accordance with our results, limit-fed cattle had greater ADG and G:F than cattle with only ad libitum access to diets ($P < 0.05$). However, gastrointestinal tract-fill may have inflated final performance calculations, as cattle had 28-d ad libitum access to feed prior to the end of the trial. Other studies confirm such adverse effects on performance calculations, with limit-fed diets preferred to equilibrate gastrointestinal tract-fill differences (Coleman et al., 1995; Watson et al., 2013).

Berry et al. (2004) fed two different dietary energy/starch combinations to young growing cattle, and morbidity was not different between high and low energy treatments, but high starch-fed groups tended to have higher morbidity. With greater inclusion of starch in 1.32LF85% diets, increased morbidity was not observed in the present study. Spore et al. (2018)

reported no detrimental impacts on antibody titer production even though pH briefly dropped into subacute acidotic ranges when newly received cattle were fed varying dietary energy concentrations at limited intakes compared to ad libitum. Based on our results, limit-fed, high-energy diets based on Sweet Bran improved efficiency of gain compared to traditional roughage-based growing strategies.

Rumination and Activity. Lower DMI and a higher energy density in 1.32LF85% diets affected behavior. 1.32LF85% cattle ruminated 37 min/d less, on average, than 0.99AL treatment cattle ($P < 0.01$; Table 2.2). There was a dietary treatment × day interaction for rumination time ($P < 0.01$; Fig. 2.1), because the difference between treatments was apparent between days 10 to 21 as well as between days 40 to 68 but not over other portions of the trial. Reasons for this interaction appearing early and later in the trial are not entirely clear. There was a dietary treatment × hour interaction for rumination time ($P < 0.01$; Fig. 2.2). 0.99AL cattle spent more time ruminating during the overnight hours ($P < 0.01$; 2000 h to 0600 h), whereas 1.32LF85% cattle ruminated longer in the morning after feeding ($P < 0.01$; 0800 h to 1200 h).

Activity appeared greater during the first portion of the experiment and reached a nadir after 3 wk which was maintained over the remainder of the experiment (Fig. 2.1). Activity averaged over the trial was not different between treatment groups ($P = 0.33$), suggesting that energy savings as a result of reduced activity are not likely to be a major contributor to the better efficiency of 1.32LF85% compared to 0.99AL. There was a treatment × day interaction for activity, but this appeared to be a result of random day-to-day variations between treatments (Fig. 2.1). A dietary treatment × hour interaction was detected for activity ($P < 0.02$; Fig. 2.2), but the differences over the day were relatively minor and unlikely to be of biological importance. As roughage inclusion in the diet decreases, rumination time decreases (Jennings et al., 2020). In contrast, Hicks et al. (1990) observed no behavioral differences upon visual observation of limit-fed steers compared to ad-lib steers fed twice per day, however quantifying behavior by visual assessment is more subjective and prone to error (Weary et al., 2009). Overall, 1.32LF85% had lower rumination times than 0.99AL cattle.

Finishing Phase Growth Performance and Carcass Characteristics. Composition of finishing diets and nutrient analyses are presented in Tables 2.3 and 2.4, respectively. Finishing growth performance is presented in Table 2.5. DMI and G:F were not statistically-analyzed, and were assessed for numerical differences. Entire backgrounding diet/sort group pens of cattle were marketed and harvested at the same time. There were no significant interactions between main effects of backgrounding diet and sort group for finishing growth performance ($P \geq 0.17$), thus only main effects are discussed. There was an effect of backgrounding diet for in-weight and ADG, with 1.32LF85% cattle having greater ($P < 0.01$) in-weight than 0.99AL cattle, but 0.99AL cattle had 5.5% better ($P = 0.03$) ADG, compared to 1.32LF85% cattle. No main effects of backgrounding diet were detected for days on feed, out-weight, morbidity, or mortality ($P \geq 0.21$). Main effects of sort group were detected for days on feed, with light-sort cattle requiring 20 more days ($P < 0.01$) on feed than heavy-sort cattle to reach a similar ($P \geq 0.24$) target out-weight. Heavy sort cattle had greater ($P < 0.01$) in-weight, by design, and better ($P = 0.03$) ADG than light-sort cattle, but light sort-cattle tended ($P < 0.07$) to have greater morbidity than heavy-sort cattle. No main effects of sort group were detected for mortality ($P \geq 0.32$). Notably, heavy-sort cattle appeared to have numerically greater DMI than light-sort cattle, but G:F differences between backgrounding diet/sort groups were minor and unlikely to be of significance.

Carcass characteristics are presented in Table 2.6. There were significant interactions detected between main effects of backgrounding diet and sort group for carcass characteristics.

1.32LF85% carcasses in the heavy-sort group had greater ($P < 0.01$) USDA yield grade scores, whereas 0.99AL carcasses in the heavy-sort group and light-sort carcasses from both 0.99AL and 1.32LF85% backgrounding diets had lower scores. 0.99AL carcasses in the light-sort group had smaller ribeye areas than the other groups ($P < 0.01$). An interaction between backgrounding diet and sort group was observed for marbling ($P = 0.02$), because 1.32LF85% carcasses tended ($P = 0.07$) to have greater marbling scores than 0.99AL carcasses for the heavy-sort group but demonstrated numerically lower marbling scores for the light-sort group. 1.32LF85% carcasses in the light-sort group had lower liver scarring, whereas 1.32LF85% carcasses in the heavy-sort group had greater liver scarring ($P = 0.04$). No other significant interactions between main effects were detected in this experiment. Main effects were detected between backgrounding diets; 1.32LF85% carcasses had greater ($P < 0.01$) backfat, whereas 0.99AL carcasses has less backfat, but 4.9% more 0.99AL carcasses graded USDA Prime than 1.32LF85% carcasses. There was a tendency ($P = 0.07$) for more 1.32LF85% carcasses to grade USDA Choice than 0.99AL carcasses. Main effects were also detected between sort groups. Heavy-sort carcasses had greater backfat ($P < 0.01$) than light-sort carcasses. 6.1% fewer heavy-sort carcasses ($P < 0.01$) graded USDA Select than light-sort carcasses, and 11.5% more heavy-sort carcasses ($P < 0.01$) graded USDA Choice than light-sort carcasses. 15% more heavy-sort carcasses had edible livers ($P < 0.01$) compared to the livers of light-sort carcasses. 6.9% more light-sort carcasses than heavy-sort carcasses had livers with large, active (A+) abscesses ($P = 0.03$). More heavy-sort carcasses had livers with no abscesses compared to light-sort carcasses ($P = 0.03$). There was a tendency ($P = 0.09$) for heavy-sort carcasses to have greater HCW than light-sort carcasses, but no other main effects between background diets or sort groups were observed in this study.

Sainz et al. (1995) fed either forage diets containing alfalfa and oat straw for ad libitum intakes or concentrate diets containing rolled wheat and rolled corn for ad libitum or limited intakes during the growing phase (237 kg to 327 kg), followed by a finishing period (327 kg to 481 kg) when the concentrate diet was offered ad libitum. They reported cattle limit-fed a concentrate-based diet during the growing phase, then given ad libitum access for finishing had better ADG than cattle fed a forage-based diet during the growing phase and finished with a concentrate-based diet ad libitum. Better ADG in steers limit-fed concentrate in the growing phase compared to steers fed forage ad libitum was largely attributed to compensatory gains. Fasted body weights were collected to determine performance, but the authors do not specify how the fast was conducted. They acknowledge gastrointestinal tract fill after the growing phase was greater in forage-fed steers than limit-fed concentrate steers. Although cattle in our experiment that were fed the 1.32LF85% diet during the backgrounding phase had lower ADG than 0.99AL cattle in the finishing phase, effect of backgrounding diet was confounded by sort group.

In our experiment, ending live weight was not different between backgrounding diet/sort groups. Similar to our trial, they reported smaller ribeye areas in cattle fed ad libitum forage-based diets in the growing phase, then given ad libitum concentrate-based diets for finishing, but backgrounding diet in our trial was confounded by sort-group in the finishing phase. Sainz et al., (1995) also found steers limit-fed a concentrate-based diet during the growing phase, then given ad libitum access during the finishing phase, had numerically greater backfat than steers fed a forage-based diet ad libitum during the growing phase and finished with ad libitum access to a concentrate-based diet. In contrast to our results, Murphy and Loerch (1994) reported reductions of carcass fat in all-concentrate fed steers with intakes restricted to 80% of ad libitum intakes throughout the growing and finishing period, but no differences in carcass characteristics due to intake restriction were observed in a subsequent experiment. Although 1.32LF85% intakes were restricted in our trial, energy was not restricted in the limit-fed diet. Cattle of Murphy and Loerch (1994) were also individually fed. By contrast, our cattle were finished in a large commercial feed yard pen setting where individual intake variation is likely greater, however this did not appear to deleteriously affect carcass quality.

Our results suggest that finishing phase sort group, confounded by days on feed and harvest date, affected final liver characteristics, because light-sort cattle had greater incidence of liver abscesses and inedible livers than heavy-sort cattle. Backgrounding diet had no effect on liver characteristics. Therefore, lighter cattle with access to high-energy diets fed for ad libitum intakes for longer finishing periods may be at a greater risk for liver abscesses development and liver condemnation. Although backgrounding diet in our experiment was confounded by energy level and intake restriction, Schmidt et al. (2005) reported no effect of intake restriction for growing and finishing cattle on liver abscess prevalence. They formulated diets to provide similar NE concentration and metabolizable protein at 90% and 80% of ad libitum intakes as ad libitum intakes by altering diet composition; restricted intake diets contained 3.9% and 6.3% more crude fat, respectively. However, final BW was greater for 80% intake-restricted cattle than cattle with ad libitum intake.

While not measured in the present study, liver size and weight in limit-fed sheep was lower than in lambs fed for ad libitum intakes (Fluharty and McClure, 1997). Loerch (1990) similarly reported that longer finishing periods of feeding high-concentrate diets increased incidence of liver abscesses. However, in contrast to our experiment, Loerch (1990) found cattle limit-fed a high-concentrate diet had greater liver condemnation compared low-energy, silage-based diets fed for ad libitum intakes. The limit-fed diets in their trial contained 80% high moisture corn, therefore, intake of fermentable starch was high. Limit-fed diets in our study contained modest levels of starch and high levels of fermentable fiber due to WCGF inclusion, and this likely led to a low amount of liver abscess development. Generally, growing phase concentrate level does not appear to affect liver condemnation, while finishing phase level does (Loerch and Fluharty, 1998). Overall, sort group appeared to have a modest impact on both finishing growth performance and carcass characteristics. Although it appears that when high-energy diets were offered for ad libitum access for longer periods of time during the finishing phase, thus greater prevalence of liver abscesses and inedible livers in light-sort cattle were observed, we conclude that limit feeding a high-energy diet based on fermentable fiber in the backgrounding phase has little carryover effect on finishing growth performance and carcass characteristics.

Experiment 2

Growing Phase Growth Performance and Health. Composition of experimental diets are the same as Exp. 1, but as gastrointestinal tract fill equilibration diet was used and is presented in Table 2.7. Performance growth data is presented in Table 2.8. Unlike Exp. 1, ADG for 1.32LF85% were, on average, 15% lower than 0.99AL cattle, due primarily to providing intakes at a fixed percentage of BW. In this experiment, G:F for heifers fed 1.32LF85% was 35% greater than for heifers receiving 0.99AL ($P < 0.01$). Nonetheless, NE_g concentration calculated based on animal performance was greater for 1.32LF groups ($P < 0.01$). The 0.99AL diet yielded 0.81 Mcal NE_g/kg DM based on performance, whereas the 1.32LF2.2 diet yielded 1.27 Mcal NE_g/kg DM. 0.99AL cattle consumed more DM than 1.32LF cattle ($P < 0.01$), except during gastrointestinal tract fill equilibration, by design (*P* = 0.23). 0.99AL treatment cattle lost BW during the first 7 d of the equilibration period. Cattle were very healthy and required little antimicrobial intervention, thus health data is not reported. There were two 1.32LF85% heifer mortalities, with one due to bovine respiratory disease and one from unknown causes, according to necropsy reports. Two 0.99AL heifer mortalities also occurred, with one caused by bovine respiratory disease and one caused by thromboembolic meningoencephalitis, according to necropsy reports.

A generally accepted and beneficial practice for newly received, comingled cattle is to use metaphylaxis or mass-medicate an entire group of cattle with an antibiotic to reduce incidence of disease (Lofgreen et al., 1980; Munoz et al., 2020; Word et al., 2020). Metaphylactic use of tulathromycin on arrival may have adequately prevented or helped minimize disease load. Schmidt et al. (2005) found cattle restricted to 80% of ad libitum intakes in two trials had 38 and 43% greater G:F, respectively. Diets were formulated to provide equal NE concentration, but the most restricted group gained 13% more than cattle fed for ad libitum intakes, suggesting actual NE concentration of the limit-fed diet based on animal performance was higher than expected; however, NE values were not reported. In the present experiment, NE values based on performance were greater relative to NE values based on performance from Exp. 1, but NE values in Exp. 2 were still lower relative to our diet formulation NE values; this is consistent with our findings in Exp. 1. Calculated 0.99AL diet NE density was 18.2% lower than diet formulation, whereas calculated 1.32LF2.2 NE density in Exp. 2 was only 3.8% lower than diet formulation. Our results indicate cattle performed worse than would have been predicted by NE_g in both Exp. 1 and 2. In light of diet differences, it is notable that 0.99AL cattle lost BW during the first 7 d of the gastrointestinal-tract fill equilibration period, which signifies the importance of this period for accuracy and comparability of performance parameters across dietary treatments, particularly when roughage-based diets are fed for ad libitum intake (Watson et al., 2013).

Rumination and Activity. In addition, 1.32LF cattle spent, on average, 154 min/d less time ruminating than 0.99AL contemporaries ($P < 0.01$; Table 2.8). An effect of diet was detected for rumination ($P < 0.01$, Fig. 2.3), which was expected due to differences in DM intake between diets. A dietary treatment × day interaction was detected for rumination ($P = 0.04$; Fig. 2.3), when time 1.32LF2.2 cattle spent ruminating increased on d 56, increased between d 56 and d 75, and increased again on d 77. A dietary treatment × hour interaction was detected for rumination ($P < 0.01$; Fig. 2.4); 0.99AL cattle spent more time ruminating overnight than 1.32LF2.2 cattle (2000 h to 0600 h; $P < 0.05$), but no differences ($P > 0.10$) were observed between treatments at 1000 h when rumination time for both groups reached a nadir. An effect of diet was detected for daily activity ($P < 0.01$; Fig. 2.3), but no dietary treatment × day interaction for daily activity was detected ($P = 0.93$). A dietary treatment × hour interaction was detected for activity ($P < 0.01$; Fig. 2.4), when 1.32LF2.2 cattle were more active 1 h before feeding at 0600 h and again 3 h to 7 h after feeding between 1000 h and 1400 h ($P < 0.01$).

Unlike Exp. 1 in which no differences in activity were observed between treatments, 1.32LF2.2 cattle were more active than 0.99AL cattle in this trial. Presumably, this is due to increased appetite from meal-eating behavior and treatment design differences; 1.32LF2.2 cattle were limit-fed at 2.2% of BW. Pen size was also larger in this trial than Exp. 1, however, this was expected to affect both treatments similarly, because 1.32LF2.2 cattle and 0.99AL cattle were allocated identical pen space. Our results confirm that limit-fed cattle on a higher-energy diet required less time to ruminate and were more active than cattle fed a forage-based diet for ad libitum intakes.

Finishing Phase Growth Performance and Carcass Characteristics. Finishing growth performance is presented in Table 2.9. A significant interaction between backgrounding diet and sort group was observed for mortality ($P = 0.03$), because 1.32LF2.2 cattle had greater mortality ($P = 0.01$) in the light-sort group than the heavy-sort group, and the 1.32LF2.2 cattle had greater mortality ($P = 0.04$) than 0.99AL cattle in the light-sort group. No other significant interactions between backgrounding diet or sort group were observed in this experiment. A main effect of backgrounding diet was observed for morbidity; it was 15.5% greater for 1.32LF2.2 cattle compared to 0.99AL cattle. In-weight tended ($P = 0.06$) to be greater for 1.32LF2.2 cattle than for 0.99AL cattle. No effect between backgrounding diets was observed for days on feed, out-weight, ADG, or mortality. A main effect between sort groups was observed for morbidity, because light-sort cattle had greater morbidity ($P = 0.01$) than heavy-sort cattle. Heavy-sort cattle had greater in-weight ($P < 0.01$), lower number of days on feed ($P < 0.01$), and better ADG ($P < 0.01$) than light-sort cattle. No effect between sort groups was observed for out-weight or mortality.

Carcass characteristics for Exp. 2 are presented in Table 2.10. Live weight ($P = 0.59$) and HCW ($P = 0.84$) was similar between backgrounding diet/sort groups. No main effects between backgrounding diets were observed, but there were main effects observed between sort groups. Heavy-sort cattle had greater backfat ($P = 0.02$) and greater USDA yield grade scores ($P = 0.01$), whereas the light-sort cattle had less backfat and lower scores. Heavy-sort cattle also tended to have greater ribeye areas ($P = 0.09$) than light-sort cattle. No effects between sort groups were observed for marbling score or USDA quality grades ($P \geq 0.39$).

Similar to Exp. 1, morbidity was affected by sort group in the finishing phase, with greater sickness apparent in light-sort cattle compared to heavy-sort cattle. In contrast to Exp. 1, there was also an effect of backgrounding diet on morbidity. One possible reason for this effect could be that intake restriction of the limit-fed, high-energy diet was numerically greater in the growing phase of Exp. 2 than Exp. 1. This may have contributed to a greater change in intakes when cattle previously limit-fed were transitioned to an ad libitum diet at the feedlot. Although cattle were generally healthy during the growing phase, as previously mentioned, it was apparent that most sickness was reported to have occurred within the first 30 d of arrival at the feedlot. Mortality was also greater during the finishing phase of Exp. 2. Length of transport cannot explain differences between finishing phase morbidity and mortality, because cattle were transported to the same commercial feed yard. Although an explanation for the difference between experiments is not clear, it is well-known that transport-induced stress, feed and water deprivation, and novel environments can cause increased morbidity and mortality in young feeder cattle (Cole et al., 1988b).

A recent study models potential economic benefits of what is termed “progressive limit feeding,” whereby newly received feedlot cattle receive a short period of restricted intakes to maintain constant metabolic body size, followed by ad libitum feeding for the rest of the finishing period (Hannon and Murphy, 2019). Limit-fed animals, authors state, experience compensatory gains due to gain efficiency and reduced metabolic activity of various organs, but it is not known how long efficiency effects from limit feeding last into the ad libitum feeding period. Several studies suggest carryover effects can occur and G:F improve if cattle are limit-fed during the growing phase and subsequently placed on an ad libitum nutritional plane until final market weight is reached (Drouillard et al., 1991; Sainz et al., 1995; Knoblich et al., 1997;

Reinhardt et al., 1998). In Exp. 1 of our study, cattle that were fed the 1.32LF85% diet during the backgrounding phase had lower ADG than 0.99AL cattle in the finishing phase, effect of backgrounding diet was confounded by sort group; in Exp. 2, finishing phase ADG was not affected by backgrounding phase diet. Although DMI was numerically greater for heavy-sort cattle, similar to Exp. 1, G:F differences between backgrounding diet/sort groups were, again, minor and unlikely to be of biological importance.

In contrast to Sainz et al., (1995), our cattle were fed a gastrointestinal tract fill equilibration diet for 2 wk prior to arrival at the feedlot for finishing, which may have eliminated compensatory gain 1.32LF2.2 cattle otherwise would have realized. In addition, the supply of energy in our experiment was similar between 1.32LF2.2 cattle and 0.99AL cattle, because BW at the end of the growing phase was not different between treatments after the 14-d equilibration period. A meta-analysis of backgrounding diets and subsequent finishing diets revealed that ad libitum feeding in the finishing growth phase effectively diminishes differences in final carcass quality regardless of previous plane of nutrition, including for cattle limit-fed during the backgrounding growth phase (Lancaster et al., 2014). Our carcass results from Exp. 2 appear to support this conclusion. Sip and Pritchard, (1991) observed no differences in carcasses of steers limit-fed growing diets formulated to provide similar NE concentration as diets fed ad libitum, then transitioned to an ad libitum finishing diet for 94 d. Results from Exp. 2 appear to agree with Exp. 1 that although sort group in the finishing phase can affect finishing growth performance and carcass characteristics to some degree, previous backgrounding diet (energy level confounded by intake restriction) has little carryover effect on finishing growth performance and carcass characteristics after a long finishing period in which cattle are offered high-energy diets ad libitum.

Experiment 3 – Intake and Digestibility Study

Intake of nutrients and digestibilities are presented in Table 2.11. Intake of DM, OM, NDF, and ADF were less by design for 1.32LF85% cattle compared to 0.99AL cattle ($P < 0.01$). Conversely, also by design, intake of starch was greater for 1.32LF85% cattle compared to 0.99AL cohorts ($P < 0.01$). By restricting intake of high-energy diets, apparent total-tract diet digestibilities of DM and OM were 5.2% and 6.4% greater, respectively ($P < 0.01$). Yet, NDF ($P = 0.94$) and ADF ($P = 0.59$) diet digestibilities were unaffected by dietary treatment. Starch digestibility was also unaffected by treatment ($P > 0.32$). 1.32LF85% cattle had slower liquid dilution rate compared to 0.99AL treatments ($P < 0.01$), but ruminal liquid volume was greater in 1.32LF85% cattle compared to 0.99AL treatment cattle ($P < 0.01$).

Ruminal pH data is presented in Fig. 2.5. Although ruminal pH in 1.32LF85% cattle rapidly declined after feeding, our results demonstrated no effect of dietary treatment on ruminal pH over the course of the experiment ($P < 0.93$; Fig. 2.9). There was a dietary treatment × hour interaction detected for ruminal pH. Ruminal pH increased overnight through morning before feeding in 1.32LF85% cattle ($P < 0.01$; 2200h to 1000h).

Ruminal characteristics are shown in Table 2.11. Ammonia concentrations were greater for 0.99AL cattle than for 1.32LF85% cattle ($P = 0.03$). There was a dietary treatment × hour interaction for ammonia concentration ($P < 0.01$; Fig. 2.6), with 0.99AL cattle having a greater concentration of ammonia 2 h after feeding and again from 8 to 18 h after feeding compared to 1.32LF85% cattle. The 0.99AL cattle had greater concentrations of total ruminal VFA than did cattle receiving 1.32LF85%, and thus was largely a result of greater concentrations of acetate ($P < 0.01$). Butyrate was also greater for 0.99AL cattle compared to 1.32LF cattle ($P < 0.01$).

Propionate, isovalerate, and valerate were not different between treatments ($P > 0.10$). There was a dietary treatment × hour interaction for straight-chain VFA including propionate, butyrate, and valerate ($P < 0.01$), resembling meal-eating behavior similarly demonstrated by ammonia concentration. VFA concentration peaked twice for 0.99AL cattle 2 h and again 12 h after feeding, while 1.32LF85% cattle peaked only once 4 to 6 h after feeding. There was a dietary treatment × hour interaction for branched chain VFA, including isobutyrate and isovalerate ($P < 0.01$), with a greater decrease in concentration 2 h after feeding in 1.32LF85% cattle than 0.99AL cattle. Acetate:propionate ratio was lower for 1.32LF85% cattle than 0.99AL cattle. Molar proportions of acetate were greater ($P < 0.01$) for 0.99AL cattle, whereas proportions of propionate, isobutyrate, isovalerate, and valerate were greater ($P < 0.01$) for 1.32LF85% cattle.

DMI was lower by design for 1.32LF85% cattle than 0.99AL cattle, and 1.32LF85% cattle in this experiment served as their own reference for determining ad libitum intake. This contrasts with Exp. 1 in which 1.32LF85% cattle were paired with a 0.99AL contemporary pen to determine intake level. While intake of the high-energy diet was restricted, energy intake was greater for 1.32LF85% cattle, suggesting that intakes still could have been close to ad libitum. It has been previously observed that as energy density of a diet increases, DMI generally decreases (Ittner et al., 1954; Merchen et al., 1987). Various reasons for reduced feed intake of high-energy diets include thermostatic and chemostatic regulation mechanisms in the body (Klieber, 1961; Fisher, 1996).

Greater NE density calculated from digestion for 1.32LF85% cattle than 0.99AL cattle was similar to our findings in Exp. 1 and 2. Although digestion of DM and OM was better for 1.32LF85% cattle than 0.99AL cattle in Exp. 3, digestion of the 0.99AL diet was better than expected. In calculation of metabolizable energy from digestible energy, a factor of 2.3% was included for monensin (NASEM, 2016). Relative to formulation of the 0.99AL diet, NE_g based on digestion was 16.2% greater, whereas NE_g based on performance was lower in Exp. 1 and 2. The 0.99AL diet based on digestion yielded 1.15 Mcal NE_g/kg DM. Relative to formulation of the 1.32LF diet, NE_g based on digestion was close (1.5% greater), and NE_g based on performance in Exp. 2 was a little lower, but much lower in Exp. 1. The 1.32LF diet based on digestion yielded 1.34 Mcal NE_g/kg DM. It was unexpected that NE_g based on digestion for the 0.99AL diet, relative to formulation, was greater, whereas NE_g based on performance was worse. Based on NASEM (2016) equations, predicted organic matter digestibility for the 0.99AL diet was 6.1% lower than our results, but a reason for this difference could not be ascertained.

Digestion of DM and OM was better for 1.32LF85% cattle than 0.99AL cattle, while fiber digestibility was unaffected by diet regimen, which agrees with Spore et al., (2019). NDF and ADF digestibilities in 1.32LF85% cattle and 0.99AL cattle potentially indicates that fiber-digesting bacteria were less active in the rumen of 1.32LF85% cattle than 0.99AL cattle. While both diets contained 40% Sweet Bran on a DM-basis, fiber in Sweet Bran represented a greater portion of total fiber in the 1.32LF85% diet compared to the 0.99AL diet. Fiber in Sweet Bran is much more digestible than fiber provided by the roughage (NASEM, 2016). The 0.99AL diet contained 45% roughage on a DM-basis, whereas the 1.32LF85% diet contained 13% roughage on a DM-basis. Starch digestion was also unaffected by diet, but this is likely due to a similar source of starch (corn), and degradation of starch to VFA was likely near completion. 70% of starch undergoes microbial fermentation in the rumen (Ørskov, 1986; Owens et al., 1986).

Limit feeding a high-energy diet could impact site of digestion by changing the rate at which nutrients flow through the gastrointestinal tract. Our results indicate 1.32LF diets had reduced liquid passage rate. Spore et al., 2019 also demonstrated limit-fed, high-energy diets for programmed rates of gain decreased liquid passage rate. Other reports where cattle were given diets with greater energy levels at restricted intakes observed decreases in liquid passage rate (Galyean et al., 1979; Murphy et al., 1994b). In opposition to these results, Clark et al., 2007 observed no differences in liquid passage rate when diet intakes were restricted to 80% of ad libitum intakes. Finding greater ruminal liquid volume in 1.32LF85% cattle than 0.99AL cattle in our experiment was unexpected and contradicts the findings of Murphy et al. (1994a) who reported limit-fed cattle had lower ruminal fill volumes than full-fed cohorts. Two potential explanations for this treatment effect include differences in meal-intake patterns and ruminal osmotic pressures; lower pH associated with rapidly fermented carbohydrates and lactic acid production can also increase ruminal osmotic pressure, elevating liquid fill volume (Howard, 1981); this can lead to dehydration and watery feces. Moreover, our experiment was conducted during the heat of summer in mid-July, potentially causing greater water intake variability. Montgomery et al. (2004) found cattle limit-fed diets based on wet corn gluten feed had greater ruminal liquid fill 4 to 8 h after feeding, compared to diets based on steam-flaked corn.

Ruminal pH differences are sensible due to different diet composition and within-day feed intake patterns between 0.99AL and 1.32LF85% cattle. pH declined more rapidly 2 h after feeding in 1.32LF85% cattle compared to 0.99AL cattle. In addition, 1.32LF85% and 0.99AL diets contained moderate quantities of roughage and Sweet Bran, which likely produced a more robust fibrolytic bacteria microbiome, preventing further ruminal pH decline. Nonetheless, diets formulated with large quantities of WCGF can lower ruminal pH due to naturally acidic pH levels in the WCGF as a result of the corn milling process and added corn steep liquor, which contains lactic acid (Huls et al., 2016). Our results generally agree with Spore et al. (2019), although they observed a greater reduction in ruminal pH for limit-fed diets. Increased intake of all-concentrate or starch-rich diets, especially processed grains, causes greater reductions in ruminal pH (Murphy et al., 1994a). However, in contrast to our results, Murphy et al. (1994a) observed steers with ad libitum intake of all-concentrate diets had lower ruminal pH during the first 2 h after feeding (5.38) compared to cattle limit-fed at 70% of ad lib intakes (5.67). In the present experiment, greater dietary energy level in the 1.32LF85% diet than the 0.99AL diet may have caused a greater decline in ruminal pH, but not intake restriction level.

Ruminal ammonia concentrations in 1.32LF85% cattle were lower than 0.99AL cattle. This contradicts Murphy et al. (1994b) who fed corn-silage based diets for ad libitum, 90%, or 80% of ad libitum intakes, finding restricted intakes increased ruminal ammonia concentration and decreased flow of bacterial protein to the small intestine due to decreased liquid passage rate. However, unlike our experiment, they did not modify dietary composition by increasing dietary energy level at restricted intakes. Greater ruminal ammonia concentration observed by Murphy et al., (1994b) in limit-fed diets may be due to less dilution of ammonia from ruminal liquid fill, causing ammonia to be concentrated to a greater extent than full-fed diets. Ammonia concentration was also greater in steers limit-fed wet corn gluten feed (Montgomery et al., 2004) and Sweet Bran (Spore et al., 2019) compared to diets with greater roughage inclusion. In our experimental diets, ammonia concentrations may have been sufficient to optimize ruminal fermentation and support microbial growth, reflecting adequate degradable protein in the diets. Supplementing diets with non-structural carbohydrates and intact degradable protein has been demonstrated to benefit diet digestibility and intake of low-quality forages (Heldt et al., 1999). Although non-protein nitrogen was not supplemented in our diets, it may be warranted if concentration of ruminal ammonia falls below 50 mg/L (Satter and Slyter, 1974). Stokes et al., (1991) reported diets fed to lactating dairy cows that contained 11.8% or 13.2% intact degradable protein as a percentage of total DM resulted in more efficient microbial fermentation and greater concentration of ammonia and total VFA. In our experiment, ruminal liquid fill was greater in 1.32LF85% cattle than 0.99AL cattle, which may explain the lower concentration of ruminal ammonia observed in 1.32LF85% cattle compared to the 0.99AL cattle. Although reasons for this divergence are not clear, the data appears to show meal-eating behavior differences between the two diets; 1.32LF85% cattle consumed daily rations within a few hours after feeding, whereas 0.99AL cattle returned for additional meals later in the day. Warm and wet environmental conditions may also have caused greater variation in consumption of water between diets, influencing concentration of ammonia in the rumen.

Total ruminal VFA concentrations in 1.32LF85% cattle were expected to be greater than 0.99AL cattle close to feeding, however, greater ruminal liquid volume in 1.32LF cattle than 0.99AL cattle could have diluted total VFA concentration. Lower total VFA concentration in 1.32LF85% cattle than 0.99AL cattle observed in this experiment agrees with Spore et al., 2019. Clark et al., 2007 also observed lower concentrations of total ruminal VFA when feeding a high-energy diet at 80% of ad libitum intake compared to ad libitum intake. A lower acetate:propionate ratio in 1.32LF85% cattle than 0.99 AL cattle can be attributed to differences in diet composition, with greater intake of starch for cattle fed high-energy, limit-fed diets than cattle fed roughage-based diets fed for ad libitum intakes. As a result of a lower acetate:propionate ratio and lower ruminal pH in 1.32LF85% cattle compared to 0.99AL cattle, less hydrogen is available for methane production, and the rumen becomes a less favorable environment for methanogenic activity (Russell, 1998). Thus, less energy is lost in the form of methane. Potentially lower energy loss in 1.32LF diets than 0.99AL diets may also help explain differences in NE values observed between these diets in Exp. 1 and 2.

APPLICATIONS

Limit feeding high-energy diets during the backgrounding phase led to 47% (Exp. 1) and 35% (Exp. 2) better gain efficiency and 5.2% greater DM diet digestibility (Exp. 3) compared to traditional ad libitum forage-based growing strategies. Health was not negatively impacted by treatment diets. Less time spent ruminating and greater levels of activity for limit-fed cattle than for those fed for ad libitum intake enabled efficient observation of cattle for assessing health. Although 1.32LF85% cattle had greater marbling scores and thicker backfat at the end of the growing phase compared to 0.99AL cattle, there was little effect of previous backgrounding diet strategy on subsequent finishing growth performance and carcass characteristics, but they were affected by sort-group in some instances. Limit feeding high-energy diets based on corn and fermentable fiber during the growing phase did not increase prevalence of liver abscesses, but more liver scars were observed. Penning cattle into light and heavy-sort groups at the feedlot revealed that greater number of days on feed likely led to greater liver condemnation in light-sort cattle. Greater gain efficiency and diet digestibility in cattle limit-fed high-energy diets can provide beef producers with a strategy to boost operational productivity and reduce manure output.

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Table 2.1. Composition and nutrient analysis of experimental diets (Exp. 1-3)

	Diet[1]	
Ingredient, % DM	0.99AL	1.32LF
Corn[2]	8.6	38.8
Wet corn gluten feed[3]	40.0	40.0
Long-stem alfalfa	22.5	6.5
Chopped prairie hay	22.5	6.5
Supplement[4]	6.4	8.2
Exp. 1		
DM, % as fed	74.5	73.3
OM	91.5	94.1
CP	15.9	15.1
Starch	13.0	33.5
NDF	36.4	24.3
ADF	18.1	9.8
Ca	1.1	0.8
P	0.6	0.6
Exp. 2		
DM, % as fed	74.7	74.2
OM	85.3	93.7
CP	15.8	15.1
Starch	10.0	29.3
NDF	40.8	25.7
ADF	20.8	9.9
Ca	1.2	1.1
P	0.5	0.6
Exp. 3		
DM, % as fed	73.1	72.7
OM	91.3	94.5
CP	17.0	15.5
Starch	11.9	33.0
NDF	36.4	24.6
ADF	18.3	9.9
Ca	0.8	0.6
P	0.6	0.7

[1] 0.99AL = 0.99 Mcal NE_g/kg DM fed for ad libitum intake. 1.32LF = 1.32Mcal NE_g/kg/DM limit-fed. In Exp. 1, the 1.32LF85% treatment was offered at 85% of 0.99AL treatment DMI. In Exp. 3 the 1.32LF2.2 treatment was offered at 2.2% of BW on a DM basis.

[2] Dry-rolled yellow #2 corn.

[3] Sweet Bran, Cargill Animal Nutrition, Blair, NE.

[4] Supplement pellet (Cargill Animal Nutrition, Minneapolis, MN) was formulated to contain (DM basis) 9.2% crude protein, 1.53% crude fat, 17.0% crude fiber, 7.4% calcium, 0.22% phosphorus, 4.62% salt, 0.50% potassium, 331 mg/kg monensin, and 60.1 mg/kg diflubenzuron.

Table 2.2. Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase on performance and behavior (Exp. 1)

	Diet[1]			
Item	0.99AL	1.32LF85%	SEM[2]	*P* – value
Number of pens	16	16		
Number of animals	205	204		
BW, kg				
Day 0	280.1	278.9	0.93	0.36
d 14	293.9	288.0	1.17	< 0.01
d 28	316.6	319.5	1.59	0.23
d 42	341.3	339.1	1.28	0.23
d 56	350.9	355.7	1.89	0.09
d 70	373.4	379.6	1.45	< 0.01
d 84	367.6	379.6	1.66	< 0.01
ADG, kg/d				
d 0 – 14	0.99	0.65	0.04	< 0.01
d 0 – 28	1.30	1.45	0.04	0.02
d 0 – 42	1.46	1.43	0.02	0.50
d 0 – 56	1.26	1.37	0.03	0.02
d 0 – 70	1.33	1.44	0.02	< 0.01
d 0 – 84	1.04	1.20	0.02	< 0.01
DMI, kg/d				
d 0 – 14	7.12	5.89	0.02	< 0.01
d 0 – 28	8.61	7.13	0.03	< 0.01
d 0 – 42	9.27	7.58	0.03	< 0.01
d 0 – 56	9.58	7.71	0.06	< 0.01
d 0 – 70	10.11	8.04	0.06	< 0.01
d 0 – 84	10.26	8.02	0.05	< 0.01
Daily intake, % of BW daily				
d 0 – 14	2.48	2.08	0.01	< 0.01
d 0 – 28	2.89	2.38	0.01	< 0.01
d 0 – 42	2.99	2.45	0.01	< 0.01
d 0 – 56	3.04	2.43	0.02	< 0.01
d 0 – 70	3.10	2.44	0.02	< 0.01
d 0 – 84	3.18	2.44	0.02	< 0.01

G:F, kg/kg				
d 0 – 14	0.140	0.111	0.01	< 0.01
d 0 – 28	0.152	0.204	0.01	< 0.01
d 0 – 42	0.158	0.194	0.01	< 0.01
d 0 – 56	0.133	0.179	0.01	< 0.01
d 0 – 70	0.132	0.180	0.01	< 0.01
d 0 – 84	0.102	0.150	0.01	< 0.01
NE_m, Mcal/kg DM[3]	1.24	1.62	0.01	< 0.01
NE_g, Mcal/kg DM[3]	0.68	1.01	0.01	< 0.01
Marbling score[4]	4.78	4.92	0.04	0.02
Muscle depth, cm[5]	5.36	5.72	0.05	< 0.01
Backfat, cm[6]	0.51	0.56	0.03	< 0.01
Rumination, min/d[7]	444.3	407.2	3.27	< 0.01
Activity, min/d[7]	319.8	317.8	1.40	0.33

[1] 0.99AL = 0.99 Mcal NE_g/kg DM fed for ad libitum intake. 1.32LF = 1.32Mcal NE_g/kg/DM limit-fed. In Exp. 1, the 1.32LF85% treatment was offered at 85% of 0.99AL treatment DMI.

[2] Largest SEM is reported.

[3] Net energy calculations from days 0 to 84: Galyean (2021) based on NRC (1996) equations.

[4] Measured via ultrasound on day 84 by the Cattle Performance Enhancement Company (CPEC, Oakley, KS). 4.00 – 4.99 = select. 5.00 – 5.99 = low choice. Scanning conducted by Mr. Lynn Allen of Stratford, TX.

[5] Measured by ultrasound (CPEC) on day 84 from bottom backfat line to the rib bones.

[6] Measured by ultrasound (CPEC) on d 84 at top of backfat line.

[7] Measured using 3-axial accelerometer ear tags (Allflex Livestock Intelligence, Madison, WI).

Table 2.3. Composition of finishing phase diets (Exp. 1)

	Finishing Step-up Diets[1]					
Item, % DM	1	2	3	4	5	6
Formulation 1[2]						
Hay[3]	47.0	37.8	28.6	19.2	9.1	10.2
Steam-flaked corn	30.6	35.6	40.7	46.9	52.6	51.6
Steam-flaked wheat	15.7	18.8	21.9	24.0	27.2	27.2
Dried distillers grain	3.3	3.3	3.4	3.4	3.4	3.4
Fat	0.0	0.6	1.2	1.8	2.5	2.5
Liquid starter #2278	3.4	2.5	1.3	0.0	0.0	0.0
Liquid finisher #2236	0.0	1.3	3.0	4.7	5.2	5.2
Formulation 2[2]						
Hay[3]	47.1	37.9	28.5	19.1	8.9	9.9
Steam-flaked corn	42.3	50.4	58.6	66.9	76.0	75.0
Corn syrup	3.7	3.7	3.7	3.8	3.8	3.8
Dried distillers grain	3.4	3.4	3.4	3.4	3.4	3.4
Fat	0.0	0.6	1.2	1.9	2.5	2.5
Liquid starter #2278	3.5	2.6	1.3	0.0	0.0	0.0
Liquid finisher #2236	0.0	1.3	3.1	4.9	5.4	5.4
Formulation 3[2]						
Hay[3]	47.1	37.9	28.5	19.1	9.9	9.9
Steam-flaked corn	42.3	50.4	58.6	66.9	75.0	75.0
Corn syrup	3.7	3.7	3.7	3.8	3.8	3.8
Dried distillers grain	3.4	3.4	3.4	3.4	3.4	3.4
Fat	0.0	0.6	1.2	1.9	2.5	2.5
Liquid starter #2278	3.5	2.6	1.3	0.0	0.0	0.0
Liquid finisher #2236	0.0	1.3	3.1	4.9	5.4	5.4

[1] Finishing step-up diets were formulated (Midwest PMS, Firestone, CO) and fed to all study cattle according to standard feeding protocols by the feed yard (Pratt Feeders, Pratt, KS).

[2] Formulation 1 contained steam-flaked wheat. Formulation 2 contained no steam-flaked wheat and were fed starting at 61 days on feed (10/21/2019). Formulation 3 were fed starting at 133 days on feed (1/1/2020).

[3] Blended ingredient: 80% chopped alfalfa and 20% cane hay.

Table 2.4. Nutrient analysis of finishing diets (Exp. 1)

	Finishing Step-up Diet[1]					
Item, % DM	1	2	3	4	5	6
Formulation 1[2]						
DM, % as fed	79.7	79.4	79.9	78.8	79.4	78.3
CP	14.7	14.4	14.0	13.0	12.8	13.6
Fat	2.6	3.3	4.0	4.7	5.4	5.4
NDF	*	*	20.1	15.4	12.5	*
Ca	0.8	0.8	0.7	0.7	0.6	0.8
P	0.3	0.3	0.2	0.3	0.3	0.3
Formulation 2[2]						
DM, % as fed	78.3	77.9	77.5	77.1	78.4	76.7
CP	14.3	14.1	13.9	13.8	13.0	13.3
Fat	2.7	3.5	4.2	4.9	5.7	5.7
NDF	*	*	*	*	13.0	*
Ca	0.8	0.8	0.8	0.8	0.6	0.8
P	0.3	0.3	0.3	0.3	0.3	0.3
Formulation 3[2]						
DM, % as fed	78.3	77.9	77.5	77.1	77.4	76.7
CP	14.3	14.1	13.9	13.8	12.3	13.3
Fat	2.7	3.5	4.2	4.9	5.7	5.7
NDF	*	*	*	*	12.4	*
Ca	0.8	0.8	0.8	0.8	0.6	0.8
P	0.3	0.3	0.3	0.3	0.3	0.3

[*] Values not reported.

[1] Finishing diets were formulated (Midwest PMS, Firestone, CO) and fed to all study cattle according to standard feeding protocols by the feed yard (Pratt Feeders, Pratt, KS). Nutrient analyses are from Midwest PMS.

[2] Formulation 1 contained steam-flaked wheat and was fed from day 7 through day 60 of the finishing phase. Formulation 2 contained no steam-flaked wheat and was fed from day 61 through day 132 (10/21/2019). Winter diets were fed starting at day 133 (1/1/2020) through the end of the finishing phase.

Table 2.5. Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase or sort group in the finishing phase on finishing growth performance (Exp. 1)

	Sort Group[1]							
	Heavy		Light					
	Backgrounding Diet[2]					P – value[4]		
Item	0.99AL	1.32LF85%	0.99AL	1.32LF85%	SEM[3]	S	B	S × B
Number of pens	1	1	1	1				
Number of animals	102	100	102	101				
Days on feed, d	145	145	166	166	0.04	< 0.01	0.99	0.67
In-weight, kg	393.3	402.8	351.5	362.0	5.5	< 0.01	< 0.01	0.67
Out-weight[5], kg	590.0	585.6	571.4	581.0	8.8	0.24	0.70	0.31
ADG, kg/d	1.42	1.31	1.32	1.29	0.03	0.03	0.03	0.17
DMI[6], kg/d	9.87	9.71	9.27	9.07	–	–	–	–
G:F, kg/kg	0.144	0.135	0.142	0.142	–	–	–	–
Morbidity, %	6.9	2.1	14.1	9.5	3.7	0.07	0.21	0.98
Mortality, %	1	2	0	1	0.9	0.32	0.32	0.99

[1] Sort groups for each treatment were created prior to finishing phase. Heavy and light sort groups were finished in 4 separate pens at a feed yard (Pratt Feeders, Pratt, KS), then sent to a commercial abattoir (National Beef, Dodge City, KS) on January 14, 2020 and February 4, 2020, respectively.
[2] Diets offered during the 84-d backgrounding phase prior to the finishing phase. First number = Mcal NE_g/kg DM. AL = ad libitum. LF85% = limit-fed at 85% of 0.99AL treatment DMI.
[3] Largest standard error of the means are reported.
[4] S = sort group; B = backgrounding diet; S × B = sort group × backgrounding diet interaction.
[5] Out-weight is equivalent to live weight in Table 2.10, calculated from hot carcass weight multiplied by dressing percentage, both collected at the abattoir (National Beef, Dodge City, KS).
[6] Dry matter intake is presented as an average per animal but was calculated on a pen basis at the feedlot.

Table 2.6. Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase or sort group in the finishing phase on final carcass characteristics (Exp. 1)

	Sort Group[1]							
	Heavy		Light					
	Backgrounding Diet[2]					P – value[4]		
Item	0.99AL	1.32LF85%	0.99AL	1.32LF85%	SEM[3]	S	B	S × B
Number of pens	1	1	1	1				
Number of animals	97	97	102	96				
Carcass traits[5]								
Live weight, kg	590.0	585.6	571.4	581.0	8.8	0.24	0.70	0.31
HCW, kg	384.3	384.6	369.3	378.0	5.7	0.09	0.31	0.34
Dressing percentage, %	65.14	65.68	64.62	65.06	–	–	–	–
Backfat, cm	1.69	1.91	1.61	1.68	0.05	< 0.01	< 0.01	0.11
USDA yield grade	2.45[a]	2.85[b]	2.52[a]	2.43[a]	0.08	0.03	0.09	< 0.01
Marbling score[6]	520	546	546	527	10.2	0.73	0.76	0.02
Ribeye area, square cm	96.5[b]	94.8[b]	90.4[a]	97.0[b]	1.0	0.07	0.02	< 0.01
USDA quality grade, %								
Select	3.1	2.0	7.8	9.4	1.7	< 0.01	0.88	0.46
Choice	91.9	93.0	76.5	85.5	2.6	< 0.01	0.07	0.16
Prime	5.9	4.9	14.0	5.2	2.3	0.13	0.02	0.06
Liver characteristics[7], %								
Scars	36.1[ab]	48.5[b]	38.2[ab]	28.1[a]	5.2	0.15	0.82	0.04
Edible	87.7	92.7	78.4	71.9	3.5	< 0.01	0.83	0.13
Telangiectasis	2.7	1.9	2.1	2.0	1.5	0.88	0.76	0.78
Liver score[8], %								
0	88.8	92.7	83.2	81.4	3.6	0.03	0.77	0.44
A-	5.2	5.2	5.9	6.3	2.3	0.67	0.94	0.99
A	0.0	1.0	1.0	1.0	0.9	0.59	0.53	0.59
A+	6.2	1.0	9.8	11.5	3.3	0.03	0.52	0.25

[ab] Least square means in the same row with different superscripts are significantly different ($P < 0.05$)

[1] Sort groups for each treatment were created prior to finishing phase. Heavy and light sort groups were finished in 4 separate pens at a feed yard (Pratt Feeders, Pratt, KS), then sent to a commercial abattoir (National Beef, Dodge City, KS) on January 14, 2020 and February 4, 2020, respectively.

[2] Diets offered during the 84-d backgrounding phase prior to the finishing phase. First number = Mcal NE_g/kg DM. AL = ad libitum. LF85% = limit-fed at 85% of 0.99AL treatment DMI.

[3] Largest SEM is reported.

[4] S = sort group; B = backgrounding diet; S × B = sort group × backgrounding diet interaction.

[5] Carcass traits collected upon slaughter at a commercial abattoir (National Beef, Dodge City, KS).

[6] Score ranges are as follows: < 400 = select. 400 – 499 = low choice. 500 – 599 = avg choice. 600 – 699 = high choice.

[7] Liver scars indicates healed abscesses which are no longer active. Edible livers are acceptable for human consumption. Telangiectasis is a disease of the liver causing small blood-filled cavities with red or purple mottling to develop.

[8] Livers scored according to Brown and Lawrence (2010). 0 indicates no abscesses. A- indicates one or two small, active abscesses. A indicates two to four small, active abscesses each with a diameter less than 2.5 cm. A+ indicates one or more large, active abscesses.

Table 2.7. Gastrointestinal tract fill equilibration diet composition and nutrient analysis (Exp. 2)

Ingredient	% of total DM
Corn[1]	23.8
Wet corn gluten feed[3]	40.7
Long-stem alfalfa	14.2
Chopped prairie hay	14.4
Supplement[2]	6.9
Item	
DM, % as fed	74.5
OM	92.9
CP	16.3
Starch	19.1
NDF	33.6
ADF	15.9
Ca	1.0
P	0.6

[1] Dry-rolled yellow #2 corn.

[2] Supplement pellet (Cargill Animal Nutrition, Minneapolis, MN) was formulated to contain (DM basis) 9.2% crude protein, 1.53% crude fat, 17.0% crude fiber, 7.4% calcium, 0.22% phosphorus, 4.62% salt, 0.50% potassium, 331 mg/kg monensin, and 60.10 mg/kg diflubenzuron.

[3] Sweet Bran, Cargill Animal Nutrition, Blair, NE.

Table 2.8. Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase on performance and behavior (Exp. 2)

	Diet[1]			
Item	0.99AL	1.32LF2.2	SEM[2]	*P* – value
Number of pens	8	8		
Number of animals	186	184		
BW, kg				
Day 0	227.2	228.5	1.20	0.43
d 14	246.5	239.3	1.17	< 0.01
d 28	267.8	255.9	1.22	< 0.01
d 42	287.4	273.6	1.47	< 0.01
d 56	306.7	288.1	1.60	< 0.01
d 70	330.7	309.8	1.31	< 0.01
d 84	342.9	325.5	2.62	< 0.01
Treatment end[3]	343.7	327.3	2.68	< 0.01
GIT equilibration, d 7[4]	340.8	335.6	1.70	0.05
GIT equilibration, d 14[4]	354.1	349.3	1.68	0.07
ADG, kg/d				
d 0 – 14	1.38	0.77	0.09	< 0.01
d 0 – 28	1.45	0.98	0.05	< 0.01
d 0 – 42	1.43	1.07	0.04	< 0.01
d 0 – 56	1.42	1.07	0.04	< 0.01
d 0 – 70	1.48	1.16	0.02	< 0.01
d 0 – 84	1.38	1.16	0.03	< 0.01
d 0 – treatment end[3]	1.33	1.13	0.03	< 0.01
GIT equilibration, d 0 – 7[4]	-0.41	1.17	0.18	< 0.01
GIT equilibration, d 7 – 14[4]	1.90	1.97	0.09	0.59
GIT equilibration, d 0 – 14[4]	0.75	1.57	0.10	< 0.01
DMI, kg/d				
d 0 – 14	5.57	4.53	0.27	0.02
d 0 – 28	6.90	5.05	0.32	< 0.01
d 0 – 42	7.93	5.33	0.36	< 0.01
d 0 – 56	8.77	5.54	0.38	< 0.01
d 0 – 70	9.37	5.72	0.38	< 0.01
d 0 – 84	9.68	5.96	0.33	< 0.01
d 0 – treatment end[3]	9.75	6.03	0.33	< 0.01
GIT equilibration, d 0 – 7[4]	8.76	8.63	0.09	0.33
GIT equilibration, d 7 – 14[4]	8.68	8.58	0.05	0.18
GIT equilibration, d 0 – 14[4]	8.72	8.61	0.06	0.23

Daily intake, % of BW daily				
d 0 – 14	2.35	1.94	0.11	0.02
d 0 – 28	2.79	2.08	0.13	< 0.01
d 0 – 42	3.08	2.12	0.13	< 0.01
d 0 – 56	3.28	2.15	0.14	< 0.01
d 0 – 70	3.36	2.13	0.14	< 0.01
d 0 – 84	3.40	2.15	0.11	< 0.01
d 0 – treatment end[3]	3.42	2.17	0.11	< 0.01
GIT equilibration, d 0 – 7[4]	2.56	2.60	0.02	0.16
GIT equilibration, d 7 – 14[4]	2.50	2.51	0.01	0.57
GIT equilibration, d 0 – 14[4]	2.53	2.56	0.01	0.13
G:F, kg/kg				
d 0 – 14	0.260	0.170	0.02	< 0.01
d 0 – 28	0.219	0.194	0.01	0.11
d 0 – 42	0.187	0.202	0.01	0.28
d 0 – 56	0.166	0.192	0.01	0.06
d 0 – 70	0.163	0.203	0.01	< 0.01
d 0 – 84	0.145	0.194	0.01	< 0.01
d 0 – treatment end[3]	0.139	0.188	0.01	< 0.01
GIT equilibration, d 0 – 7[4]	-0.045	0.136	0.02	< 0.01
GIT equilibration, d 7 – 14[4]	0.219	0.229	0.01	0.49
GIT equilibration, d 0 – 14[4]	0.087	0.183	0.01	< 0.01
NE_m, Mcal/kg DM[5]	1.39	1.91	0.04	< 0.01
NE_g, Mcal/kg DM[5]	0.81	1.27	0.03	< 0.01
Rumination, min/d[6]	455.7	302.8	12.01	< 0.01
Activity, min/d[6]	346.2	369.5	3.12	< 0.01

[1] 0.99AL = 0.99 Mcals NE_g/kg DM offered for ad libitum intake prior to gut-fill equilibration. 1.32LF2.2 = 1.32 Mcals NE_g/kg DM limit-fed at 2.2% of body weight on a DM basis prior to gut-fill equilibration.

[2] Largest SEM is reported.

[3] Treatment-end date was day 84 for 2 blocks, and day 91 for 2 blocks.

[4] GIT = Gastrointestinal tract fill equilibration diet; it was fed for 14 d. It was formulated to provide 1.16 Mcal NE_g/kg DM, and it was limit-fed at 2.5% of BW daily on a DM basis.

[5] Net energy calculations from day 0 through gastrointestinal tract fill equilibration phase: Galyean (2021) using NRC (1996) equations.

[6] Measured using 3-axial accelerometer ear tags (Allflex Livestock Intelligence, Madison, WI).

Table 2.9. Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase or sort group in the finishing phase on finishing growth performance (Exp. 2)

	Sort Group[1]							
	Heavy		Light					
	Backgrounding Diet[2]					P – value[4]		
Item	0.99AL	1.32LF2.2	0.99AL	1.32LF2.2	SEM[3]	S	B	S × B
Number of pens	1	1	1	1				
Number of animals	94	91	92	92				
Days on feed, d	144	144	200	200	0.5	< 0.01	0.99	0.99
In-weight, kg	386.9	381.7	336.8	332.8	2.6	< 0.01	0.06	0.78
Out-weight[5], kg	603.1	601.7	602.5	595.4	6.4	0.51	0.53	0.59
ADG, kg/d	1.51	1.53	1.33	1.31	0.03	< 0.01	0.90	0.43
DMI, kg/d	9.97	9.44	8.66	8.69	–	–	–	–
G:F, kg/kg	0.151	0.162	0.154	0.151	–	–	–	–
Morbidity, %	5.3	16.0	10.4	30.6	4.5	0.01	< 0.01	0.19
Mortality, %	2[ab]	0[a]	1[a]	5[b]	1.3	0.14	0.46	0.03

[ab] Least square means in the same row with different superscripts are significantly different ($P < 0.05$)

[1] Sort groups for each treatment were created prior to finishing phase. Heavy and light sort groups were finished in 4 separate pens at a feed yard (Pratt Feeders, Pratt, KS), then sent to a commercial abattoir (National Beef, Dodge City, KS) on November 17, 2020 and January 12, 2021, respectively.

[2] Diets offered during the backgrounding phase prior to the finishing phase. First number = Mcal NE_g/kg DM. AL = ad libitum. LF2.2 = limit-fed at 2.2% of body weight daily on a DM basis.

[3] Largest standard error of the means are reported.

[4] S = sort group; B = backgrounding diet; S × B = sort group × backgrounding diet interaction.

[5] Out-weight is calculated from hot carcass weight multiplied by dressing percentage, both collected at the abattoir (National Beef, Dodge City, KS).

Table 2.10. Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase or sort group in the finishing phase on final carcass characteristics (Exp. 2)

	Sort Group[1]							
	Heavy		Light					
	Backgrounding Diet[2]					*P* – value[4]		
Item	0.99AL	1.32LF2.2	0.99AL	1.32LF2.2	SEM[3]	S	B	S × B
Number of pens	1	1	1	1				
Number of animals	92	88	88	83				
Carcass traits[5]								
Live weight, kg	603.1	601.7	602.5	595.4	6.4	0.51	0.53	0.59
HCW, kg	385.7	385.5	384.3	385.5	4.0	0.83	0.91	0.84
Dressing percentage, %	63.95	64.07	63.78	64.74	–	–	–	–
Backfat, cm	1.77	1.79	1.91	1.89	0.06	0.02	0.97	0.74
USDA yield grade	2.58	2.65	2.83	2.85	0.10	0.01	0.62	0.80
Marbling score[6]	540	531	523	528	17.4	0.39	0.84	0.56
Ribeye area, sq. cm	96.6	94.9	93.8	94.1	1.1	0.09	0.52	0.32
USDA quality grade, %								
Select	4.8	6.4	8.8	5.1	3.1	0.57	0.65	0.26
Choice	86.4	83.7	81.9	87.5	3.5	0.92	0.67	0.24
Prime	8.9	8.8	9.4	6.5	3.4	0.74	0.59	0.62

[1] Sort groups for each treatment were created prior to finishing phase. Heavy and light sort groups were finished in separate pens at a feed yard (Pratt Feeders, Pratt, KS), then sent to a commercial abattoir (National Beef, Dodge City, KS) on November 17, 2020 and January 12, 2021, respectively.

[2] Diets offered during the backgrounding phase prior to the finishing phase. First number = Mcal NE_g/kg DM. AL = ad libitum intake. LF2.2 = limit-fed at 2.2% of BW on a DM-basis.

[3] Largest SEM is reported.

[4] S = sort group; B = backgrounding diet; S × B = sort group × backgrounding diet interaction.

[5] Carcass traits collected at the National Beef abattoir in Dodge City, Kansas.

[6] Score ranges are as follows: < 400 = select. 400 to 499 = low choice. 500 to 599 = avg choice. 600 to 699 = high choice.

Table 2.11. Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase on diet digestibility and ruminal characteristics (Exp. 3)

Item	Diet[1] 0.99AL	1.32LF85%	SEM[2]	*P* – value
Number of observations	8	8		
Intake, kg/d				
DM	8.06	6.23	0.37	< 0.01
OM	7.36	5.88	0.35	< 0.01
NDF	2.92	1.54	0.11	< 0.01
ADF	1.47	0.62	0.05	< 0.01
Starch	0.95	2.05	0.08	< 0.01
Ruminal[3]				
Ammonia, m*M*	5.22	3.89	0.49	0.03
A:P ratio	2.80	1.98	0.15	< 0.01
Total VFA, m*M*	109.37	82.81	5.02	< 0.01
Acetate, m*M*	66.90	44.18	2.48	< 0.01
Propionate, m*M*	23.77	24.63	2.20	0.63
Butyrate, m*M*	13.78	9.05	0.53	< 0.01
Valerate, m*M*	2.24	2.62	0.38	0.42
Isobutyrate, m*M*	0.89	0.67	0.04	< 0.01
Isovalerate, m*M*	1.66	1.65	0.24	0.98
Ruminal VFA, molar % of total[3]				
Acetate	61.3	54.0	0.73	< 0.01
Propionate	21.8	29.0	1.15	< 0.01
Butyrate	12.49	11.11	0.54	0.02
Valerate	1.99	2.95	0.31	0.02
Isobutyrate	0.79	0.87	0.06	0.02
Isovalerate	1.51	2.12	0.32	0.06
Liquid passage rate[4], %/h	11.3	5.7	1.04	< 0.01
Ruminal liquid volume, L	32.6	48.2	3.86	< 0.01
Apparent total tract digestibility, %				
DM	74.8	78.7	0.77	0.01
OM	77.1	82.0	0.62	< 0.01
NDF	73.4	73.5	1.45	0.94
ADF	67.6	66.4	1.54	0.59
Starch	94.4	96.2	1.16	0.32

[1] 0.99AL = 0.99 Mcal NE_g/kg DM fed for ad libitum intake. 1.32LF85% = 1.32Mcal NE_g/kg/DM limit-fed at 85% of 0.99AL treatment DM intake.

[2] Largest SEM is reported.

[3] Average of values collected at 0, 2, 4, 6, 8, 12, 18, and 24 h after feeding.

[4] Calculated from samples collected at 0, 2, 4, 6, 8, 12, and 18 h after dosing of Co-EDTA at time of feeding.

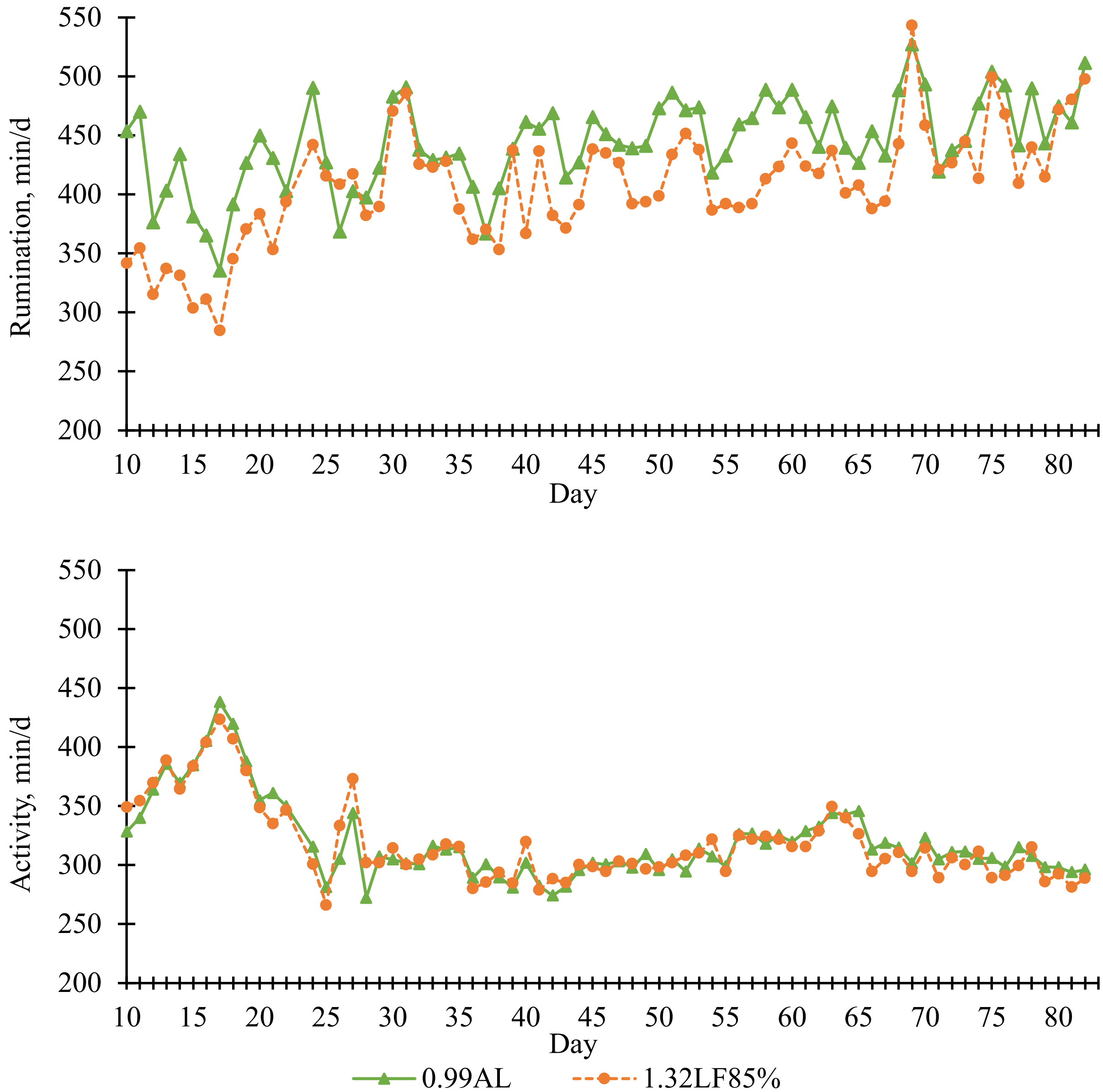

Figure 2.1 Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase on daily rumination and activity in Exp. 1. Top graph: 0.99AL (▲) = 0.99 Mcal NE_g/kg DM offered for ad libitum DMI, n = 205; 1.32LF85% (●) = 1.32 Mcal NE_g/kg DM limit-fed at 85% of 0.99AL DMI, n = 204. Diet effect: $P < 0.0001$, Day effect: $P < 0.0001$. Diet × day effect: $P < 0.0001$. SEM = 14.23. Bottom graph: 0.99AL (▲) = 0.99 Mcals NE_g/kg DM offered for ad libitum DMI, n = 205; 1.32LF85% (●) = 1.32 Mcal NE_g/kg DM limit-fed at 85% of 0.99AL DMI, n = 204. Diet effect: $P = 0.33$, Day effect: $P < 0.0001$. Diet × day effect: $P = 0.04$. SEM = 8.12.

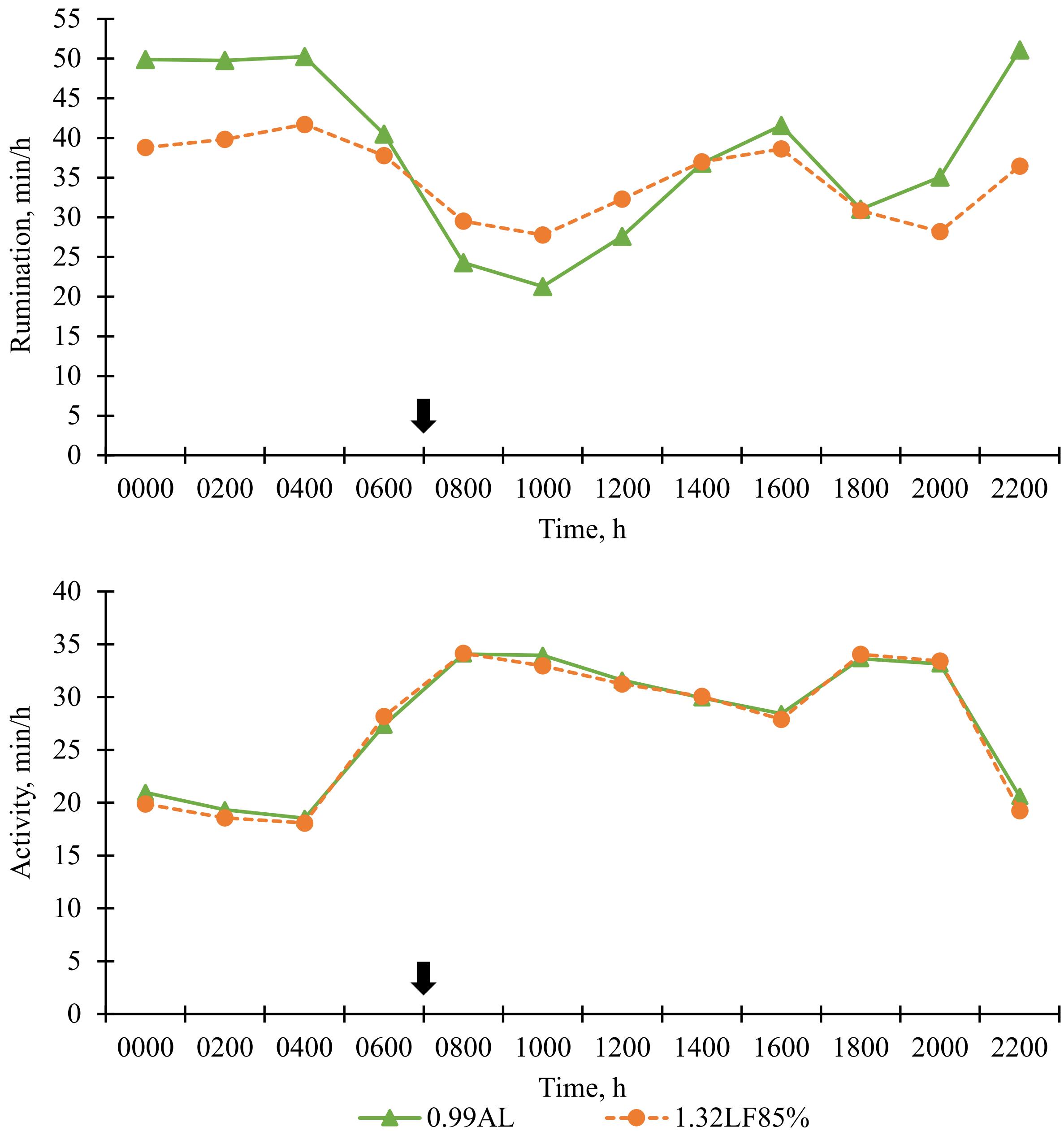

Figure 2.2 Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase on hourly rumination and activity in Exp. 1. Top graph: 0.99AL (▲) = 0.99 Mcals NE_g/kg DM offered for ad libitum DMI, n = 205; 1.32LF85% (●) = 1.32 Mcal NE_g/kg DM limit-fed at 85% of 0.99AL DMI, n = 204. The arrow represents time of feeding (0700 h). Diet effect: $P < 0.0001$. Hour effect: $P < 0.0001$. Diet × hour effect: $P < 0.0001$. SEM = 0.76. Bottom graph:0.99AL (▲) = 0.99 Mcal NE_g/kg DM offered for ad libitum DMI, n = 205; 1.32LF85% (●) = 1.32 Mcal NE_g/kg DM limit-fed at 85% of 0.99AL DMI, n = 204. The arrow represents time of feeding (0700 h). Diet effect: $P = 0.02$. Hour effect: $P < 0.0001$. Diet × hour effect: $P = 0.02$. SEM = 0.33.

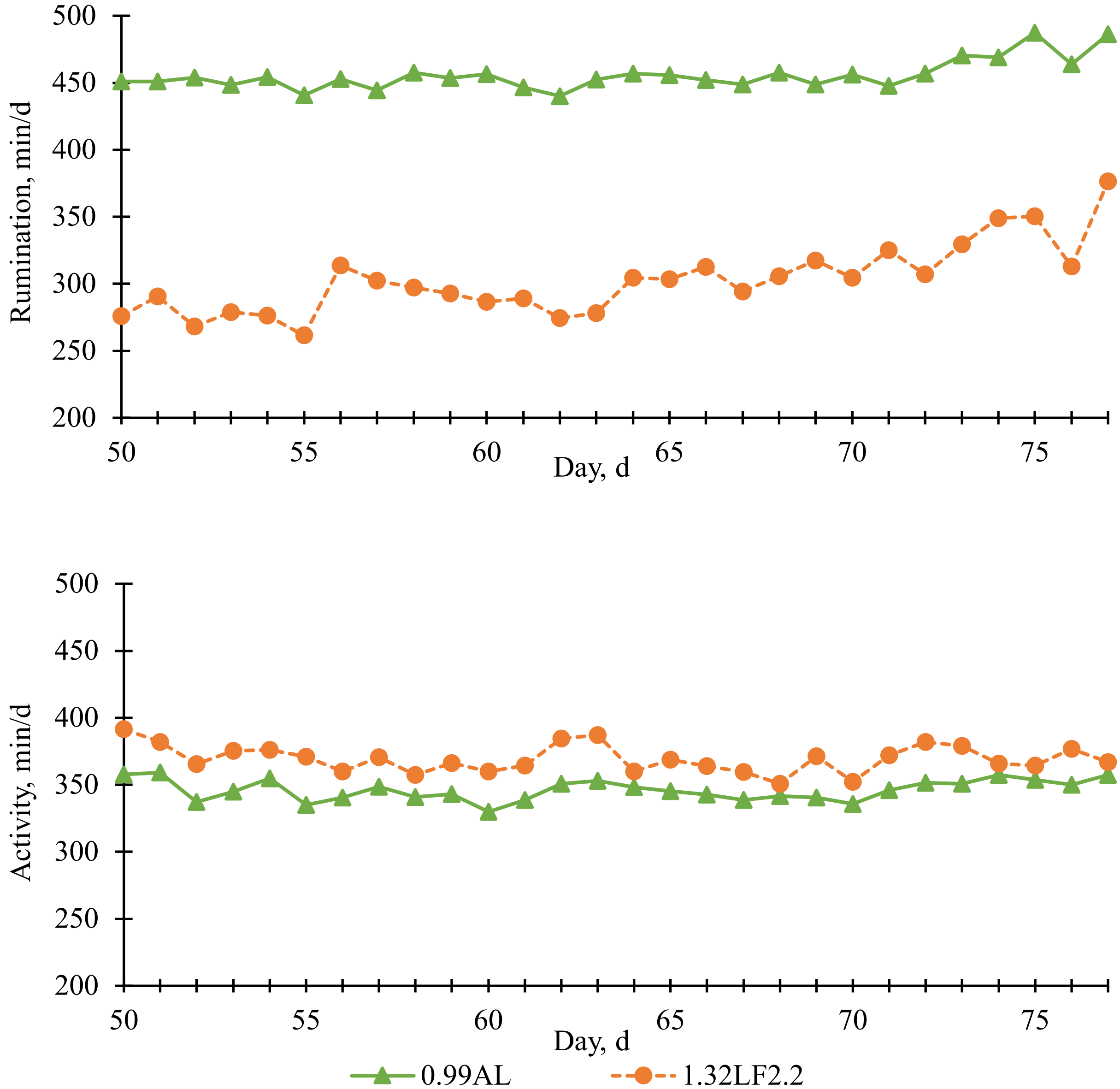

Figure 2.3 Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase on daily rumination and activity in Exp. 2. Top graph: 0.99AL (▲) = 0.99 Mcal NE_g/kg DM offered for ad libitum DMI, n = 186; 1.32LF2.2 (●) = 1.32 Mcal NE_g/kg DM limit-fed at 2.2% of BW, n = 184. Diet effect: $P < 0.0001$. Day effect: $P < 0.0001$. Diet × day effect: $P = 0.04$. SEM = 15.94. Bottom graph: 0.99AL (▲) = 0.99 Mcal NE_g/kg DM offered for ad libitum DMI, n = 186; 1.32LF2.2 (●) = 1.32 Mcal NE_g/kg DM limit-fed at 2.2% of BW, n = 184. Diet effect: $P < 0.001$. Day effect: $P = 0.01$. Diet × day effect: $P = 0.93$. SEM = 9.55.

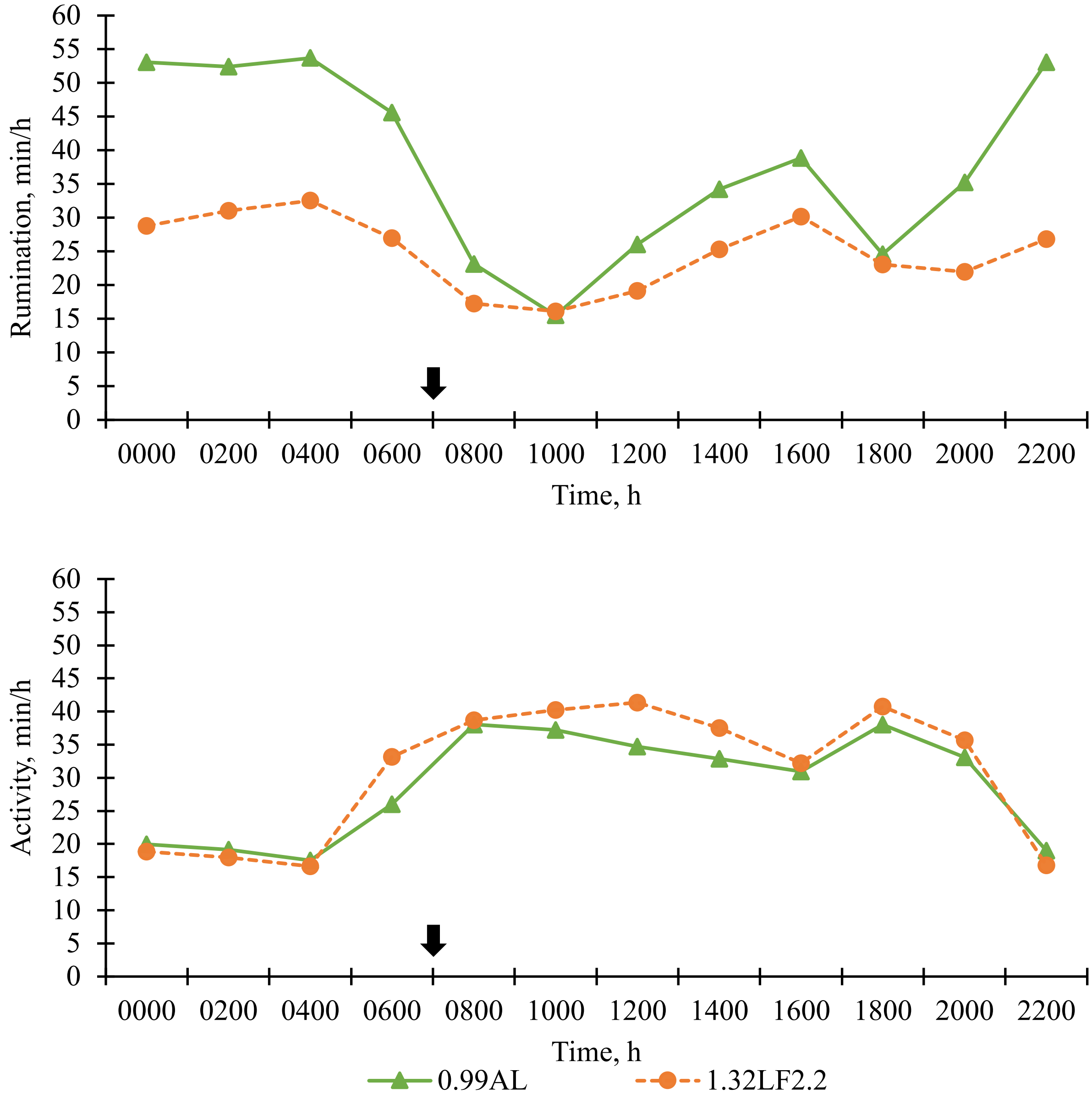

Figure 2.4 Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase on hourly rumination and activity in Exp. 2. Top graph: 0.99AL (▲) = 0.99 Mcal NE_g/kg DM offered for ad libitum DMI, n = 186; 1.32LF2.2 (●) = 1.32 Mcal NE_g/kg DM limit-fed at 2.2% of BW, n = 184. The arrow represents time of feeding (0700 h). Diet effect: $P < 0.0001$. Hour effect: $P < 0.0001$. Diet × hour effect: $P < 0.0001$. SEM = 1.18. Bottom graph: 0.99AL (▲) = 0.99 Mcal NE_g/kg DM offered for ad libitum DMI, n = 186; 1.32LF2.2 (●) = 1.32 Mcal NE_g/kg DM limit-fed at approximately 2.2% of BW, n = 184. The arrow represents time of feeding (0700 h). Diet effect: $P < 0.0001$, Hour effect: $P < 0.0001$. Diet × hour effect: $P < 0.0001$. SEM = 0.65.

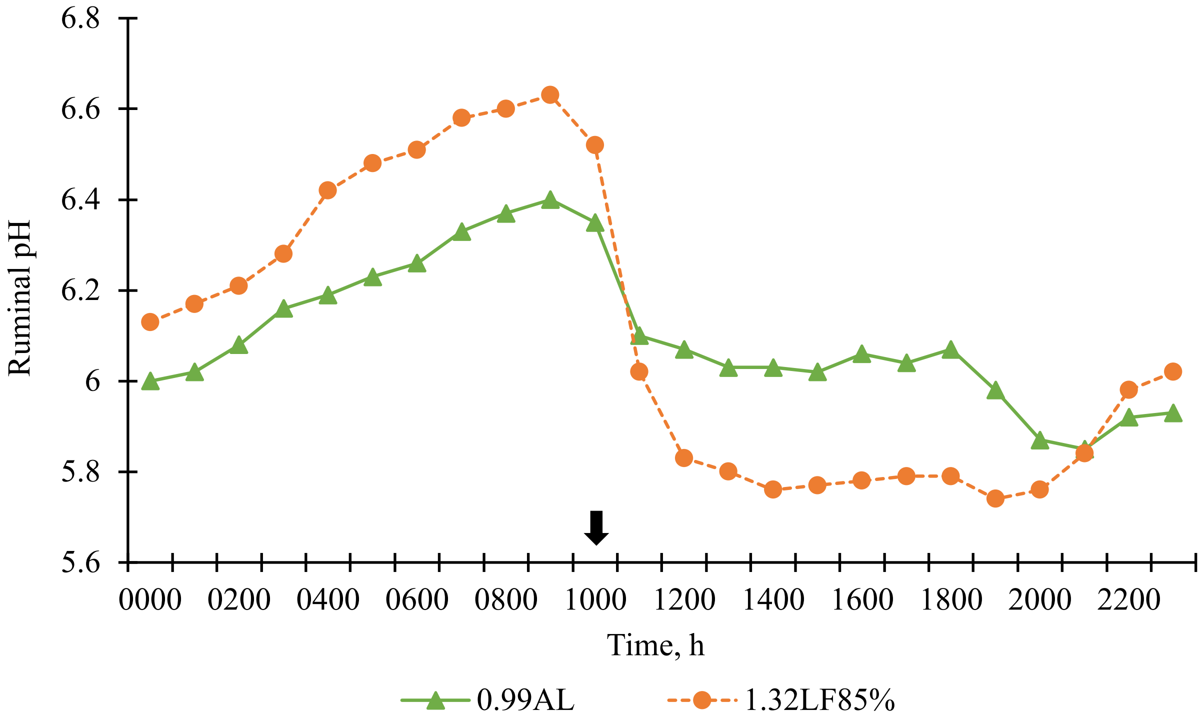

Figure 2.5 Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase on hourly pH in Exp. 3. 0.99AL (▲) = 0.99 Mcal NE_g/kg DM offered for ad libitum DM intake, n = 7; 1.32LF85% (●) = 1.32 Mcal NE_g/kg DM limit-fed at 85% of 0.99AL DMI, n = 8. The arrow represents time of feeding (1000 h). Diet effect: $P = 0.93$. Hour effect: $P < 0.0001$. Diet × hour effect: $P < 0.0001$. SEM = 0.11.

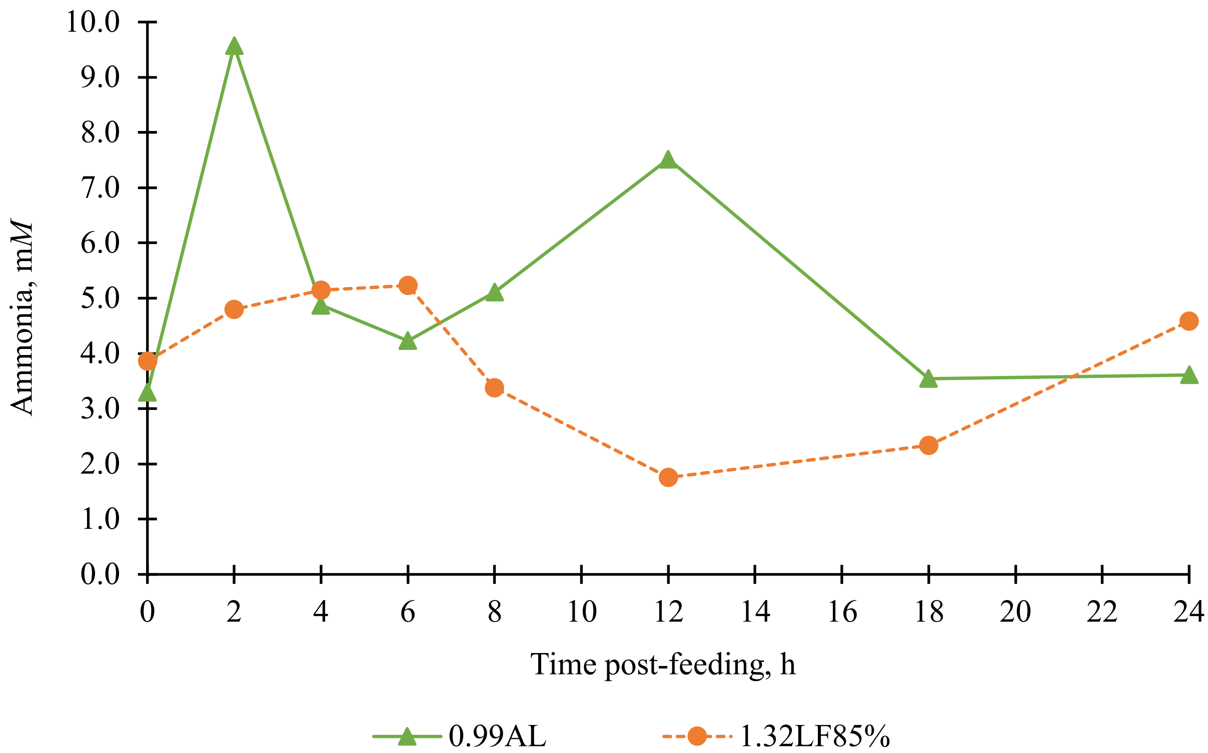

Figure 2.6 Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase on ruminal ammonia concentrations over 24 h in Exp. 3. 0.99AL (▲) = 0.99 Mcal NE_g/kg DM offered for ad libitum DMI, n = 7; 1.32LF85% (●) = 1.32 Mcal NE_g/kg DM offered at 85% of 0.99AL DMI, n = 8. Diet effect: $P = 0.03$. Hour effect: $P < 0.0001$. Diet × hour effect: $P < 0.0001$. SEM = 0.73.

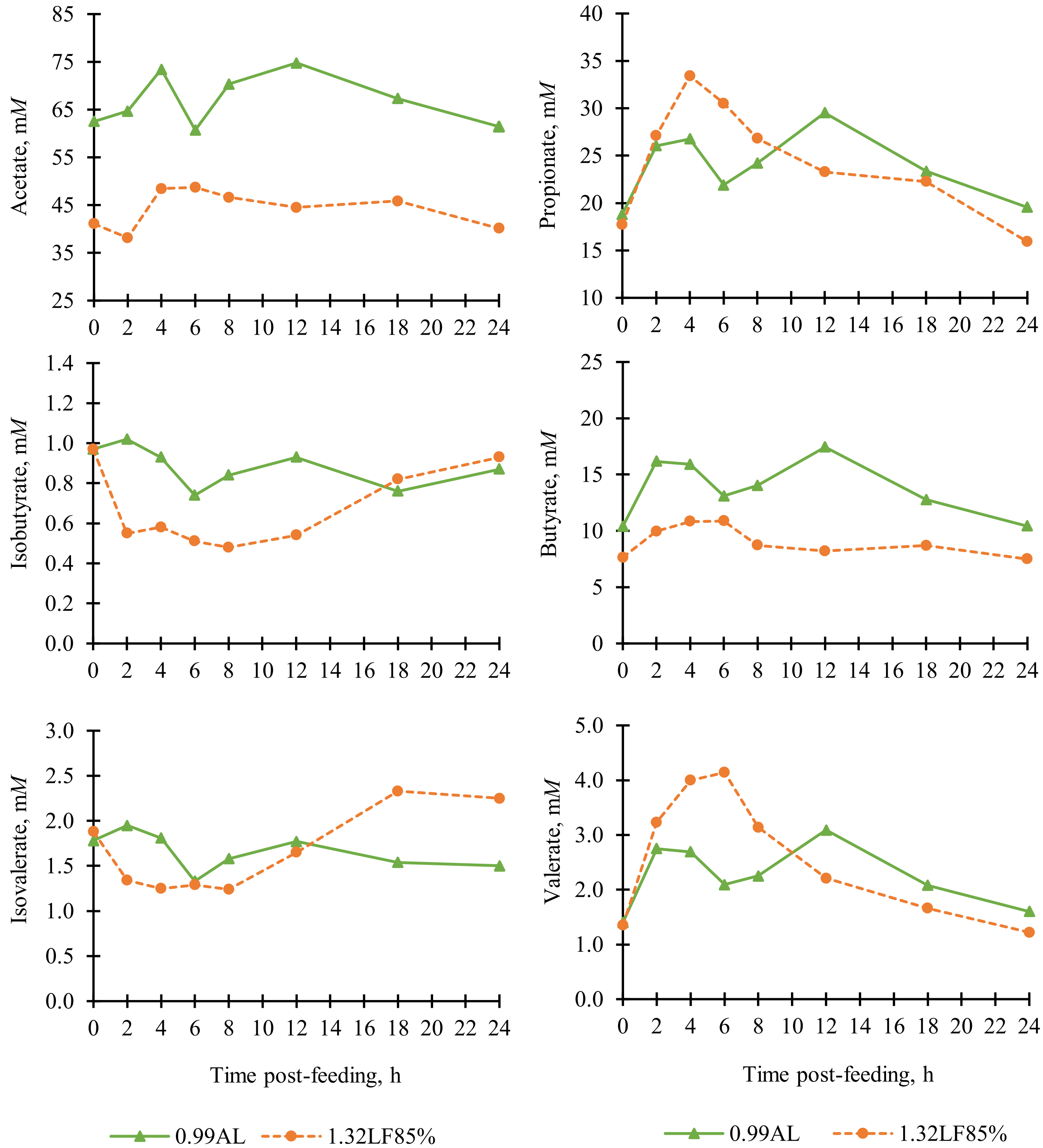

Figure 2.7 Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase on ruminal VFA concentrations over 24 h in Exp. 3. 0.99AL (▲) = 0.99 Mcal NE_g/kg DM offered for ad libitum DMI, n = 7; 1.32LF85% (●) = 1.32 Mcal NE_g/kg DM offered at 85% of 0.99AL DMI, n = 8. Acetate: Diet effect: $P < 0.0001$. Hour effect: $P < 0.01$. Diet × hour effect: $P = 0.21$. Propionate: Diet effect: $P = 0.63$. Hour effect: $P < 0.0001$. Diet × hour effect: $P < 0.001$. Isobutyrate: Diet effect: $P < 0.0001$. Hour effect: $P < 0.0001$. Diet × hour effect: $P < 0.0001$. Butyrate: Diet effect: $P < 0.0001$: Hour effect: $P < 0.0001$. Diet × hour effect: $P < 0.01$. Isovalerate: Diet effect: $P = 0.98$. Hour effect: $P = 0.04$. Diet × hour effect: $P < 0.01$. Valerate: Diet effect: $P = 0.42$. Hour effect: $P < 0.0001$. Diet × hour effect: $P < 0.0001$.

Appendix A - Ultrasound prediction of finishing phase growth performance and carcass characteristics

Table A.1 Pearson coefficients for ultrasound predictions of carcass characteristics and final carcass characteristics (Exp. 1)

	Variable[1]										
Variable[1]	1	2	3	4	5	6	7	8	9	10	11
1 HCW											
2 Yield grade	0.35*										
3 Marbling score	0.21	0.43									
4 REA	0.57**	-0.17	-0.24								
5 Backfat	0.53**	0.67**	0.22	0.40*							
6 US backfat[2]	0.54**	0.50**	0.27	0.40*	0.75**						
7 US marbling score[2]	0.35*	0.54**	0.44*	0.08	0.60**	0.68**					
8 US muscle depth[2]	0.60**	0.45*	0.08	0.53**	0.69**	0.74**	0.68**				
9 US predicted backfat[3]	-0.25	0.14	0.05	-0.02	0.22	0.34	0.18	0.06			
10 US predicted marbling score[3]	-0.34	0.07	0.17	-0.44*	-0.21	-0.42*	0.33	-0.12	-0.12		
11 US predicted HCW[3]	0.40*	-0.08	-0.09	0.07	-0.23	-0.37*	-0.13	0.11	-0.61**	0.23	

$^{*}P < 0.05$. $^{**}P < 0.01$.

[1] Variables 1 through 5 are carcass traits observed at the abattoir (National Beef, Dodge City, KS). Variables 6 through 8 are carcass traits observed on d 84 of the backgrounding phase by ultrasound scanning live cattle conducted by the Cattle Performance Enhancement Company (CPEC, Oakley, KS). Variables 9 through 11 are predicted carcass traits from ultrasound scans and prediction equations developed by CPEC.

[2] US = ultrasound. Collected on day 84 of the backgrounding phase.

[3] Predicted by equations (CPEC).

Table A.2. Effect of ad libitum high-roughage or limit-fed high-energy diets in the backgrounding phase on predicted carcass characteristics by ultrasound (Exp. 1)

	Sort Group[1]					
	Heavy		Light			
	Backgrounding Diet[2]					
Item	0.99AL	1.32LF85%	0.99AL	1.32LF85%	SEM[3]	*P* – value
Predicted performance[4]						
Days on feed	130[b]	115[c]	148[a]	138[b]	3.51	< 0.01
Live weight, kg	568.9	559.2	561.5	556.4	5.24	0.39
HCW, kg	359.8	352.6	354.3	350.6	3.78	0.36
Backfat, cm	1.45	1.50	1.47	1.45	0.03	0.25
Marbling score[5]	6.79	6.94	7.07	6.90	0.08	0.16
Probability of final USDA yield grade[6], %						
YG 2	30.6	26.3	28.5	28.8	1.43	0.22
YG 3	61.5	64.8	63.1	62.6	1.06	0.20
YG 4	6.5	7.8	6.6	7.3	0.42	0.15
Probability of final USDA quality grade[7], %						
Select	0.5	0.6	0.1	0.8	0.25	0.35
Choice	99.4	99.1	99.6	99.3	0.30	0.68
Prime	8.1	13.3	13.5	9.4	2.08	0.19
Probability of Certified Angus Beef[8], %	71.8	73.3	79.6	74.0	2.24	0.09

[abc] Least square means in the same row with different superscripts are significantly different ($P < 0.05$)

[1] Sort groups for each treatment were created prior to finishing phase. Heavy and light sort groups were finished in separate pens at a feed yard (Pratt Feeders, Pratt, KS), then sent to a commercial abattoir (National Beef, Dodge City, KS) on January 14, 2020 and February 4, 2020, respectively.

[2] Diets offered during the 84-d backgrounding phase prior to the finishing phase. First number = Mcal NE_g/kg DM. AL = ad libitum. LF85% = limit-fed at 85% of 0.99AL treatment DM intake.

[3] Largest SEM is reported.

[4] Predicted final carcass quality traits for cattle on d 84 in the backgrounding phase using ultrasound scanning and prediction equations (CPEC, Oakley, KS).

[5] 5.00-5.99 = low choice, 6.00-6.99 = avg choice. 7.00-7.99 = high choice

[6] Using Cattle Performance Enhancement Company software (CPEC), values reported are probabilities from 0 to 100% that the final yield grade of a carcass will be USDA 2, 3, or 4, respectively.

[7] Using Cattle Performance Enhancement Company software (CPEC), values reported are probabilities from 0 to 100% that the final quality grade of a carcass will be USDA Select, Choice, or Prime, respectively.

[8] Using Cattle Performance Enhancement Company software (CPEC), values reported are probabilities from 0 to 100% that a carcass will meet requirements for the Certified Angus Beef program.

Chapter 3 - Effect of Enogen corn hybrids or conventional hybrids in diets containing corn coproducts on performance and digestion in newly received growing cattle

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Running head: Enogen corn hybrids in growing cattle diets

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ABSTRACT: In Exp. 1, 384 crossbred heifers (initial BW = 264 ± 19.1 kg) were used in completely randomized design, 81-d receiving and growing study, with a 2 × 2 factorial arrangement of 4 dietary treatments. The objective was to evaluate the effect of feeding corn grain and corn silage from Enogen corn hybrids (EC; Syngenta Seeds, LLC., Downers Grove, IL) or conventional corn hybrids (CON) in diets containing either wet distillers grain (WDG; ICM Biofuels, St. Joseph, MO) or Sweet Bran [proprietary wet corn gluten feed (WCGF); Cargill Animal Nutrition, Blair, NE]. Experimental unit was pen. There were 8 pens per treatment, with 12 heifers stratified by weight to each pen. Experimental diets were formulated to contain 30% WDG or 30% WCGF on a dry matter (DM) basis and provide 1.12 Mcal of NE_g/kg DM. All diets were fed once daily for ad libitum consumption. In Exp. 2, eight ruminally cannulated crossbred heifers (initial BW = 370 ± 42.6 kg) were used concurrently with Exp. 1 to evaluate intake and digestibility of dietary treatments from Exp. 1 in a replicated 4 × 4 Latin square design. Four consecutive, 15-d periods consisted of 10 d for diet adaptation, 4 d of fecal sampling, and 1 d of ruminal sampling; experimental unit was animal. In Exp. 1, no corn source × coproduct interactions were observed ($P > 0.10$) for performance or fecal starch analysis, with the exception of dry matter intake (DMI; $P < 0.01$) and G:F ($P = 0.01$) at day 14. An effect of coproduct was observed at day 64, with heifers fed WDG having greater ADG than heifers fed WCGF ($P < 0.03$). Effect of coproduct on DMI or gain:feed (G:F) was not significantly different after day 14 ($P > 0.05$). Heifers fed EC had greater ADG at days 28 and 56 ($P < 0.01$) than heifers fed CON, but G:F was not different between corn sources after day 28 ($P > 0.13$). Starch concentration of fecal DM was greater in CON heifers than EC heifers ($P < 0.02$). In Exp. 2, corn source × coproduct interactions were not observed ($P > 0.16$). A main effect of coproduct occurred for molar percentage of isobutyrate ($P < 0.05$), and there was a tendency for greater

digestibility of starch in EC diets than CON diets ($P < 0.07$), but neither DM nor fiber digestibility was affected by corn source or coproduct ($P > 0.34$). Results indicate EC when fed with WCGF or WDG did not enhance growth performance of growing cattle, possibly due to similar dietary net energy densities fed in all diets.

Key words: amylase enzyme, corn silage, growing cattle, Sweet Bran, wet distillers grain, yellow dent corn

INTRODUCTION

Starch, among other energy sources, is an important consideration in growing ruminant diets, especially given widespread availability of grains such as corn. During movement of growing cattle through marketing and transport, high stress levels and extensive variation in nutritional regimens can significantly affect health and performance (Hutcheson and Cole, 1986). In recent studies, Enogen corn hybrids (EC; Syngenta Seeds, LLC., Downers Grove, IL) containing a heat tolerant, pH-stable α-amylase enzyme, when fed as grain or silage, have been shown to improve gain:feed (G:F) and average daily gain (ADG) by increasing starch availability and improving digestion in growing (Johnson, 2019) and finishing cattle (Baker et al., 2019; Jolly-Breithaupt et al., 2019). Furthermore, corn coproducts have become widespread in receiving and feedlot diets in recent decades (Klopfenstein et al., 2008; Berger and Singh, 2010). A survey of consulting nutritionists reported nearly 96% of receiving diets are formulated with a grain coproduct, with wet distillers grain (WDG) and wet corn gluten feed (WCGF) comprising 83% of coproducts selected (Samuelson et al., 2016). Both coproducts are excellent sources of protein, energy, and highly fermentable fiber (Firkins et al., 1985; Krehbiel et al., 1995), but they can be highly variable in nutrient composition (DePeters et al., 2000; Buckner et al., 2011) and contain high levels of sulfur (Drewnoski et al., 2014), which can affect the ruminal microbiome and lead to metabolic or neurological disorders (Cummings et al., 1995). Nevertheless, studies with growing cattle have demonstrated 40% inclusion of Sweet Bran (proprietary WCGF; Cargill Animal Nutrition, Blair, NE) does not lead to negative effects on animal health or performance (Spore, 2017; Spore et al., 2018). The objective of the present research was to determine the impact of EC or conventional corn grain hybrids (CON) in diets containing 30% WDG or WCGF on a dry matter basis on growth performance and digestion in newly received growing cattle. Our hypothesis was diets containing EC would enhance feed efficiency.

MATERIALS AND METHODS

All procedures and materials used were approved by the Kansas State University Institutional Animal Care and Use Committee. This study was conducted at the Kansas State University Beef Stocker Unit, Manhattan, KS.

Exp. 1 – Growth Performance Study

Design and Animal Management. Five hundred twenty-two crossbred heifers [initial body weight (BW) = 264 ± 30.5 kg] of Wyoming and Nebraska origin were loaded on trucks at a ranch 8 km north of Stapleton, NE and shipped 579 km to the receiving facility. Of these cattle, 384 heifers [initial body weight (BW) = 264 ± 19.1 kg] were used in a completely randomized design, with a 2 × 2 factorial arrangement of 4 dietary treatments. Experimental unit was pen. Cattle were fed in an outdoor receiving facility containing 32 soil-surfaced pens, each with an adjoining 9.1 m concrete bunk attached to a 3.6 m apron. All pens were equipped with automatic tank waterers (Lil' Spring 3000; Miraco Livestock Water Systems, Grinnell, IA), and daily total mixed rations (TMR) were delivered using a Roto-Mix feed wagon (model 414-14B, Dodge City, KS). On arrival (d -2), cattle were individually weighed and assigned a visual ear tag, while being assessed for pre-existing tags, physical injuries, or morbidity. Before processing and allocation to experimental pens on d 0, cattle were allowed ad libitum access to long-stem prairie hay and water. Because heifers had an extensive preconditioning and vaccination history, they were not vaccinated on arrival. The preconditioning program from previous ownership included an initial vaccination and booster with each of the following: Bovishield Gold FP5, One Shot, and UltraBac 8 (Zoetis, Parsippany, NJ). On d 0, heifers were individually weighed (model T20, Te Pari Products, Burnsville, MN), identified with visual and electronic identification (EID) ear tags, and drenched with an oral dewormer (Synanthic, Boehringer Ingelheim Animal Health, Duluth, GA). Heifers were stratified by d -2 BW to 1 of 32 pens, with 8 pens per dietary treatment and 12 heifers per pen. Pen weights were recorded on d 0 and used for initial BW in performance calculations.

Dietary treatments (Table 3.1) were formulated to provide 1.12 Mcal NE_g/kg DM, with main effects of corn source (CON or EC) and coproduct (WCGF or WDG) with coproducts comprising 30% of diet dry matter. All corn grain was dry-rolled by a commercial feed mill (Key Feeds, Clay Center, KS). Each treatment was provided to 8 pens in a completely randomized design, and all pens had ad libitum access to diets throughout the study. Bunks were visually assessed, and orts were estimated each morning at 0700 h. Daily orts were targeted at 9 kg per pen, collected weekly from each bunk, and weighed on a small portable scale (model iGB; Ishida, Kyoto, Japan) to precisely determine dry matter intake (DMI) weekly. A scale (Rice Lake Weighing Systems, Rice Lake, WI) was used to record pen weights on d 0, 14, 28, 42, 56, 64, and 81. Individual body weights were measured and a fecal grab sample for starch determination was collected on day 42. Final growth performance was calculated for each period from d 0 to 81. Treatment diets were provided from day 0 through day 64. Then, to minimize differences in gastrointestinal-tract fill all pens were limit-fed the CON/WCGF diet at 2.2% of day 64 BW daily from day 64 to 81. Feed samples were collected on a weekly basis throughout the study and frozen at -20°C. Upon study completion, samples were thawed, composited, refrozen, and delivered to a commercial laboratory (SDK Laboratories, Hutchinson, KS) for nutrient analysis.

Exp. 2 – Intake and Digestibility Study

Design and Animal Management. Eight ruminally cannulated crossbred Angus heifers (initial BW = 370 ± 42.6 kg) were used in a complete 4 x 4 Latin square design with 4 consecutive 15-d periods, conducted concurrently with Exp. 1. Experimental unit was animal within period. Treatment diets were the same as Exp. 1 (Table 3.1). During the first 2 periods, daily rations were removed from the beginning of the wagonload, whereas during periods 3 and 4, diets were mixed using a portable tub mixer (model 2030, Marion Process Solutions, Marion IA).

Heifers were housed in 8 soil-surfaced 6.1 m × 12.2 m pens in a large outdoor holding facility. Each heifer had access to a manually filled water tank, and cattle were fed once daily at 1000 h. Each 15-d period included 10 d for diet adaption, 4 d for fecal sampling, and 1 d for ruminal sampling. Orts were collected each morning and weighed using a portable scale (model iGB; Ishida, Kyoto, Japan). Additionally, orts were targeted at 1.8 kg/d during diet adaption and sampling to ensure ad libitum consumption of diets.

Sample Collection. On d 4 to 14, 10 g of chromic oxide (Cr_2O_3) as an external digestion marker was top dressed and hand mixed into each TMR to allow calculation of apparent total-tract diet digestibility. Feed samples were collected on days 10 to 14. Orts were collected on days

11 to 14 for each animal. In addition, fecal samples were collected from the rectum of each animal on days 11 to 14 at 8-h intervals after feeding. Fecal sampling time advanced by 2 h each day, thus, 2 h intervals were represented through 24 h after feeding. Following collection, feed, ort, and fecal samples were frozen at -20°C. Feed samples were separate from those collected for Exp. 1. Following study completion all feed, ort, and fecal samples were thawed, subsampled, and composited by animal within period, then refrozen and delivered to a commercial laboratory for nutrient analysis (SDK Laboratories, Hutchinson, KS). Dry, ground sample aliquots were obtained following analysis.

On d 15 of each period, four locations in the rumen were sampled prior to feeding, and at 2, 4, 6, 8, 12, 18, and 24 h after feeding to determine ruminal VFA profile and ammonia concentration. pH of each sample was measured using a calibrated pH meter (Pinpoint; American Marine Inc., Ridgefield, CT). Approximately 100 mL of ruminal contents were strained through 8 layers of cheesecloth. One mL of strained ruminal fluid was pipetted into each of four 2-mL microcentrifuge tubes containing 250 µL of 25 % (wt/vol) *m*-phosphoric acid. Following collection of 0 h samples, 3 g of Co-EDTA dissolved into 200 mL of distilled water was immediately dosed through the ruminal cannula. At 2, 4, 6, 8, 12, 18, and 24 h sampling times, 15 mL of additional rumen fluid was pipetted into 20-mL scintillation vials for use in measuring concentration of Co and calculating liquid passage rate and ruminal liquid volume. Immediately after collection, all ruminal fluid samples were frozen at -20°C pending analysis.

Laboratory Analysis and Calculations. To prepare ruminal fluid samples for analysis of Co, 5 mL of sample aliquots were transferred from scintillation vials to centrifuge tubes and centrifuged at 25,000 × g, for 25 min at 4°C using a JA-14 centrifuge rotor and centrifuge. Supernatant was pipetted into another test tube and promptly refrigerated at 4°C for immediate analysis or frozen at -20°C for later analysis by atomic absorption spectrophotometry (Perkin Elmer AAnalyst 100; PerkinElmer, Waltham, MA). If necessary, samples were diluted with deionized water to remain within the linear range of the assay. Samples of the Co-EDTA solution originally dosed into the rumen were also analyzed to determine Co concentration.

To prepare acidified ruminal fluid samples for analysis of volatile fatty acid (VFA) concentrations, samples were centrifuged in 2-mL microcentrifuge tubes at 17,000 × g for 30 min at 4°C using a microcentrifuge (accuSpin Micro 17R; Thermo Fisher Scientific, Waltham, MA). Supernatant was pipetted into 2-mL gas chromatograph (GC) vials and frozen at -20°C for future analysis. Analysis was conducted by gas chromatography.

To prepare acidified ruminal fluid samples for analysis of ammonia concentration, samples were centrifuged in 2-mL microcentrifuge tubes at 17,000 × g at 4°C for 30 min using a microcentrifuge (accuSpin Micro 17R; Thermo Fisher Scientific, Waltham, MA). Ammonia analysis was conducted following the procedures of Broderick and Kang (1980). Analysis was conducted using a BioTek PowerWave XS plate reader (BioTek, Winooski, VT) with wavelength set to 630 nm.

To calculate apparent total-tract diet digestibility, all samples were prepared for analysis of Cr concentration by weighing 3 g of wet feces or 0.5 g of dried, ground orts into pre-tared glass beakers and drying at 105°C in a forced-air oven overnight. Samples were ashed at 550°C for 4 h in a muffle furnace (Thermolyne, Thermo Fisher Scientific, Waltham, MA). Analysis of Cr followed procedures of Williams et al. (1962). Ort and fecal Cr analysis was conducted by atomic absorption spectrophotometry (Perkin Elmer AAnalyst 100; PerkinElmer, Waltham, MA). Dry matter intake (DMI), neutral detergent fiber intake (NDFI), acid detergent fiber intake (ADFI), and starch intake were calculated, and fecal output (g/d) was estimated by dividing Cr intake (g/d) by Cr concentration in the feces (g Cr/g feces). Apparent total-tract diet digestibilities were calculated as 1 – (fecal output/intake)] × 100%.

Net Energy Calculations

Animal performance data from Exp. 1 were used to calculate net energy (NE) for maintenance and gain using equations from Galyean (2021) based on NRC (1996) nutrient requirements. Initial BW was included in the calculation after adding a 4% shrink to account for gastrointestinal tract fill when cattle were offered ad libitum access to hay. Final BW on d 81 was not shrunk, because it was measured following the gastrointestinal tract fill equilibration period.

Statistical Analyses

In Exp. 1, performance data, net energy calculations, and fecal starch concentrations were analyzed using the MIXED procedure of SAS (v9.4, SAS Institute Inc., Cary, NC). Corn source, coproduct, and corn source × coproduct interaction were included as fixed effects in the model, and least square means were generated to compare parameters measured. Pen was the experimental unit.

In Exp. 2, all data were analyzed using the MIXED procedure of SAS. Experimental unit was heifer within period. For intakes and nutrient digestibilities, period, corn source, coproduct, and corn source × coproduct interactions were fixed effects, and animal was a random effect. For ruminal pH, ammonia, and VFA, corn source, coproduct, period, hour, corn source × coproduct, corn source × hour, coproduct × hour, and corn source × coproduct × hour interactions were included as fixed effects in the model; animal was included as a random effect. Hour was a repeated measure, with animal × period as the subject. Based on the dependent variable, the covariance structure selected was spatial power or compound symmetry as determined by better-fit characteristics of the model using AIC and BIC statistics. Liquid passage rate (LPR) was estimated by regressing the natural logarithm of cobalt concentration for samples from 2 to 18 h after dosing against time for each animal in each period using the NONLINEAR procedure in SAS. Liquid passage rate was identified as the negative slope of the regression. Ruminal liquid volume was calculated by dividing the concentration of Co dosed at 0 h after feeding by the constant, *e*, raised to the power of the y-intercept of the regression. Liquid passage rate and ruminal liquid volume were analyzed as described above for digestibilities. Significance was declared at $P \leq = 0.05$, and tendencies at $P \leq 0.10$.

RESULTS

Exp. 1 – Growth Performance Study

Composition of experimental diets are presented in Table 3.1 and 3.2, and growth performance data for Exp. 1 is reported in Table 3.3. With the exception of minor interactions for DM and G:F between days 0 and 14, no interactions between main effects of corn source and coproduct were noted for this study. In our 81-d growing trial there were significant corn source × coproduct interactions detected from days 0 through 14 for DMI ($P < 0.01$) and G:F ($P = 0.05$). While heifers consuming CON/WCGF had lower ($P < 0.01$) DMI than EC heifers, heifers consuming CON/WDG had greater ($P < 0.01$) DMI than EC heifers. There was a tendency ($P = 0.054$) for CON/WCGF heifers to have greater G:F compared to EC heifers.

There were main effects ($P \leq 0.03$) of coproduct for BW and ADG at the time provision of treatment diets concluded (day 64) as well as after the gastrointestinal tract fill equilibration

(GFE) period (d 81); heifers fed WDG had greater BW and ADG than heifers fed WCGF. Because DMI was not markedly affected by coproduct, heifers consuming WDG also tended to have better G:F at day 64 ($P = 0.06$) as well as numerically better G:F at day 81 than heifers fed WCGF. At d 14, heifers fed WCGF had greater ($P < 0.05$) G:F than those fed WDG, which resulted from greater DMI for heifers fed WDG. Heifers consuming EC had greater BW and ADG at day 28 and day 56 ($P \leq 0.03$) compared to heifers fed CON. At day 28, heifers fed EC also had better ($P < 0.01$) G:F than those fed CON, with a similar tendency ($P = 0.06$) was observed for DMI. No differences between corn sources were observed for G:F or DMI after d 28. Main effect of corn source for net energy (NE) values was not observed in this study, but WDG diets had numerically greater NE values calculated from animal performance than WCGF diets. EC heifers had less starch in the feces ($P < 0.02$) than CON heifers, but there was no main effect detected for coproduct.

Exp. 2 – Intake and Digestibility Study

In Exp. 2, intake and nutrient digestibilities are presented in Table 3.4. No significant corn source × coproduct interactions were observed ($P \leq 0.16$), thus only main effects are discussed. No main effect differences between corn sources were observed for DMI, NDFI, ADFI, or starch intake ($P \geq 0.21$). EC heifers tended to have greater starch digestibility ($P = 0.07$) than those fed CON, confirming fecal starch results from Exp. 1. No other detectable differences in DM, NDF, or ADF digestibilities were observed between corn sources ($P > 0.34$). Differences between corn sources were also not detected for ruminal pH, ammonia concentration, VFA total concentration, liquid passage rate, and ruminal liquid volume. Heifers fed CON had a greater molar percentage of acetate ($P < 0.01$) compared to EC heifers. Conversely, heifers fed EC had a greater molar percentage of butyrate than those fed CON ($P <$

0.05). Heifers fed EC also tended to have greater molar percentages of propionate and isovalerate ($P < 0.10$) than heifers fed CON.

Heifers consuming WCGF had lower intake of NDF and ADF ($P < 0.05$) than those fed WDG, and this was associated with a tendency ($P = 0.07$) for lower DMI for heifers fed WCGF. No main effect between coproducts were detected for starch intake ($P = 0.30$). No other detectable differences in DM, NDF, ADF, or starch digestibilities were observed for main effect of coproduct ($P > 0.29$). Main effect differences between coproducts were also not observed for ruminal pH, ammonia concentration, VFA total concentration, liquid passage rate, and ruminal liquid volume, but heifers fed WCGF had numerically greater ruminal liquid volume than those fed WDG. Heifers fed WDG had a greater molar proportion of isobutyrate ($P < 0.05$) than heifers fed WCGF, whereas heifers fed WCGF had a greater molar percentage of valerate ($P < 0.01$) than those fed WDG. Heifers fed WDG had a greater molar percentage of butyrate than those fed WCGF ($P < 0.05$). No main effect between coproducts was observed for molar proportions of acetate ($P < 0.19$), propionate ($P > 0.75$), or isovalerate ($P > 0.35$).

There were no corn source × coproduct × hour interactions for any ruminal parameters, and no corn source × hour interactions were observed ($P > 0.05$). However, there were coproduct × hour interactions for concentration of ruminal ammonia ($P < 0.01$; Fig. 3.1) and two branched chain fatty acids, isobutyrate ($P < 0.01$) and isovalerate ($P < 0.01$). In heifers fed WCGF, isobutyrate and isovalerate concentrations reached a peak at 2 h after feeding, then declined between 2 and 24 h after feeding, whereas in heifers fed WDG, isobutyrate and isovalerate concentrations were greatest at 0 h after feeding, then declined between 0 h through 24 h after feeding. Concentration of isobutyrate and isovalerate in heifers fed WDG increased above concentrations of isobutyrate and isovalerate in heifers fed WCGF between 12 h and 24 h after feeding.

DISCUSSION

While Johnson (2019) recently conducted trials with newly received growing cattle that demonstrated EC hybrids can enhance G:F and ADG, no such findings were consistently observed in the present study. Johnson (2019) evaluated main effects of EC and grain processing in growing cattle, finding cattle consuming dry-rolled EC had 2.4% better G:F than those consuming whole corn CON, but effects of amylase and grain processing were confounded. In a subsequent experiment utilizing dry-rolled EC or CON grain and EC or CON silage, cattle fed EC silage had 5% greater ADG than those fed CON silage, but no main effects between corn grain or corn silage were observed for G:F. Our findings in the present study are also in contrast to recent determinations in finishing cattle, where G:F was improved by feeding EC silage and EC grain compared to CON silage and CON grain (Baker et al., 2019). Jolly-Breithaupt et al. (2019) reported a 1.6% numerical increase of G:F in finishing steers fed EC compared to steers fed CON, and diets contained modified distillers grains plus solubles. However, a 10.9% improvement occurred for EC diets compared to CON diets that contained 25% Sweet Bran (proprietary WCGF). Another trial evaluating EC fed in diets containing distillers grains showed that replacing CON ground corn with EC ground corn did not improve finishing growth performance or carcass characteristics (Schoonmaker et al., 2014). Rusche et al. (2020) observed no differences in G:F, ADG, or final BW of finishing steers when fed EC or CON corn silage at 12 or 24% of diet DM in diets containing approximately 19% modified distillers grains plus solubles. Use of EC in other species such as swine has demonstrated no improvement in G:F, but

ADG tended to increase when pigs were fed EC compared to pigs fed CON (Ochonski et al., 2021). Although there is some contradictory evidence, our results appear to agree with several experiments that suggest there are some situations where EC has little overall effect on growing cattle performance.

Over the course of Exp. 1, there was a notable change in the response to EC compared to CON. Cattle fed EC grew faster than cattle fed CON between days 0 and 28 and again between days 28 and 56, but this effect disappeared by day 64 and similarly after provision of the gastrointestinal tract fill equilibration period between days 64 and 81. Although there was a tendency for DMI to be greater for cattle fed EC than for CON between day 0 and 28, this also disappeared later in the trial. Early gains in EC cattle may have been due to intake differences, which signifies the importance of using a gastrointestinal tract fill equilibration period to account for differences in gastrointestinal tract fill. Early effects between corn sources may also have been the result of tissue gains, not gastrointestinal tract fill, in the cattle fed EC, and the cattle fed CON were able to recover by the end of the trial.

Our data from Exp. 2 demonstrated a tendency for greater apparent total tract digestibility of starch in cattle fed EC rather than CON, which is supported by low fecal starch concentration for cattle fed EC than for those fed CON in Exp. 1. These observations contrast findings of Johnson (2019) where feeding EC, relative to CON, led to greater digestibility of dietary DM but not starch in growing cattle. However, Johnson (2019) did observe lower fecal starch concentrations in fecal samples collected from growing cattle fed EC either dry-rolled or whole-shelled EC corn when compared to similarly processed conventional corn. At the same time, relatively small increases in starch digestibility due to exogenous addition of α-amylase, or through endogenous expression of the enzyme in corn (as in our experiment), may not necessarily lead to noticeable improvements in cattle performance (McCarthy et al., 2013; Lara et al., 2018). However, in the first of two experiments, Tricarico et al. (2007) fed 120 finishing steers 950 dextrinizing units of supplemental α-amylase/kg DM. Greater ADG and DMI was reported in amylase supplemented diets containing cottonseed hulls after day 28 of the trial, but responses to amylase were not observed when alfalfa hay was the primary roughage source. Increased performance in response to amylase additions to the cottonseed hull-containing diet was attributed to greater crude protein content provided by urea in the cottonseed hull diet, differences in available Ca^{+2}, or slower passage rate. Moreover, lower concentration of propionate, authors suggested, may have contributed to increased feed intake, but no ruminal VFA data was collected during the trial. We did not observe greater ruminal propionate for EC than CON, thus our data does not support the hypothesis of Tricarico et al., (2007) that amylase provision would reduce propionate concentration. Another study with exogenous supplementation of α-amylase enzymes to wether lambs in corn silage-based diets found inconsistent results regarding feed intake and growth performance (Lara et al., 2018).

Our results suggest using coproducts such as WCGF or WDG in growing cattle may affect performance outcomes. In our trial, feeding WDG improved ADG by 5.0% compared to WCGF. Other studies have found improvements in G:F and ADG from feeding diets containing 30% WDG compared to 30% WCGF in growing (Schlegel et al., 2013) and finishing cattle (Loza et al., 2010). While no analyses for fat content were conducted in the present experiment, expected fat content for our WDG was 6.0% on a DM basis. A potential explanation for improvement in G:F and ADG is higher dietary fat and crude protein content in WDG, thus greater dietary energy density (NASEM, 2016). It is notable that NE values calculated from animal performance were lower than what was formulated in the diets, which may be due to environmental factors such as heat stress, cold stress, or poor pen conditions. The experiment took place during the fall when ambient temperature swings are common.

To compare diet formulation of NE density, NE was calculated based on digestion of OM. In calculation of metabolizable energy from digestible energy, a factor of 2.3% was included for monensin (NASEM, 2016). Relative to formulation of the CON/WCGF diet, NE_g based on digestion was 8.0% greater, whereas NE_g based on performance was lower in Exp. 1. The CON/WCGF diet based on digestion yielded 1.21 Mcal NE_g/kg DM. Relative to formulation of the CON/WDG and EC/WCGF diets, NE_g based on digestion was 11.6% greater, and NE_g based on performance was lower in Exp. 1. The CON/WDG and EC/WCGF diets based on digestion yielded 1.25 Mcal NE_g/kg DM. Relative to formulation of the EC/WDG diet, NE_g based on digestion was 13.4% greater, and NE_g based on performance was lower in Exp. 1. The EC/WDG diet based on digestion yielded 1.27 Mcal NE_g/kg DM. It was unexpected that NE_g based on digestion for each diet, relative to formulation, was greater, whereas NE_g based on performance was worse. Based on NASEM (2016) equations, predicted organic matter digestibility for the CON/WCGF, CON/WDG, EC/WCGF, and EC/WDG diets were 3.5%, 5.1%, 4.9%, and 5.8% lower than our results, but a reason for this difference could not be ascertained.

In Exp. 2, differences between concentrations of branched chain VFA, isobutyrate and isovalerate, and ammonia can be explained by differences in protein digestibility of WCGF and WDG. Rumen undegradable protein comprises a greater proportion of crude protein in WDG compared to WCGF or Sweet Bran (NASEM, 2016). Thus, protein in WCGF is more extensively catabolized in the rumen. More degradable protein in WCGF diets can explain a more rapid response in ruminal ammonia production post-feeding, compared to WDG diets. Exp.

2 confirmed this phenomenon of greater ruminal protein degradability in WCGF compared to WDG.

CONCLUSION

Our results revealed no effect of replacing CON corn grain and silage with EC corn and silage on the growth performance of growing cattle, even though total tract digestibility of starch improved in cattle fed EC compared to cattle fed CON. This contradicts some, but not all published literature. Using WDG resulted in better G:F and ADG compared to WCGF. Although patterns of ruminal fermentation end-products, notably ammonia and branched chain volatile fatty acids, reflected greater protein degradability for WCGF than for WDG, overall concentrations of VFA and ammonia were not different between coproducts, nor was diet DM or fiber digestibility different. Although not examined in our experiments, market price and regional availability will likely determine specific coproducts producers utilize in growing and receiving cattle diets.

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Table 3.1 Composition and nutrient analysis of experimental diets (Exp. 1-2)

		Corn Source[1]			
		CON		EC	
		Coproduct[2]			
Ingredient, % of total DM	GFE[3]	WCGF	WDG	WCGF	WDG
Conventional corn hybrids	21.0	21.0	19.0	0.0	0.0
Enogen corn hybrids	0.0	0.0	0.0	21.0	19.0
Conventional corn silage	20.0	20.0	20.0	0.0	0.0
Enogen corn silage	0.0	0.0	0.0	20.0	20.0
Wet corn gluten feed	30.0	30.0	0.0	30.0	0.0
Wet distillers grain	0.0	0.0	30.0	0.0	30.0
Long-stem alfalfa hay	12.0	12.0	13.0	12.0	13.0
Chopped prairie hay	12.0	12.0	13.0	12.0	13.0
Supplement[4]	5.0	5.0	5.0	5.0	5.0
Exp. 1					
DM, % as fed	72.48	55.56	48.55	58.12	50.30
CP	14.38	14.06	16.48	14.01	15.40
Starch	28.15	23.31	19.23	23.16	20.77
NDF	27.75	31.27	32.49	31.25	32.33
ADF	11.56	15.20	15.86	15.07	15.72
Ca	0.83	0.75	0.86	0.76	0.83
P	0.57	0.50	0.56	0.50	0.53
Exp. 2					
DM, % as fed	–	56.45	50.78	52.93	48.24
CP	–	14.31	15.47	14.28	15.87
Starch	–	24.93	23.23	25.00	22.88
NDF	–	29.31	29.64	30.94	31.88
ADF	–	14.02	14.32	15.24	15.75
Ca	–	0.69	0.73	0.76	0.85
P	–	0.41	0.46	0.39	0.46

[1] CON = Conventional corn hybrids, dry-rolled. EC = Enogen corn hybrids, dry-rolled (Syngenta Seeds, LLC., Downers Grove, IL).

[2] WCGF = wet corn gluten feed (Sweet Bran, Cargill Animal Nutrition, Blair, NE) WDG = wet distillers grain (ICM Biofuels, St. Joseph, MO).

[3] GFE = gastrointestinal tract fill equilibration diet fed from days 64 to 81 to all cattle.

[4] Supplement pellet (Cargill Animal Nutrition, Minneapolis, MN) was formulated to contain (DM basis) 9.2% crude protein, 1.53% crude fat, 17.0% crude fiber, 7.4% calcium, 0.22% phosphorus, 4.62% salt, 0.50% potassium, 331 mg/kg monensin, and 60.10 mg/kg diflubenzuron.

Table 3.2 Analysis of nutrients in silage and corn coproducts fed (Exp. 1-2)

	Ingredient[1]			
Item, % DM	CS	ES	WCGF	WDG
Exp. 1 nutrient composition				
DM, % as fed	27.2 ± 2.0	31.6 ± 2.6	61.1 ± 2.5	37.5 ± 1.2
CP	9.5 ± 0.9	8.7 ± 0.5	22.4 ± 0.5	28.1 ± 1.0
Starch	23.5 ± 4.2	27.5 ± 3.6	–	–
ADF	21.7 ± 2.3	20.4 ± 1.5	8.5 ± 0.6	9.7 ± 2.1
NDF	38.4 ± 3.5	36.2 ± 2.1	30.5 ± 1.8	33.1 ± 5.1
Ca	0.27 ± 0.03	0.23 ± 0.03	0.05 ± 0.02	0.09 ± 0.03
P	0.21 ± 0.03	0.19 ± 0.01	1.06 ± 0.07	1.15 ± 0.14
Exp. 2 nutrient composition				
DM, % as fed	29.7 ± 0.8	32.2 ± 0.6	60.5 ± 1.2	36.6 ± 0.3
CP	8.5 ± 0.3	8.9 ± 0.2	22.5 ± 0.3	27.8 ± 1.3
Starch	26.7 ± 2.1	24.4 ± 0.1	8.7 ± 0.0	2.1 ± 1.3
ADF	22.3 ± 3.0	21.4 ± 0.7	8.4 ± 0.8	8.7 ± 0.5
NDF	39.7 ± 4.6	38.1 ± 1.0	30.7 ± 3.3	30.7 ± 1.2
Ca	0.27 ± 0.01	0.27 ± 0.01	0.07 ± 0.05	0.12 ± 0.04
P	0.18 ± 0.01	0.18 ± 0.01	1.02 ± 0.08	1.19 ± 0.12

[1] CS = conventional corn hybrids silage. ES = Enogen corn hybrids silage (Syngenta Seeds, LLC., Downers Grove, IL). WCGF = wet corn gluten feed (Sweet Bran, Cargill Animal Nutrition, Blair, NE). WDG = wet distillers grain (ICM Biofuels, St. Joseph, MO).

Table 3.3 Effect of Enogen corn hybrids or conventional hybrids and corn coproduct on performance and fecal starch output (Exp. 1)

	Corn Source[1]							
	CON		EC					
	Coproduct[2]					*P* – value[3]		
Item	WCGF	WDG	WCGF	WDG	SEM[4]	S	CP	S × CP
Number of pens	8	8	8	8				
Number of animals	96	96	96	96				
BW, kg								
Day 0	249.0	250.1	248.9	248.0	0.88	0.21	0.95	0.26
d 14	286.2	287.6	285.6	284.2	1.37	0.15	0.99	0.31
d 28	303.1	303.5	311.1	309.1	2.12	< 0.01	0.72	0.59
d 42	320.1	326.4	325.9	323.7	2.35	0.64	0.50	0.12
d 56	343.5	348.2	351.0	351.2	2.28	0.03	0.29	0.34
d 64	359.9	367.8	362.0	366.5	2.65	0.88	0.03	0.54
d 81, after GFE[5]	362.0	369.7	365.7	369.2	2.59	0.49	0.03	0.48
ADG, kg/d								
d 0 – 14	2.66	2.68	2.62	2.59	0.10	0.50	0.98	0.76
d 0 – 28	1.93	1.91	2.22	2.18	0.07	< 0.01	0.70	0.93
d 0 – 42	1.71	1.82	1.83	1.81	0.05	0.32	0.50	0.23
d 0 – 56	1.69	1.75	1.82	1.84	0.04	< 0.01	0.33	0.62
d 0 – 64	1.73	1.84	1.77	1.85	0.04	0.53	0.02	0.80
GFE d 64 – 81[5]	0.06	0.05	0.10	0.08	0.04	0.35	0.78	0.87
d 0 – 81[6]	1.39	1.48	1.44	1.50	0.03	0.25	0.03	0.72
DMI, kg/d								
d 0 – 14	5.99[a]	7.24[c]	6.59[b]	6.69[b]	0.15	0.86	< 0.01	< 0.01
d 0 – 28	7.59	7.98	8.02	8.13	0.15	0.06	0.10	0.36
d 0 – 42	8.55	8.69	8.83	8.88	0.17	0.18	0.59	0.82
d 0 – 56	9.12	9.23	9.36	9.48	0.16	0.15	0.49	0.97
d 0 – 64	9.42	9.48	9.54	9.68	0.17	0.36	0.55	0.81
GFE d 64 – 81[5]	7.78	7.94	7.87	7.92	0.06	0.57	0.11	0.37
d 0 – 81[6]	9.08	9.12	9.19	9.31	0.14	0.30	0.55	0.78

G:F, kg/kg								
d 0 – 14	0.446	0.371	0.399	0.387	0.02	0.35	0.01	0.05
d 0 – 28	0.255	0.239	0.277	0.269	0.01	< 0.01	0.17	0.65
d 0 – 42	0.200	0.209	0.208	0.203	0.01	0.91	0.73	0.26
d 0 – 56	0.186	0.190	0.195	0.195	0.01	0.13	0.66	0.62
d 0 – 64	0.184	0.194	0.185	0.192	0.01	0.85	0.06	0.67
GFE d 64 – 81[5]	0.008	0.006	0.014	0.010	0.01	0.34	0.63	0.81
d 0 – 81[6]	0.154	0.162	0.157	0.161	0.01	0.78	0.12	0.68
NE_m, Mcal/kg DM[7]	1.56	1.61	1.58	1.60	0.02	0.96	0.16	0.54
NE_g, Mcal/kg DM[7]	0.96	1.01	0.97	0.99	0.02	0.86	0.17	0.49
Fecal analysis								
DM, % as fed	16.4	16.0	15.8	16.0	0.46	0.52	0.83	0.52
Starch, % of DM	15.2	17.1	13.5	11.4	1.35	0.02	0.91	0.15

[abc] Least square means in the same row with different superscripts are significantly different ($P < 0.05$)

[1] CON = Conventional corn hybrids, dry-rolled. EC = Enogen corn hybrids, dry-rolled (Syngenta Seeds, LLC., Downers Grove, IL). Treatment diets formulated to contain 1.78 Mcal NE_m/kg DM and 1.12 Mcal NE_g/kg DM.

[2] WCGF = wet corn gluten feed (Sweet Bran, Cargill Animal Nutrition, Blair, NE). WDG = wet distillers grain (ICM Biofuels, St. Joseph, MO).

[3] S = corn source. CP = coproduct.

[4] Largest standard error of least square means reported.

[5] Gastrointestinal tract fill equilibration (GFE) period. GFE diet (Table 3.1) was limit-fed at 2.2% of BW daily on a DM basis from days 64 to 81.

[6] Includes gastrointestinal tract fill equilibration period.

[7] Net energy calculations of day 0 to 81 from (Galyean, 2021) based on NRC (1996) requirements.

Table 3.4 Effect of Enogen corn hybrids or conventional hybrids and corn coproduct on diet digestibility and ruminal characteristics (Exp. 2)

	Corn Source[1]							
	CON		EC					
	Coproduct[2]					P – value[3]		
Item	WCGF	WDG	WCGF	WDG	SEM[4]	S	CP	S × CP
Number of obs.	8	8	8	8				
Intake, kg/d								
DM	12.04	12.49	12.29	13.11	0.56	0.21	0.07	0.58
NDF	3.72	3.99	3.60	3.89	0.19	0.40	0.05	0.90
ADF	1.82	1.97	1.72	1.88	0.09	0.22	0.04	0.95
Starch	3.01	2.88	3.08	3.06	0.16	0.30	0.53	0.66
Ruminal[5]								
pH	6.11	6.10	6.04	6.16	0.07	0.99	0.34	0.28
Ammonia, m*M*	3.48	3.26	3.25	3.33	0.31	0.77	0.80	0.58
Total VFA, m*M*	79.83	77.59	78.04	76.88	1.82	0.39	0.25	0.71
Ruminal[6], molar %								
Acetate	62.77	62.08	61.25	60.81	0.47	< 0.01	0.19	0.76
Propionate	20.66	21.05	21.63	21.50	0.46	0.09	0.75	0.53
Butyrate	12.10	12.56	12.57	13.01	0.31	0.05	0.05	0.96
Valerate	1.81	1.65	1.86	1.69	0.05	0.28	< 0.01	0.95
Isobutyrate	0.86	0.90	0.87	0.93	0.03	0.45	0.04	0.82
Isovalerate	1.79	1.75	1.82	2.06	0.12	0.09	0.35	0.16
Liquid passage rate,[7] %/h	10.5	10.5	10.8	11.0	0.01	0.44	0.80	0.79
Ruminal liquid volume[7], L	64.3	58.0	63.1	60.2	4.16	0.88	0.16	0.61

Total tract digestibility, %								
DM	76.5	77.6	77.9	78.3	1.28	0.37	0.55	0.76
NDF	70.8	72.2	71.0	70.6	1.91	0.72	0.79	0.64
ADF	69.8	69.5	67.9	67.6	2.07	0.34	0.89	0.99
Starch	89.3	91.5	92.5	92.8	1.18	0.07	0.29	0.40

[1] CON = Conventional corn hybrids, dry-rolled. EC = Enogen corn hybrids, dry-rolled (Syngenta Seeds, LLC., Downers Grove, IL).
[2] WCGF = wet corn gluten feed (Sweet Bran, Cargill Animal Nutrition, Blair, NE). WDG = wet distillers grain (ICM Biofuels, St. Joseph, MO).
[3] S = Corn source. CP = coproduct.
[4] Largest standard error of least square means reported.
[5] Average of values collected at 0, 2, 4, 6, 8, 12, 18, and 24 h after feeding.
[6] Individual VFA expressed as a molar percentage of total ruminal VFA concentration.
[7] Calculated from samples collected at 0, 2, 4, 6, 8, 12, and 18 h after dosing of Co-EDTA at time of feeding.

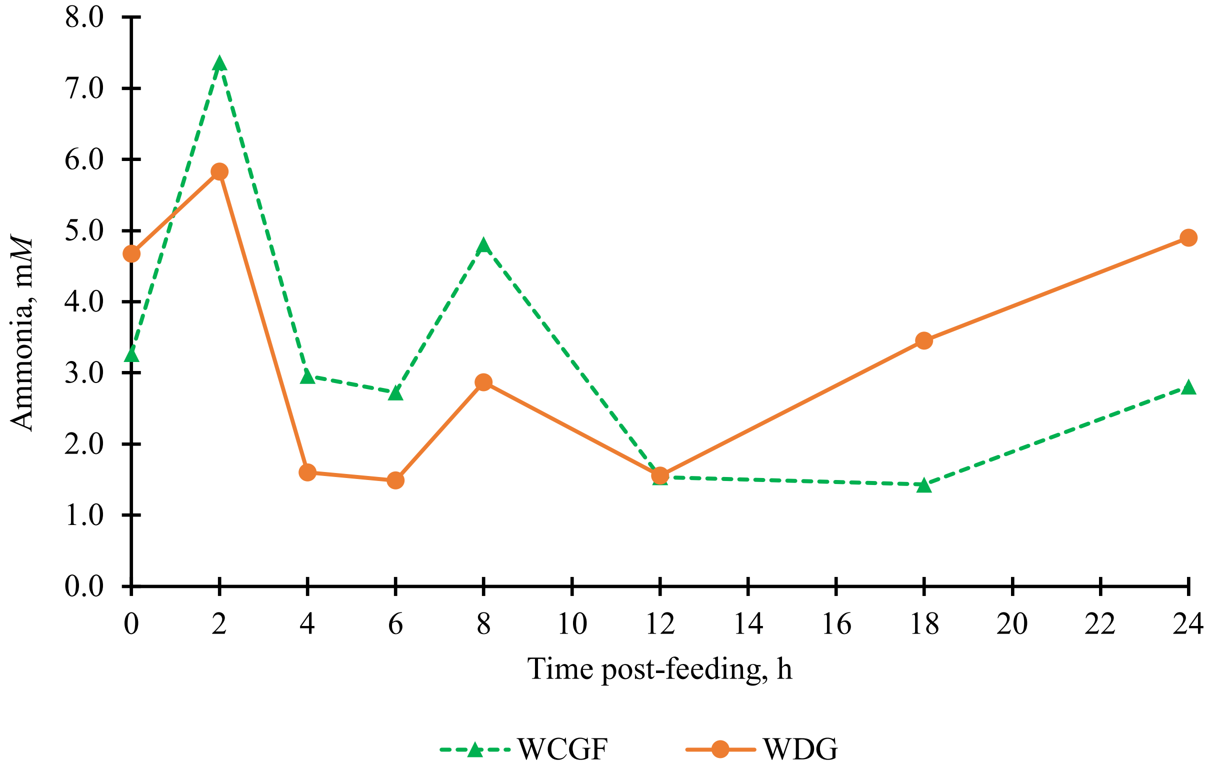

Figure 3.1. Significant interaction of coproduct variety and hour on ruminal ammonia concentration after feeding over 24 h (Exp. 2). WCGF (▲) = wet corn gluten feed (Sweet Bran, Cargill Animal Nutrition, Blair, NE), n=8; WDG (●) = wet distillers grain, n=8. Coproduct effect: $P = 0.80$. Hour effect: $P < 0.0001$, coproduct × hour effect: $P < 0.0001$. Standard error of means (SEM) = 0.46.