

Post-weaning development of beef bulls: impacts of omega-3 supplementation and accuracy of
nutrient requirement-based predictions

by

Brandon Joseph Fraser

A.S., Northeastern Oklahoma A&M College, 2020
B.S., Kansas State University, 2022

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Animal Sciences and Industry
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2025

Approved by:

Major Professor
Dr. Jason Warner

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Abstract

Two studies were conducted to evaluate (1) the effects of omega-3 fatty acid supplementation on post-weaning development of beef bulls and (2) the accuracy of nutrient requirement model predictions for feed intake and growth in developing bulls. In the first study, spring-born Angus, Hereford, and Simmental bulls were weaned each September and developed at the Kansas State University Precision Feed Intake Facility using Insentec® bunks for individual DMI collection. The effects of supplementing an omega-3 fatty acid-based product on growth performance and reproductive development of post-weaning beef bulls were evaluated in two experiments. In Experiment 1, bulls ($n = 42$; 352 ± 19 kg; 292 ± 6.3 d of age) were stratified by BW and age and randomly assigned to one of three omega-3 supplement levels added to a common corn silage and wet corn gluten feed-based growing diet: 0.0 (**CON**), 0.22 (**MOD**), or 0.43 (**HI**) kg^{hd/d} (DM basis). Treatments were applied for about 60 d. Dry matter intake did not differ among treatments ($P = 0.64$). Bulls receiving the **HI** treatment had greater ADG ($P \leq 0.05$) compared with **CON** and **MOD**, although final BW and gain to feed ratio were similar ($P \geq 0.52$). Scrotal circumference and serum fatty acids were unaffected ($P \geq 0.67$). Supplementation increased IMF% ($P = 0.03$) in **MOD** and **HI** and tended to increase LMA in **MOD** ($P = 0.06$). Rib fat did not differ ($P = 0.50$). In Experiment 2, bulls ($n = 39$; 332 ± 14 kg; 291 ± 6.3 d of age) received identical supplementation treatments for 80 d using an isonitrogenous formulated corn silage and dried distillers grains-based diet with corn germ meal as an added protein source. Final BW ($P = 0.86$), ADG ($P = 0.49$), and DMI ($P = 0.39$) did not differ. Gain to feed tended to differ ($P = 0.08$), but SC, IMF%, LMA, and rib fat were not affected ($P \geq 0.61$). Initial serum fatty acids were similar among treatments, but by d 80 supplemented bulls had greater ω -3 concentrations and a lower ω -6: ω -3 ratio ($P < 0.01$); MOD also had greater total FA and SFA

than CON ($P = 0.03$), with HI intermediate. Omega-3 supplementation at 0.22 and 0.43 kg per hd per day improved growth performance in Experiment 1, but no performance differences occurred in Experiment 2 when diets were formulated to be isonitrogenous, indicating that responses were likely driven by dietary protein rather than omega-3 inclusion. For the second study, a four-year retrospective analysis of purebred bull performance (2021 to 2024; $n = 154$) compared observed performance with predictions from the BRaNDS Growing Bull module. Actual DMI averaged 1.69 to 9.29 kg/hd per d while predicted DMI averaged 9.10 kg/d (bias = -0.20 kg/d). Correlations between observed and predicted DMI were moderate across years ($r = 0.55$ to 0.56 ; $P < 0.01$) and stronger within individual years ($r = 0.71$ to 0.84). Actual ADG averaged 0.34 to 1.61 kg/d whereas the BRaNDS model predicted 1.04 to 1.21 kg/d, generating underprediction biases of -0.50 to -0.57 kg/d. Year-specific ADG biases were -0.76, -0.51, -0.84, and +0.07 kg/d for years 1 through 4, respectively, and corresponding DMI biases were +1.23, +0.42, -1.15, and -1.18 kg/d. Adjusting BRaNDS inputs for temperature, mud, body condition score, or mature BW did not meaningfully improve accuracy. These results show that BRaNDS equations moderately predict DMI but consistently underestimate ADG of growing beef bulls under the constraints utilized in this retrospective analysis. Refinement of metabolizable energy and protein equations, as well as additional use of individual animal intake and performance data collected under various model input constraints are needed to improve accuracy of prediction models.

Key words: bulls; omega-3 fatty acids; dry matter intake; average daily gain; nutrient requirement models

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Acknowledgements

The time I spent at Kansas State University was a time of significant personal growth and learning. There were many rewards and many challenges. I enjoyed the courses I took and the many people I met during my time in graduate school.

A special thank you need to go to my Major Professor, Dr. Jason Warner. His guidance and encouragement is invaluable. I cannot thank him enough for his mentorship and confidence in me. He helped me to grow in so many ways. I. can't thank you enough.

Committee members, Dr. Dale Blasi and Dr. Karol Fike were willing to give me their time and guidance whenever I needed it. They helped me look at things with a different perspective. It was invaluable to my program. Thank you.

Another special thank you goes to Dr. Dave Nichols. He was someone who I could always talk to when I needed a little extra guidance and support. He gave me some much-appreciated wisdom.

I would like to say thank you to my fellow graduate students for their willingness to help and their kinship. It made my time living in the U.S.A. enjoyable.

Also, thank you to all the other people who I met while I was in Kansas. From the staff in the Animal Science department, the managers of the Intake Unit and the Purebred Unit to the families that opened their homes to me. It helped so much when I was feeling a little homesick.

Thank you to Mum and Dad for their unwavering support and allowing me the opportunity to live six years outside of Canada. They were there when things got tough and encouraged me to persevere. They have been my biggest cheerleaders.

I will be forever grateful for my time at Kansas State University. It will always be a part of me as I move on to the next chapter of my life.

Dedication

I dedicate this thesis to my parents Kevin and Joanne Fraser. I could not have accomplished this without their unwavering support and love. I will be forever grateful for everything they have done for me.

Chapter 1 - Review of Literature

The Importance of the Beef Cow-Calf Industry

The cow-calf sector serves as the foundation of North American beef production, supplying feeder and breeding stock that sustain both domestic and export-oriented cattle systems. In the United States, the beef cow inventory on January 1, 2024, was estimated at 28.2 million head, reflecting a contraction from 29.0 million head in 2014 and 32.7 million head in 2004 (USDA-NASS, 2004; USDA-NASS, 2014; USDA-NASS, 2024a). This downward trend signals a typical phase of cattle cycle liquidation, largely influenced by persistent drought, rising feed costs, and shifting producer economics.

Regionally, Kansas as of 2024, had a beef cow inventory of 1.26 million head reflecting a decline from the previous year, while the states total cattle inventory stood at 6.15 million head, ranking third in the nation due to its extensive feedlot infrastructure (USDA-NASS, 2024b). Although Kansas ranks sixth nationally in beef cow numbers, its centrality to both seedstock, cow-calf and feedlot production reinforces its national significance.

Economically, cow-calf operations are a major contributor to both farm receipts and downstream value chains. In 2024, cattle and calf sales accounted for approximately 22% of total U.S. farm cash receipts, generating \$113.3 billion out of \$520 billion in total agricultural revenue (USDA-ERS, 2025). The broader beef industry generated \$167 billion in gross sales, supported 721,488 jobs, and contributed \$30.1 billion in value added to the U.S. economy (English et al., 2020). Within this, on-farm cow-calf and feedlot operations represented \$55.9 billion in sales and over 543,000 jobs. When indirect and induced economic effects were included, total value-added rose significantly due to strong linkages with sectors such as feed manufacturing, transportation, and real estate (English et al., 2020). At the state level, the Kansas Department of

Agriculture estimated that cow calf and feedlot operations contributed \$13.6 billion in state output in 2024, supporting over 45,211 jobs (KDA, 2025).

While commercial cow-calf operations form the base of beef production, they depend heavily on the genetic and reproductive resources provided by the seedstock sector.

Understanding the structure, contribution, and evolution of this sector is essential to evaluating long-term industry sustainability and genetic advancement.

The Importance of the Beef Seedstock Industry

Genetic Improvement

Genetic improvement in beef cattle is primarily driven by the seedstock sector, which supplies superior sires and dams for the commercial cow-calf industry. Breed associations such as the American Angus Association (AAA) and American Hereford Association (AHA) oversee national cattle evaluations that generate EPDs for a wide array of traits, including growth, maternal function, fertility, and carcass quality (Kuehn and Thallman, 2016).

The advent of genomic-enhanced EPDs (GE-EPDs) has markedly increased the accuracy of selection, particularly for young animals without progeny data. The use of DNA markers allows breeders to make more informed decisions earlier, with GE-EPDs achieving accuracies equivalent to those of animals with up to 10 offspring (Miller, 2023). As of 2024, 72% of registered Angus cattle were genotyped, and over 218,000 genomic profiles were submitted that year alone (AAA, 2024).

Breed associations are also integrating sustainability and efficiency traits into their evaluation platforms. For instance, the Hereford National Reference Sire Program (NRSP) has enabled rapid genetic progress through large-scale progeny testing and collection of feed intake and methane emission data. Over 200,000 Hereford genotypes are now incorporated into the

evaluation system, and sires enrolled in the NRSP influence over 7% of all AHA pedigrees (AHA, 2024).

Use of AI vs. Natural Mating Systems

Artificial insemination remains underutilized in the broader cow-calf sector despite its advantages such as a more uniform calf crop from elite sires and maintaining a smaller herd bull battery. In the United States, only 11.6% of cow-calf operations used AI in 2017, with higher adoption in larger herds (USDA-APHIS, 2020).

Conversely, natural service remains the dominant breeding strategy, with more than 90% of U.S. beef cows bred eventually via bull exposure (USDA-APHIS, 2020). Bulls are typically expected to service 15 to 25 cows in their first season depending on age and condition (Kniffen and Comerford, 2025). This limited breeding capacity means the national herd relies heavily on a large inventory of bulls. In 2024, the U.S. had approximately 2.03 million beef bulls over 500 pounds to breed roughly 28 million beef cows (USDA-NASS, 2024).

A notable development in recent years is the continued rise in the use of beef semen within U.S. dairy herds. In 2024, domestic beef semen sales totaled 9.7 million units, an increase of 304,000 units from 2023. Of these, 7.9 million units were used in dairy herds, while only 1.8 million units were used in beef herds, underscoring the dominance of the beef-on-dairy strategy in the domestic market (NAAB, 2025). Beef-on-dairy semen sales increased by approximately 317,000 units across domestic and export channels, while beef-on-beef sales also rebounded, rising by 408,000 units following two years of decline. Producers are increasingly combing sex-sorted dairy semen for replacement heifer production with beef semen on lower-genetic-merit cows to maximize economic returns. In 2024, beef-on-dairy semen ranked as the second-largest semen type in the U.S., with 7.9 million units, trailing only gender sorted dairy semen, which

reached 9.9 million units. The high market value of F1 beef × dairy calves, along with the rising cost of raising dairy heifers, continues to drive widespread adoption of this strategy (NAAB, 2025).

Embryo transfer (ET), while costly and management-intensive, is more common in elite seedstock herds. The American Angus and Hereford associations also report that approximately 10 to 15% of their annual calf crops are derived from ET programs (AAA, 2024; AHA, 2024).

The seedstock sector, though small in scale, plays a critical role in genetic dissemination. In the U.S., only 5.9% of cow-calf operations are exclusively seedstock producers, with an additional 16.9% raising both seedstock and commercial cattle (USDA-APHIS, 2020). This minority of operations supplies virtually all the herd bulls and semen used in the cow-calf sector, underlining the sector's strategic importance.

Current Status of the Seedstock Industry

Assuming an estimated bull replacement rate of 20 to 25%, the U.S. seedstock sector must supply approximately 400,000 new bulls annually to replace culled sires in a national inventory of over 2 million bulls (USDA-NASS, 2024).

Angus remains the dominant breed in bull sales. The AAA registered 302,716 calves in 2024 and recorded 141,378 ownership transfers, most of which were bulls (AAA, 2024). Hereford ranks among the top breeds as well, with 7,182 bulls sold at an average of \$6,751 in 2024 (AHA, 2024). Red Angus follows, with strong representation across Western Canada and the U.S. Plains. Yearling bulls, when properly managed, can successfully service 15 to 25 cows in their first season (Kniffen and Comerford, 2018).

Registrations serve as a proxy for bull supply. Angus registrations have remained consistently above 300,000 head over the past five years, reflecting breed stability and continued

demand (AAA, 2024). Hereford registrations also increased by 3.1% in 2023, with AHA members submitting nearly 37,000 DNA samples and over 7,000 bull transfers (AHA, 2024).

Bulls are the most economically impactful individuals in the herd as bulls will influence weaning weights, carcass value, and maternal traits for multiple years as their genetic contribution is 50 percent contribution per calf crop. Bulls routinely sell for approximately \$5,000 to \$7,000, with elite sires reaching much higher values (AAA, 2024; AHA, 2024). The economic return per bull can be substantial for both the bull seller and purchaser. Thompson et al. (2022) showed that birthweight, longissimus muscle area, and weaned calf value significantly impacted bull sale prices, while GE-EPDs improved EPD accuracy but were not consistently valued unless linked to economically relevant traits. Dhuyvetter et al. (1996) similarly found that sale price was influenced by breed, physical traits, and EPDs particularly birth weight and milk EPDs. Smith (2020) also reported that calving ease, growth, and stayability EPDs were strongly correlated with higher Red Angus bull prices. These studies underline that producers now assign economic value to objective genetic tools when making sire selection decisions.

Since seedstock herds provide the sires that drive genetic change in beef production systems, it is important to understand how bulls develop across life stages. This includes examining reproductive development, nutrient needs, and management strategies influencing bull growth and fertility.

Growth and Development of the Bull

Prepartum Development

In the developing bovine fetus, male reproductive differentiation begins around day 40 of gestation with the formation of seminiferous cords and the emergence of fetal Leydig cells (Wrobel, 2000; McGowan et al., 2018). This process is triggered by the expression of the SRY

gene on the Y chromosome, which directs the bipotential gonads to follow the male pathway. Testosterone production by fetal Leydig cells then supports the masculinization of internal (Wolffian ducts) and external genitalia (McGowan et al., 2018). Around this time, Leydig cells also produce insulin-like peptide 3 (INSL3), which initiates testicular descent. This occurs in two phases: a transabdominal phase driven by INSL3 between days 80 and 90, and a second inguinoscrotal phase that depends on androgens and concludes near day 120 (McGowan et al., 2018; Menzies et al., 2024). By the time of parturition, the testes are fully descended into the scrotum, and while structurally developed, the seminiferous cords remain inactive with no ongoing spermatogenesis (Wrobel, 1990; Curtis and Amann, 1981).

Throughout fetal development, seminiferous cords are composed of immature Sertoli cells and quiescent germ cells (prespermatogonia) that will not become active until after birth (Wrobel, 2000). The number of Sertoli cells established during this period are critical, as they ultimately set the foundation for sperm production capacity in the mature bull. This makes maternal nutrition a key factor in determining a bull's reproductive potential (Bielli et al., 2002; Sullivan et al., 2010; Bollwein et al., 2016; McCoski et al., 2021).

Sullivan et al. (2010) reported that in Senepol-influenced crossbred heifers (35% BeefX: $\frac{1}{2}$ Senepol, $\frac{1}{4}$ Brahman, $\frac{1}{8}$ Charolais, $\frac{1}{8}$ Red Angus; 65% CBX: $\frac{1}{2}$ Senepol, $\frac{1}{4}$ Brahman, $\frac{1}{4}$ Charolais), reduced protein and energy intake during early gestation increased FSH and testicular development measures in prepubertal bull calves, whereas elevated dam nutrition in the first trimester impaired testicular growth. Contrasting findings in sheep have shown that undernutrition during gestation reduces Sertoli cell numbers in the fetal testis (Bielli et al., 2002). In Santa Gertrudis heifers, Copping et al. (2018) found that a low-protein diet during peri-

conception delayed puberty, reduced semen quality, and altered testicular histology in bull progeny, effects linked to suppressed FSH.

Postpartum to Weaning

At birth, the bull's testes contain only immature germ cells (prespermatogonia) and undifferentiated Sertoli cells. For the first few weeks after birth, testicular growth is minimal, and the prespermatogonia remain quiescent until about 4 weeks of age (Wrobel, 2000). This early period reflects the still-developing hypothalamic-pituitary-gonadal (HPG) axis, with low levels of circulating gonadotropins such as LH and FSH. Around one month of age, however, both endocrine and testicular activity begin to increase.

Bull calves experience a distinct rise in LH and FSH during early postnatal life. Luteinizing hormone levels tend to peak around 12 to 16 weeks, followed by a decline near 6 months (Rawlings et al., 2008). Following a similar pattern FSH drops back to baseline by about 25 weeks.

This neonatal phase is characterized by early HPG axis activation. Secretion of GnRH becomes more pulsatile within the first month of life, stimulating gonadotropin release and supporting Leydig and Sertoli cell development (Rawlings et al., 2008). Testosterone begins to rise gradually around 5 to 6 months of age, laying the foundation for puberty.

Structurally, the testes develop rapidly during this period. Between 4 and 15 weeks, seminiferous tubules expand, roughly doubling in diameter as prespermatogonia resume mitosis (Wrobel, 2000). Sertoli cells proliferate under FSH stimulation, which is crucial since the number of Sertoli cells largely determine future sperm production capacity (Barth et al., 2008). A second peak in germ cell proliferation is often observed by 18 to 20 weeks of age (Wrobel, 2000). At this stage, the seminiferous tubules are typically 100 to 120 μm in diameter but still

lack a lumen, and spermatogenesis has not yet begun. Sertoli cells complete their final transformation and exit the cell cycle around 5 to 6 months, finalizing the bull's future sperm-producing potential (Rawlings et al., 2008).

Management during this time plays an important role. Nutritional inputs between 2 and 6 months of age can have lasting effects on testicular development and puberty timing. For example, Brito et al. (2007) showed that bulls fed a high-energy diet (barley silage base with 18 to 22% rolled barley, canola oil, and canola meal; 15 to 21% CP, 1.74 to 1.82 Mcal/kg NE_m, 1.12 to 1.19 Mcal/kg NE_g) reached puberty earlier and developed larger testes compared with bulls on a control diet (barley silage with 8% rolled barley, 13.5% CP, 1.57 Mcal/kg NE_m, 0.98 Mcal/kg NE_g). Similarly, Dance et al. (2015) reported that enhanced early nutrition (from 1 to 7 months) resulted in earlier increases in LH, FSH, and IGF-I, leading to earlier puberty by about 45 days. On the other hand, feed restriction even if temporary has been shown to delay GnRH/LH secretion and testis development (Brito et al., 2007). Moura and Erickson (1997) also noted that elevated pre-weaning FSH was associated with smaller testes and fewer Sertoli cells by one year of age.

The early LH surge seems to influence how soon puberty occurs. Evans et al. (1995) found that bulls reaching puberty around 41 to 42 weeks of age had higher LH concentrations during wk. 12 to 17 compared to their later-maturing counterparts. In short, stronger early hormonal responses may help accelerate sexual development.

By the typical weaning age of six months, testicular weight has tripled since birth, though spermatogenesis remains incomplete. Immature spermatogonia are still present, and full spermatogenic activity typically does not begin until 32 to 40 weeks of age (Rawlings et al.,

2008). As Leydig and Sertoli cells mature, hormonal output declines due to increased negative feedback, especially from inhibin and testosterone (Bollwein et al., 2016).

Postweaning to First Service

Following weaning (typically between 6 and 8 months of age), bull calves enter a period of rapid reproductive development that continues until their first service, often around 12 to 15 months (Brito et al., 2012; Bollwein et al., 2016). Although little testis growth occurs earlier in calfhood, a noticeable surge in testicular size begins around six months and continues through puberty, after which the rate of growth slows as the bull reaches sexual maturity (Rawlings et al., 2008).

This developmental phase is closely tied to changes in hormone production. After an earlier, temporary rise in LH and testosterone during the prepubertal period (roughly 2 to 5 months), hormone levels begin to increase again as puberty approaches (Rawlings et al., 2008). Bulls from *bos taurus* breeds usually reach puberty between 10 and 12 months under good management, though individual variation exists (Evans et al., 1995). In contrast, *bos indicus* bulls tend to mature later, often between 18 and 24 months (Moura and Erickson, 1997). Puberty in bulls is typically defined by the first ejaculate containing at least 50 million sperm with at least 10% progressive motility (Wolf et al., 1965).

However, it's important to distinguish between reaching puberty and achieving full fertility. Although some bulls begin producing sperm by 10 to 12 months, semen quality is often inconsistent during this time. During the early post-pubertal period, bulls often produce sperm with morphological abnormalities, most commonly proximal cytoplasmic droplets located at the neck of the sperm or detached heads (Moura and Erickson, 1997). These defects typically decline over the following month or two as testicular and epididymal functions continue to mature

(Rawlings et al., 2008). Full sexual maturity is generally considered to be reached when $\geq 70\%$ of sperm in an ejaculate are morphologically normal, which may not occur until several weeks after puberty (Arteaga et al., 2001).

Arteaga et al. (2001) evaluated semen quality and scrotal circumference in 1,641 yearling beef bulls across 14 breeds between 11 and 15 months of age. Criteria for a satisfactory spermiogram included $\geq 400 \times 10^6$ sperm/mL, $\geq 60\%$ progressive motility, and $\geq 70\%$ morphologically normal sperm. The proportion of bulls achieving satisfactory spermiograms was 20% at 11 months, 30% at 12 months, 51% at 13 months, 52% at 14 months, and 61% at 15 months of age. Mean scrotal circumference increased steadily with age (33.4 cm at 11 months to 35.8 cm at 14 months) and was strongly correlated with the proportion of bulls achieving $\geq 70\%$ normal sperm. The most common defects in immature bulls included proximal droplets and midpiece abnormalities. Data from Arteaga et al. (2001) indicate that only a minority of bulls have mature semen quality by 12 months of age, whereas just over half reach acceptable standards by 14 to 15 months. Lunstra et al. (1978) found that 11 to 13-month-old bulls were capable of breeding females but had limited-service capacity. Bull breeding capacity is commonly estimated as one cow per month of age, meaning a 12-month-old bull can manage to breed approximately 12 cows (Barth et al., 2008). These findings, along with Lunstra et al. (1978), indicate that although some bulls are capable of breeding by 11 to 13 months, service capacity is limited, and yearlings under 15 months should be managed conservatively in breeding programs.

Behavioral and physical readiness also influence breeding success in bulls 10 to 18 months of age. Chenoweth (1981) observed that younger bulls tend to have lower libido and less physical endurance than mature bulls, especially when housed in multi-age groups. Younger

bulls are often socially subordinate to older bulls, which can reduce their opportunity to breed. For this reason, it is usually recommended to group bulls by age and size during early breeding seasons to ensure more even reproductive opportunities.

By 15 to 18 months, most well-managed bulls that have developed normally will pass a breeding soundness evaluation (BSE) with $\geq 30\%$ motile and $\geq 70\%$ morphologically normal sperm, along with an appropriate SC (Barth et al., 2008). However, even at this stage, bulls are still considered to be in the process of reproductive development and may not yet have reached full reproductive capacity.

First Service to Maturity

After their first breeding season, bulls continue to develop reproductively until approximately 3 to 4 years of age (Amann and Walker, 1983). During this time, testicular size, daily sperm production, and sperm reserves increase significantly. For example, a yearling bull typically produces 4 to 5 billion sperm per day, while a fully mature bull can produce 7 to 9 billion (Moura and Erickson, 1997). Epididymal storage capacity also improves with age; bulls around 15 months may store only 1.5 to 2 days' worth of sperm, compared to 4 to 5 days' worth by age two (Rawlings et al., 2008).

By about 24 months, most bulls reach near-adult scrotal circumference (SC) and semen quality. Sperm abnormalities such as proximal droplets usually decline as spermatogenesis stabilizes. Arteaga et al. (2001) reported that most bulls reach $\geq 70\%$ morphologically normal sperm by 16 months, although some may require additional time, up to 18 months. By the second breeding season, around two years of age, bulls are typically considered sexually mature and capable of settling more cows.

Development continues into the fourth year of life. Amann and Walker (1983) observed that testicular growth and hormonal function may still be increasing until this point. Long-term fertility potential is also influenced by earlier management. For example, Coulter et al. (1987b) found that postweaning nutrition and growth rate affected final testis size and sperm production. Barth et al. (2008) cautioned that over conditioning can reduce semen quality, largely due to increased testicular fat and heat stress.

By 3 to 4 years of age, bulls typically reach full reproductive capacity. Fertility defined as the ability to successfully impregnate cows is highest during this period assuming the bull is healthy and properly managed. However, a bull that passes a BSE at 15 months may still fall short in the field if issues like poor libido, conformation faults, or subclinical health problems are present (Chenoweth, 2004). For this reason, many breeding programs include not only BSEs but also assessments of serving capacity to ensure bulls are fully capable of contributing to herd fertility.

Postweaning Bull Growth & Development

Performance Testing and Implications on Genetic Advancement

Bull performance testing emerged prominently in the mid-20th century, driven by the need for objective evaluation of postweaning growth and genetic improvement in beef cattle. Early U.S. bull test programs began in the 1950s, with key stations such as Auburn University's Alabama Agricultural Experiment Station (1951), California Polytechnic State University (1956), and Montana's Midland Bull Test (1962). These programs established standardized evaluations focusing primarily on average daily gain (ADG), feed conversion efficiency, and weight-for-age (Patterson et al., 1982). Emphasis on these traits was due to their economic importance and moderate-to-high heritability, offering genetic advancement opportunities.

Arthur et al. (2001) reported moderate heritabilities ($h^2 = 0.28-0.40$) for feed intake and efficiency traits, validating residual feed intake (RFI) as an effective selection trait. Schenkel et al. (2004) confirmed moderate heritability for RFI and negligible genetic correlations with growth rate or body size, suggesting that selection for feed efficiency would not compromise growth performance. However, pre-test management, especially early-life nutrition, significantly impacts test outcomes, underscoring the need to account for these factors in evaluations (Schenkel et al., 2004; Awda et al., 2013).

The integration of performance testing into breed association evaluations and national cattle breeding strategies transformed industry selection practices, emphasizing measurable traits over visual appraisal alone (Patterson et al., 1982). Performance-tested bulls, particularly those with superior growth and efficiency traits, became influential in genetic progress across the beef cattle industry.

Current Industry Management Practices

Current bull development and testing practices emphasize breed-specific growth and management strategies. Brito et al. (2004) documented notable differences between *Bos indicus* and *Bos taurus* breeds, with *Bos taurus* breeds such as Angus, Hereford, Simmental, and Charolais typically reaching puberty earlier (11 to 13 months) and achieving targeted scrotal circumferences sooner. These breeds are commonly featured in North American centralized test stations, which utilize moderate-to-high energy diets to support target growth rates of approximately 1.2 to 1.6 kg/d.

Feed efficiency, particularly residual feed intake (RFI), has become economically critical due to feed costs comprising a substantial portion of total beef production expenses (Basarab et al., 2003). Selecting for low RFI can significantly reduce feed costs; however, potential fertility

implications exist, as highly feed-efficient bulls sometimes exhibit reduced sperm motility and smaller scrotal circumferences (Awda et al., 2013). Nevertheless, balanced selection can mitigate these concerns, optimizing both efficiency and reproductive performance (Wang et al., 2012).

Nutritional management strategies aim for controlled growth to achieve optimal body condition (approximately a score of 6 out of 9) at breeding season onset. Excessive dietary energy intake is linked to reduced semen quality and fertility issues due to increased scrotal fat deposition (Coulter et al., 1997). Thus, moderate feeding programs that balance growth performance with reproductive soundness are essential (Barth, 2012)

Technological advances, including automated feed intake measurement systems (e.g., GrowSafe® or Insentec®) and genomic testing, have enhanced the accuracy and predictive power of bull evaluations. These technologies facilitate precise measurement of traits such as RFI and enable reliable predictions of growth and reproductive traits early in life (Vytelle, 2021).

Dietary Philosophies

Feeding strategies for postweaning bull development typically involve either high-energy concentrate-based systems or forage-based moderate-energy diets, with each having significant implications for growth, reproductive development, and fertility outcomes. Concentrate-based diets prioritize rapid growth and early puberty, allowing bulls to achieve desirable sale weights at younger ages (Brito et al., 2012). These diets commonly provide approximately 60 to 70% total digestible nutrients (TDN) and 12 to 14% crude protein on a dry matter basis, promoting accelerated weight gains (Bourgon et al., 2018).

However, aggressive high energy feeding carries reproductive risks. Coulter and Kozub (1984) demonstrated impaired spermatogenesis in bulls on high-energy diets composed of 80% concentrates manifesting as reduced epididymal sperm reserves and increased abnormal sperm

morphology. Furthermore, Coulter et al. (1997) identified elevated scrotal temperatures and increased scrotal fat deposition as significant factors negatively impacting semen motility in grain-fed bulls. Barth et al. (2008) similarly noted that although high-nutrition diets increase BW and SC, these increases frequently reflect increased fat deposition rather than actual testicular tissue growth, potentially misleading breeding evaluations.

Seekford et al. (2023) provided contemporary evidence that subclinical reproductive impairments, such as reduced embryo viability, can occur in bulls maintained on high-gain diets, despite normal semen morphology. Their findings underscore the subtle fertility risks associated with prolonged grain-heavy feeding, further supporting the need for moderate dietary management in developing bulls.

Conversely, forage-based or moderate-energy diets emphasize slower, steadier growth aimed at enhancing skeletal soundness, long-term reproductive fitness, and overall bull longevity (Brito et al., 2012; Coulter et al., 1997). Bulls managed on forage-based diets generally demonstrate lower incidence of joint and foot problems, and consistently high semen quality (Barth et al., 2008). However, the slower growth rates inherent to forage-based systems often result in delayed puberty and smaller SC at yearling evaluation, necessitating later marketing ages to achieve competitive breeding readiness (Coulter et al., 1987; Brito et al., 2012).

Although nutrition is a major driver of reproductive development, several additional factors influence bull fertility. These include age, breed, environment, and management conditions, which interact to determine breeding soundness and reproductive efficiency.

Factors Influencing Bull Fertility

Age

Bull fertility is closely linked to age-related physiological development, particularly during the postweaning phase leading to first service. Puberty in beef bulls is defined as the first ejaculate containing at least 50×10^6 total sperm with at least 10% progressive motility (Wolf et al., 1965). Age at puberty varies by breed, but SC at puberty is remarkably consistent around 28 cm across bos taurus breeds (Lunstra and Echternkamp, 1982).

Semen quality continues to improve after the initial attainment of puberty. Lunstra and Echternkamp (1982) found that progressive motility and normal head morphology increase significantly during the first 6 to 16 weeks post-puberty, while proximal cytoplasmic droplets decline. Fields et al. (1979) further demonstrated that older yearling bulls (closer to 18 months) produce higher quality semen and greater sperm counts than younger contemporaries at 12 months, reinforcing the benefit of additional age and sexual maturity on fertility outcomes.

In Bos indicus and indicus-cross bulls, puberty occurs later, typically between 360 and 460 days of age, though semen quality improves similarly with advancing age (Brito et al., 2004). Brito et al. (2012) showed that although BW and testicular size at weaning influenced the timing of puberty, most bulls required several weeks beyond initial puberty to reach semen quality thresholds necessary for successful breeding. Murphy et al. (2018) confirmed in Holstein bulls that semen production and motility substantially improved as bulls matured from 12 to 15 months, with yearlings showing markedly better fertility potential than calves under 1 year of age. Collectively, these studies emphasize that while achieving puberty is a key developmental milestone, bulls continue to undergo critical testicular maturation over several months. Age at

first service should allow for sufficient post-pubertal development to optimize semen quality and breeding soundness.

Breed

Breed differences profoundly influence bull fertility traits, particularly puberty timing, testis size, sperm production, and breeding soundness outcomes. *Bos taurus* bulls, such as Angus and Hereford, generally reach puberty earlier than *Bos indicus* bulls, such as Brahman and Nellore, when reared under similar conditions (Godfrey et al., 1990). Lunstra and Echternkamp (1982) reported that age at puberty varied widely among *Bos taurus* breeds for example, Hereford bulls reached puberty around 326 days, while Brown Swiss bulls attained it as early as 264 days although SC at puberty remained consistent at 28 cm.

Brahman-sired bulls were significantly older and heavier at puberty than Hereford or Angus contemporaries (Godfrey et al., 1990; Lunstra and Cundiff, 2003). Brahman bulls exhibited smaller SC and testis volumes at similar ages, especially when reared outside tropical environments (Godfrey et al., 1990). Similarly, Chase et al. (2001) observed that Brahman × Angus bulls reached puberty later and had lower libido scores compared to Senepol × Angus and Tuli × Angus bulls.

Within *Bos taurus* breeds, differences also emerge. Coulter et al. (1987a) showed that Simmental bulls generally possessed larger SC at two years of age compared to Angus and Hereford bulls, reflecting breed differences in frame size and testis mass. These differences have practical implications for breeding soundness evaluations, as SC minimums are breed-adjusted to account for inherent genetic variation.

Nutrition

Postweaning nutrition plays a crucial role in shaping bull reproductive development, affecting puberty timing, testis growth, semen quality, and breeding soundness. Adequate energy and protein intake during the critical postweaning growth phase is essential to support the hormonal and cellular changes necessary for puberty and optimal fertility.

High-energy diets generally promote earlier puberty onset by stimulating earlier LH and testosterone surges, larger testis growth, and earlier sperm production. Barth et al. (2008) reviewed multiple studies and concluded that superior postweaning nutrition enhances Sertoli cell proliferation and accelerates testicular growth, key components of sperm-producing capacity. Brito et al. (2012) similarly demonstrated that bulls achieving higher growth rates between 6 and 16 months had larger testes and slightly earlier puberty without compromising semen quality.

However, excessively high-energy diets can be detrimental. Mwansa and Makarechian (1991) reported that bulls on very high-energy postweaning diets developed a larger SC but produced semen with lower motility and more abnormalities compared to bulls on moderate diets. Coulter et al. (1997) found that bulls on high-energy rations accumulated excess scrotal fat, leading to elevated scrotal temperatures and impaired sperm quality.

Beyond energy and protein, mineral nutrition, particularly trace elements like zinc and selenium, is vital for male fertility. Kumar et al. (2006) demonstrated that zinc supplementation improved semen volume, sperm concentration, motility, and testosterone levels in crossbred bulls. Selenium supplementation has been shown to enhance sperm motility and reduce oxidative damage in bull semen (Pratt et al., 1980). These minerals are essential for maintaining sperm membrane integrity, DNA stability, and antioxidative defense systems.

Ultimately enhanced nutrition can accelerate sexual maturation and reproductive potential. Development programs should balance energy and protein supply to promote early testicular growth without inducing excessive fattening, while ensuring adequate mineral supplementation to optimize semen quality and long-term fertility.

Environment

Environmental factors notably heat stress, photoperiod, and housing conditions significantly influence bull fertility by affecting testicular function, semen quality, and overall breeding performance. Heat stress is one of the most detrimental challenges, elevated ambient temperatures impair scrotal thermoregulation and raise testicular temperature, disrupting spermatogenesis and reducing semen quality (Morrell, 2020). A recent study by Netherton et al., (2022) suggest that high temperatures can depress bull semen quality. Semen from the same bulls had approximately 90% acceptable cryopreservation “pass” rates in winter but fell to under 50% during summer; furthermore, individual bulls could be categorized as “heat-sensitive,” showing severe fertility impairment in hot conditions (Netherton et al., 2022). Studies reviewing scrotal insulation provide a physiological explanation: bulls exposed to acute scrotal heating exhibited altered Sertoli and Leydig cell function, with reduced testosterone secretion even before any visible decline in semen parameters, indicating that endocrine disruption precedes sperm quality declines under heat stress (Ferrer et al., 2022). Managing thermal environment via shade, ventilation, and cooling is therefore critical for preserving bull reproductive potential, especially during the sensitive post-weaning development period.

Photoperiod also modulates bull reproductive development. Tatman et al. (2004) observed that Brahman bulls born in the fall (short daylength) reached sexual maturity later than spring-born cohorts, due to a longer interval between puberty and full sexual maturity for fall-

born bulls. Even under intensive management, seasonal photoperiodic effects persist. Murphy et al. (2018) and Valeanu et al. (2015) both documented seasonal variation in semen output and quality in AI center bulls. In their findings, colder winter months were associated with lower total sperm output, yet sperm from winter collections often exhibited higher post-thaw motility or viability compared to summer collections. These patterns suggest that both light exposure and ambient temperature changes subtly regulate testicular function and semen characteristics across the year. Effective environmental management controlling heat and providing appropriate lighting and housing is therefore essential to optimize young bulls' fertility.

To effectively evaluate these multifactorial influences on reproductive potential, standardized assessments are needed. The Breeding Soundness Examination (BSE) serves as a practical, widely accepted tool to screen bulls for fertility prior to the breeding season

Breeding Soundness Examinations

Development and Implementation of the Exam

Breeding soundness examinations were developed in the mid-20th century in response to concerns over bull infertility affecting herd productivity. A notable catalyst was the severe Colorado blizzard of 1949, after which roughly 10 to 12% of healthy bulls were found to have subfertile or unsatisfactory semen upon testing (Youngquist, 2014). This discovery underscored the need for a standardized bull fertility exam. In 1953, the first regional bull testing program, the Colorado Bull Testing Service was established to systematically evaluate breeding bulls (Youngquist, 2014). Veterinarians and ranchers soon organized the Rocky Mountain Society for the Study of Breeding Soundness of Bulls in 1954, which evolved into the American Veterinary Society for the Study of Breeding Soundness in 1963 and ultimately became the Society for Theriogenology (SFT) in 1974 (Youngquist, 2014).

Early summary data on BSE outcomes further validated the need for such exams. Carroll et al. (1963) surveyed 10,940 bull exams and found that approximately 10% of bulls were unsatisfactory breeders. Through the 1960s-80s, BSE criteria gradually evolved. In 1993, the Society for Theriogenology formally adopted revised BSE guidelines that replaced subjective scoring with minimum thresholds for SC, progressive motility, and sperm morphology (Hopkins and Spitzer, 1997).

Large field studies supported the practical value of these standards. Kennedy et al. (2002) reported that only about 76% of 3,648 yearling bulls met all BSE criteria under the 1993 system, while the rest were classified as unsatisfactory or deferred. This demonstrated that BSEs effectively identify sub fertile bulls before they can reduce herd fertility. Today, the SFT oversees these guidelines, and their application is widespread across the U.S. and internationally.

Components of the Exam

The BSE includes four major components: general physical examination, SC measurement, semen motility assessment, and sperm morphology evaluation (Hopkins and Spitzer, 1997; Society for Theriogenology, 2016).

1. General Physical Examination: This evaluates the bull's health, especially systems affecting breeding ability such as the eyes, teeth, sheath, penis, and general body condition. Bulls with lameness, poor vision, or structural defects may be disqualified from breeding regardless of semen quality (Barth and Waldner, 2002).
2. Scrotal circumference is a reliable indicator of testicular size and sperm production. Measurements are age-adjusted: minimums include ≥ 30 cm at 12 to 15 months, ≥ 31 cm at 15 to 18 months, and ≥ 34 cm for bulls over 24 months. Scrotal circumference also correlates with earlier puberty in female offspring (Hopkins and Spitzer, 1997; Barth et al., 2008).

3. Semen Motility: Collected via electroejaculation or artificial vagina, semen must exhibit $\geq 30\%$ progressive motility. Motility reflects the sperm's ability to travel through the female reproductive tract and fertilize the oocyte.
4. Sperm Morphology: At least 70% of sperm must have normal morphology to pass. Evaluation includes assessment of head, midpiece, and tail defects using staining and microscopy. Abnormalities like proximal droplets or detached heads reduce fertilization capacity (Kennedy et al., 2002).

Although not required for minimum classification, some evaluations also include libido and serving capacity testing. These behavioral assessments help predict bull performance in multi-sire pastures, where social hierarchy and sexual aggressiveness can affect conception rates (Palmer, 2016).

Additionally, advancements like computer-assisted semen analysis (CASA) systems, reproductive tract ultrasonography, and genomic testing are being explored as adjunct tools to increase diagnostic accuracy and improve bull selection in seedstock operations (Fordyce et al., 2006; Palmer, 2016).

While the BSE provides a snapshot of a bull's fertility status, it does not function in isolation. Nutritional management post-weaning plays a foundational role in determining the physical and reproductive development measured during these examinations.

Nutrient Requirements of Growing and Mature Bulls

Water

Water is a critical nutrient for bulls across all physiological stages. According to the 2016 NASEM, water intake in beef bulls is primarily influenced by body weight, DMI, ambient temperature, and physiological status. For growing beef bulls weighing approximately 364 kg,

daily water intake ranges from about 29.9 liters at moderate ambient temperatures (14.4°C) up to approximately 56.8 liters under hot conditions (32.2°C). Mature bulls, due to their greater body mass and increased feed intake, require even higher quantities; a bull weighing around 727 kg may consume approximately 40.9 liters per day at moderate temperatures (14.4°C), increasing to approximately 78 liters daily under hot weather conditions (32.2°C; (NASEM, 2016).

Diet composition also significantly influences water consumption. Bulls fed high-forage diets typically consume more water compared to those fed high-concentrate diets, due to increased fiber content and lower moisture levels in forage-based diets (NASEM, 2016).

Brew et al. (2011) studied water intake specifically in growing beef cattle under controlled conditions, reporting an average water intake of about 30 liters per day for bulls gaining approximately 1.4 kg daily. Their findings indicated no significant differences between sexes regarding water consumption per unit of metabolic body weight, suggesting general water intake prediction models for steers and heifers can be effectively applied to bulls.

Dry Matter Intake

Dry matter intake fundamentally determines nutrient supply and growth performance in beef bulls. Multiple factors, including physiological status, diet composition, and body weight, influence voluntary feed intake in cattle (NASEM, 2016). Post-weaning bulls typically consume between 2.5 to 3.0% of their body weight per day, though actual intakes vary with dietary energy levels, environmental conditions, and animal-specific factors (Block et al., 2001; Anele et al., 2014).

Physiological regulation of feed intake involves metabolic feedback related to body composition. Increased adiposity, for example, negatively impacts intake through metabolic signaling mechanisms such as leptin production. Fox et al. (1988) demonstrated that a 1%

increase in body fat could decrease voluntary intake by approximately 2.7%. This suggests effective body condition management is crucial for maintaining optimal feed intake in growing beef bulls (Fox et al., 1988; NASEM, 2016). Additionally, sex differences in DMI are notable, with bulls generally having slightly lower feed intake capacities compared to heifers and steers at lighter body weights (Ingvarsen and Andersen, 1992).

Dietary composition significantly affects voluntary intake due to its influence on both ruminal fill and metabolic energy demand (Mertens, 1987). Forage-based, high-fiber diets tend to restrict intake through physical rumen fill, whereas high-energy diets with lower fiber content enable greater consumption regulated more by metabolic demand (Ketelaars and Tolkamp, 1992; NASEM, 2016). Dietary energy concentration and digestibility thus play central roles in determining the actual feed intake bulls achieve (Block et al., 2001; Anele et al., 2014).

Management strategies aiming at optimized intake must consider these multiple interacting factors, such as diet formulation, energy density, and physiological state, to support desired growth and reproductive development in beef bulls (Anele et al., 2014; NASEM, 2016).

Energy

Energy requirements in bulls differ from other sex classes due to greater lean tissue accretion, larger organ mass, and higher activity levels. Cabezas-García et al. (2021) indicated that maintenance energy requirements in bulls typically exceed those in steers by approximately 10 to 15%. According to the NASEM, (2016), bulls require approximately 0.077 Mcal per $SBW^{0.75}$ of net energy for maintenance (NE_m), with further adjustments based on physical activity and environmental conditions. NASEM (2016) provides nutrient requirement examples for growing bulls based on a mature SBW of 900 kg. For instance, a 400-kg bull gaining 1.2 kg/d

requires about 9.2 Mcal of NE_m, 3.8 Mcal of NE_g, and 859 g of MP, while a 600-kg bull at the same gain requires 13.7 Mcal of NE_m, 4.5 Mcal of NE_g, and 1,042 g of MP NASEM (2016).

Protein

Protein is a critical nutrient for the growth and reproductive development of beef bulls. (NASEM, 2016). The 2016 NASEM provides recommendations on a MP basis, which accounts for ruminal degradation and intestinal absorption of dietary protein (NASEM, 2016). For growing bulls gaining approximately 0.8 kg per day, MP requirements range from 700 to 800 grams per day depending on diet energy density and body weight. These values typically correspond to diets containing 11 to 12.5 percent crude protein. For mature bulls at maintenance, MP needs decline to approximately 400 grams per day, which can be met by rations containing as little as 8 percent crude protein, provided that intake is adequate. Diets containing less than 7 percent CP are known to impair fiber digestibility and reduce dry matter intake due to insufficient nitrogen supply for ruminal microbes (NASEM, 2016).

Breed differences in protein utilization may exist. Gomes et al. (2017) reported that Angus bulls had slightly higher MP requirements than Nellore bulls under similar conditions, attributed to their greater lean tissue gain and higher metabolic rate. Although the absolute differences were modest, the study highlights that protein efficiency may vary among genotypes and should be considered when formulating rations for different breeds.

Rekwot et al. (1987) examined the effect of protein intake on the onset of puberty in Bunaji and Friesian × Bunaji crossbred bulls. Animals fed isocaloric rations containing either 14.45 percent or 8.51 percent CP were monitored for 16 months. Bulls on the high-protein diets reached puberty significantly earlier than those on the low-protein diets. In Bunaji bulls, mean age at puberty was 14.8 months for the high-protein group and 15.5 months for the low-protein

group. Among crossbreds, puberty occurred at 12.9 months for the high-protein group compared to 17.8 months for the low-protein group. Bulls on higher-protein diets also had improved sperm motility and body condition at puberty, although they were lighter and had smaller SC than their low-protein counterparts at that point.

Complementing these findings, Rekwot et al. (1988) evaluated how dietary protein level influenced SC, BW, and semen characteristics in Bunaji and Friesian × Bunaji crossbred bulls. Bulls fed higher-protein diets exhibited increased scrotal SC, improved semen quality, and greater BW than those on protein-deficient rations. These data indicate that dietary protein not only affects the timing of reproductive maturity but also influences the structural and functional development of the reproductive tract.

Minerals

Minerals are essential nutrients that support growth, metabolic function, and reproductive development in beef bulls. While mineral requirements for bulls are broadly similar to those for other classes of beef cattle, they vary based on physiological state, rate of gain, and feed intake. According to the NASEM, (2016), mineral nutrition should be formulated to meet, but not exceed, the recommended levels, as both deficiency and excess can impair performance and fertility.

Among the macrominerals, Ca and P are critical for skeletal development and metabolic function. For growing bulls, dietary concentrations of 0.5 to 0.6 percent Ca and approximately 0.3 percent P on a DM basis are recommended. For mature bulls at maintenance, requirements are reduced to approximately 0.2 percent Ca and 0.16 percent P, assuming adequate feed intake (NASEM, 2016). Magnesium is required at approximately 0.10 percent of dietary DM and plays a role in neuromuscular function and enzyme activity. Potassium is important for osmotic

balance and acid-base regulation, with growing bulls typically requiring around 0.6 percent dietary K. Bulls consuming forage-based diets may require less, depending on forage mineral composition (NASEM, 2016).

Sodium and chloride are recommended at 0.10 percent and 0.05 percent of DM, respectively, to maintain electrolyte balance and support hydration and nerve function. Sulfur is required at 0.15 percent, though elevated concentrations can interfere with Cu metabolism by promoting thiomolybdate formation in the rumen, thereby reducing Cu absorption (NASEM, 2016).

Trace mineral requirements are quantitatively small but biologically significant. Zinc is required at 30 milligrams per kilogram of dietary dry matter and plays an essential role in spermatogenesis, cellular replication, and testosterone production (NASEM, 2016). In a controlled study, Kumar et al. (2006) found that Zn supplementation improved semen quality and increased serum testosterone levels in crossbred bulls consuming Zn -deficient diets, underscoring the importance of Zn sufficiency for reproductive development.

Copper is required at 10 milligrams per kilogram of dietary dry matter. Geary et al. (2021) evaluated the effects of trace mineral supplementation, including Cu, Zn, and Mn, on bull fertility traits. They observed no improvements in traditional breeding soundness traits when minerals were supplemented above recommended levels, though some benefits were noted in sperm viability under oxidative stress conditions. These findings support meeting, but not exceeding, Cu requirements in bulls consuming well-balanced diets (NASEM, 2016).

Selenium is required at 0.10 milligrams per kilogram of dry matter and supports antioxidant function and sperm membrane integrity (NASEM, 2016). Geary et al. (2021) similarly reported no improvement in fertility metrics when Se was supplemented beyond

requirement. Cobalt, Mn, I, and Fe are also required for enzyme function, thyroid hormone synthesis, and immune support. NASEM (2016) recommends 0.10 mg/kg of Co, 20 mg/kg of Mn, 0.5 mg/kg of I, and 50 mg/kg of Fe for growing bulls. Although these elements were not the focus of the cited studies, their physiological roles are well established and support their inclusion in properly balanced mineral programs.

Vitamins

Vitamin requirements for bulls, critical to reproductive function and overall health, have been clearly defined by NASEM (2016). Recommended dietary concentrations for vitamins include approximately 2,200 IU/kg dry feed for Vitamin A, 275 IU/kg dry feed for Vitamin D, and 35 IU/kg dry feed for Vitamin E. These recommended values ensure reproductive health, proper immune function, and adequate antioxidant status.

Vitamin A is particularly important due to its role in reproductive performance. Hodgson et al. (1946) reported severe reproductive impairments in bulls due to Vitamin A deficiency, including sterility, reduced libido, and irreversible reproductive tissue damage. Rode et al. (1995) further demonstrated that chronic dietary Vitamin A deficiency decreased sperm production, testes weight, epididymal sperm reserves, and sperm motility, highlighting the importance of adequate Vitamin A supplementation for optimal bull fertility. However, Rode et al. (1995) also noted that under typical feeding conditions, marginal or short-term deficiencies would have minimal lasting effects if quickly corrected through dietary re-alimentation.

Primary Nutrients Impacting Growth and Fertility

Protein

Protein is a critical nutrient for postweaning growth and reproductive development in beef bulls. Both the quantity and type of protein specifically the balance between RDP and RUP

can influence endocrine responses, testicular development, and fertility traits (NASEM, 2016; Schwab and Broderick, 2017). RDP serves as the primary nitrogen source for rumen microbes, enabling microbial protein synthesis, which contributes significantly to metabolizable protein supply (NASEM, 2016). RUP, in contrast, bypasses rumen degradation and is digested in the small intestine, directly supplying amino acids to the animal (Schwab and Broderick, 2017). The balance between these fractions is particularly important in growing bulls, where both tissue deposition and endocrine function rely on adequate amino acid availability (Brito et al., 2007; Johnson et al., 2019).

In terms of total protein intake, studies show that inadequate CP delays puberty and reduces sperm output, while higher protein levels support earlier sexual maturation. Rekwot et al. (1988) observed that bulls fed a 14.5% CP diet reached puberty earlier and had better semen quality than bulls fed 8.5% CP. Similarly, Dance et al. (2015) reported that a high plane of nutrition including increased protein during early growth advanced LH secretion, increased IGF-1 concentrations, and promoted earlier testicular development and puberty onset in Holstein bulls.

With respect to RUP, Rocha et al. (1995) compared fish meal (high RUP) and soybean meal (moderate RUP) in Brahman bulls and found that fish meal increased average daily gain but had no effect on age at puberty, scrotal circumference, or semen quality. Henley et al. (2020) found that distillers grains (also high in RUP) increased weight gain and fat deposition in yearling bulls.

However, protein quality and source can matter. Velasquez-Pereira et al. (1998) showed that gossypol-containing cottonseed meal reduced sperm motility, increased sperm defects, and lowered libido in Holstein bulls compared to those fed soybean meal. Vitamin E partially

mitigated these effects, highlighting the importance of protein source and antioxidant balance. Similarly, Chase et al. (1994) observed that whole cottonseed (high in free gossypol) delayed puberty and impaired seminiferous tubule architecture in Brahman bulls.

Physiologically, protein nutrition impacts Sertoli cell proliferation, testicular size, and hormone secretion. Brito et al. (2007) found that high-nutrition bulls exhibited more frequent LH pulses, higher IGF-1 levels, and earlier testosterone production, with IGF-1 explaining over 70% of the variation in scrotal circumference and testis volume. Dance et al. (2015) showed that a high-protein diet upregulated genes related to steroid biosynthesis and Sertoli cell maturation in Holstein bull testes.

Starch

Starch is a key nonstructural carbohydrate in ruminant diets and the principal energy source in concentrate based growing rations (Owens et al., 1986; NASEM, 2016). Its inclusion level, fermentability, and processing method can significantly affect postweaning growth, hormonal status, and reproductive development. In feeding programs, energy intake through starch rich diets is often manipulated by varying grain sources like corn vs. barley and processing such as steam flaking or dry rolling etc., which influence nutrient availability and ruminal fermentation (NASEM, 2016; DelCurto-Wyffels, 2021).

Energy rich rations consistently support faster ADG, feed efficiency, and earlier physiological maturity. For example, DelCurto-Wyffels et al. (2021) reported that steers fed high starch corn diets gained weight faster and reached heavier final weights compared to those fed barley. In contrast, Jørgensen et al. (2007) demonstrated that a lower starch diet (25% starch and straw) maintained similar gains but reduced the risk of liver abscesses and improved feed conversion, highlighting that starch excess can have metabolic drawbacks.

Reproductive development is also sensitive to energy supply. Bulls on higher energy postweaning diets often experience accelerated testis growth and earlier puberty, driven by increases in IGF 1, LH, and testosterone. Dance et al. (2015) showed that Holstein bulls on enhanced early life diets reached puberty approximately 45 days earlier with larger testis size. Byrne et al. (2017) observed similar hormonal shifts and fertility benefits in Holstein Friesians. In beef breeds, Pruitt et al. (1986) noted greater SC in bulls on higher energy diets, although age at puberty remained similar.

Starch driven increases in circulating glucose and insulin further support anabolic tone and testis development. Jorge Smeding et al. (2021) found that Charolais bulls fed high starch corn silage had greater plasma insulin and lower insulin sensitivity than grass fed controls, reinforcing the endocrine effects of dietary energy.

Fat

Fat supplementation in beef bull development programs primarily aims to increase dietary energy density, modify tissue fatty acid profiles, and influence reproductive performance (Byrne et al., 2017; Rossi et al., 2019; Gholami et al., 2011). The type of fat, particularly the balance between omega-3 (n-3) and omega-6 (n-6) polyunsaturated fatty acids (PUFAs) and the method of rumen protection determine both systemic absorption and physiological outcomes (Ngcobo et al., 2021). In ruminants, extensive ruminal biohydrogenation rapidly saturates most dietary unsaturated fatty acids, making fat source and protection strategy important for delivering bioactive n-3 PUFAs to the small intestine (Hess et al., 2008). Despite this, incomplete biohydrogenation still allows measurable flows of unsaturated fatty acids to the duodenum especially when supplemental fats are highly unsaturated or rumen-protected, supporting the potential to modify tissue lipids (Hess et al., 2008). Oilseeds such as flaxseed, soybeans, canola,

and sunflower are commonly used sources of unsaturated fatty acids. Flaxseed provides the highest concentration of ALA (18:3 n-3) among major oilseeds, whereas soybean and sunflower products are predominately linoleic acid (18:2 n-6). Hess et al. (2008) reported that whole oilseeds can partially protect PUFA from ruminal biohydrogenation, but this protection decreases as seeds are processed (e.g., rolling, grinding, or extruding), increasing ruminal exposure and saturation of unsaturated fatty acids. Byproduct feeds such as distillers grains, corn germ, and full-fat oilseed meals also supply moderate levels of PUFA. Distillers grains contain concentrated corn oil and are therefore high in linoleic acid (18:2 n-6), a result of starch removal during ethanol production (Schingoethe et al., 2009). Corn germ similarly provides substantial linoleic acid because it represents the lipid-dense portion of the kernel (Klopfenstein et al., 2008). Oilseed meals such as soybean or sunflower also contribute significant n-6 PUFA to ruminant diets (Hess, 2008). These ingredients consequently widen the dietary n-6:n-3 ratio unless paired with an n-3-rich source such as flaxseed or marine oils (Ponnampalam et al., 2001). Omega-3 fatty acids such as EPA and DHA are generally associated with improved sperm membrane fluidity, antioxidative protection, and better cryosurvival of sperm cells (Khoshniat et al., 2020; Kalo et al., 2022).

Recent studies show nuanced effects. Khoshniat et al. (2020) supplemented Holstein bulls with varying levels of rumen-protected linseed oil (high in ALA) and reported no difference in fresh semen parameters, but significant improvements in post-thaw motility, membrane integrity, and morphology. Similarly, Kalo et al. (2022) demonstrated that feeding bulls fish oil or flaxseed oil reduced ROS levels, improved membrane fluidity, enhanced acrosomal integrity, and increased blastocyst rates after IVF indicating a paternal carryover

effect. These benefits suggest that n-3 fatty acids enhance sperm cryotolerance and early embryo development without necessarily increasing fertilization rates.

Lipidomic studies confirm that bull sperm membranes are rich in long-chain PUFAs, especially DHA, which constitutes 55 to 60% of phospholipid fatty acids (Kelso et al., 1997). This high DHA content ensures optimal membrane flexibility, vital for sperm motility and survival during freezing. However, these unsaturated membranes are also prone to oxidative damage, necessitating robust antioxidant systems. Wathes et al. (2007) and Gulliver et al. (2012) explain that omega-3s can modulate prostaglandin pathways by reducing PGF₂α synthesis and may indirectly support steroidogenesis and anti-inflammatory balance in reproductive tissues.

Despite these physiological benefits, effects on overall fertility outcomes (e.g., pregnancy rates) remain inconsistent. Gulliver et al. (2012) noted that while omega-3s modulate markers like PGF₂α and embryo survival pathways, direct evidence for improved conception rates is limited. Rossi et al. (2019) and Byrne et al. (2017) found that although sperm membrane fatty acid profiles improved after PUFA supplementation, motility and morphology were often unaffected in vivo. Ultimately, the impact of fat supplementation depends on fat source, rumen protection, dose, duration, and bull maturity.

While dietary fatty acids play a known role in development, growth, and reproductive function, most research has focused on steers and heifers. Postweaning bull development remains underrepresented in the literature, despite this being a critical window for testicular growth, endocrine programming, and future fertility. Limited studies have evaluated the effects of omega-3 fatty acid supplementation on developing bulls, leaving a gap in our understanding of how these nutrients influence growth and reproductive outcomes.

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Chapter 2 - Effects of dietary inclusion of an omega-3 fatty acid-based supplement to developing beef bulls on growth and performance

Abstract

Two experiments were designed to evaluate including an omega-3 fatty acid-based supplement in the basal diet of developing bulls post-weaning. In both experiments, spring-born bull calves of either Angus, Simmental, or Hereford breeding were weaned in September and developed in an automated feed intake management system. Bulls were managed as common groups and individually fed from precision intake management bunks; thus individual bull was considered the experimental unit in both experiments. In experiment 1, in a completely randomized design, bulls ($n = 42$) were stratified by age and BW and randomly assigned to 1 of 3 treatments with 14 bulls per treatment: 0.0 (**CON**), 0.22 (**MOD**), or 0.43 (**HI**) kg per hd per day (DM basis) of an omega-3-based supplement added to a common corn silage and wet corn gluten feed-based growing diet. Dietary treatments began in December (352 ± 19 kg of initial BW; 292 ± 6.25 d of age) and were applied for approximately 60 d. Data were analyzed using the GLIMMIX procedure of SAS with significance declared at $P \leq 0.05$. Initial age and BW were similar among treatments ($P \geq 0.98$). Dry matter intake (DMI) did not differ ($P = 0.64$). Bulls on the **HI** treatment had greater ($P \leq 0.05$) daily gain compared to **CON** and **MOD**, although ending BW and gain-to-feed ratio did not differ ($P \geq 0.52$). Scrotal circumference (SC) and blood serum fatty acid levels were not influenced, however supplementation increased ($P = 0.03$) IMF% in (2.92) **MOD** and (2.97) **HI** compared to **CON** (1.64). LMA tended ($P = 0.06$) to larger in **MOD** (81.5 cm^2) compared to **CON** (73.5 cm^2) Rib fat did not differ ($P = 0.50$). In

experiment 2, bulls ($n = 39$, 332 ± 14 kg of initial BW; 291 ± 6.25 d of age) received the same supplementation treatments for 80 days applied to an isonitrogenous corn silage and dried distillers grain based diet. No treatment differences were detected for final BW ($P = 0.86$), average daily gain ($P = 0.49$), and DMI ($P = 0.39$). Feed efficiency tended to be different ($P = 0.08$), but SC was not impacted by dietary treatments ($P = 0.84$). There were no differences for IMF % ($P = 0.61$), LMA ($P = 0.62$), and Rib Fat ($P = 0.69$). Initial serum fatty-acid concentrations did not differ among treatments. By d 80, supplemented bulls had greater serum ω -3 concentrations and a lower ω -6: ω -3 ratio than controls ($P < 0.01$). MOD also showed higher total FA and SFA than **CON** ($P = 0.03$), with **HI** intermediate. No other fatty-acid classes differed ($P \geq 0.06$). Omega-3 supplementation altered performance outcomes in Exp. 1, but these responses were not evident in Exp. 2 when diets were isonitrogenous, indicating that differences were more likely related to dietary protein rather than omega-3 inclusion. Scrotal circumference and intake were not affected in either experiment. Overall, moderate inclusion of this omega-3 supplement did not meaningfully change growth or reproductive development when dietary CP was consistent among treatments.

Key words: bulls, fatty acid, growth

Introduction

Post-weaning development is a critical period for beef bulls, marked by rapid growth and reproductive development. From weaning (approximately 7 months of age) to their expected breeding readiness (approximately 15 months), bulls must accumulate body mass, mature sexually (Barth et al., 2008; Barth and Waldner, 2002). Managing nutrition during this stage is essential to ensure bulls meet both growth and fertility benchmarks.

From an economic perspective, growth performance traits such as ADG, DMI, and feed efficiency (G:F), along with reproductive indicators like scrotal circumference (SC) and breeding soundness, directly influence bull valuation. Bulls that demonstrate superior growth and reproductive soundness are more likely to be retained as sires and command premium prices at auction (Dhuyvetter et al., 1996). Average daily gain, in particular, has been consistently shown to impact sale price of bulls. Atkinson et al. (2010) reported that each one-pound increase in ADG corresponded to a \$209 increase in value, while Boyer et al. (2019) found that ADG significantly influenced bull sale price every year since 2010, with premiums ranging from \$171 to \$1,244 per pound gained. These findings suggest that cow-calf producers consistently value bulls that grow faster during post-weaning development and place a premium on performance-tested growth.

Post-weaning nutrition programs for developing bulls are typically designed to promote moderate to high rates of gain while minimizing negative impacts on reproductive performance (Corah et al., 2000; Walker et al., 2008). Energy and protein intake are well-documented to influence testicular development, puberty onset, and semen quality (Coulter and Kozub, 1984; Rekwot et al., 1987; Barth and Waldner, 2002). Scrotal circumference, in particular, remains one of the most widely used and practical indicators of reproductive development in beef bulls. Burns et al. (2011) reported that SC is moderately to highly heritable ($h^2 = 0.4\text{--}0.6$) and strongly correlated with semen quality traits such as sperm motility and morphology.

Although protein and energy have been studied extensively in this context, few studies have examined the role of dietary lipid composition particularly omega-3 polyunsaturated fatty acids (n-3 PUFAs) in post-weaning bull development. Typical bull development diets found in the midwestern United States such as corn silage and corn co-products have high levels of

omega-6 fatty acids and conversely low omega-3 concentrations. Feedstuffs such as flax, linseed, canola, fish oils which are difficult to source by producers in regions with little no production of these sources of omega-3 and thus not widely used in diets. Omega-3 fatty acids influence cell membrane integrity, inflammation, and steroidogenesis in ruminants (Wathes et al., 2007; Gulliver et al., 2012). Despite this, their inclusion in ruminant diets is complicated by extensive ruminal biohydrogenation, which reduces the post-ruminal availability of active omega-3s such as α -linolenic acid (ALA). Over 85% of unprotected dietary ALA can be saturated to stearic acid by rumen microbes, effectively diminishing its biological efficacy (Jenkins, 1993; Jenkins and Bridges, 2007).

To counter this, technological advances such as extrusion, encapsulation, and matrix blending have been developed to increase rumen bypass of unsaturated fats. One such strategy involves using an extruded flaxseed and microalgae product, designed to enhance dietary ALA and eicosapentaenoic acid (EPA) supply. In a study using a similar product (GreatOPlus®; NBO3 Technologies), ruminally cannulated steers fed the extruded blend at 10% dietary DM had a fourfold increase in duodenal ALA flow compared to control steers, despite ongoing biohydrogenation suggesting partial protection of omega-3 fatty acids via extrusion (Thorn and Drouillard, 2024).

Although omega-3 supplementation has been explored in beef and dairy cows and heifers, often focusing on reproduction measurements like conception and hormonal differences, very little literature exists focusing on omega-3 supplementation in developing beef bulls. Furthermore, much of the bull nutrition literature has focused on the impact of dietary energy or protein on semen quality, with little emphasis on lipid type or fatty acid profile.

Therefore, the objective of these experiments was to evaluate the effect of omega-3 fatty acid supplementation from an extruded flaxseed-algae blend on post-weaning beef bull development. Specifically, we tested the hypothesis that inclusion of the fatty acid blend would enhance growth performance (ADG, DMI, G:F), alter serum fatty acid profiles, and influence early reproductive traits such as scrotal circumference. These experiments aim to fill the knowledge gap surrounding dietary omega-3 supplementation in bull development programs and contribute to the development of effective, biologically sound nutritional strategies in seedstock production systems.

Materials and Methods

Experimental Procedures

Two sequential experiments were conducted on bulls born in spring 2023 (n = 41) and bulls born in spring 2024 (n = 39) consisting of Angus, Hereford, and Simmental bull calves from the Kansas State University Purebred Beef Unit at Manhattan, KS. At weaning, bulls initially had access to both native prairie hay and a commercial creep feed for *ad libitum* consumption for approximately 2 wk before being transitioned to a TMR which was subsequently fed for 4-5 wk.

Following the weaning and diet transition period in both experiments, bulls were tagged with an electronic identification (EID) button tag and then moved to the Kansas State University Precision Feed Intake Facility in which the Insentec® Roughage Intake Control system (Hokofarm, Emmeloord the Netherlands), which measures individual animal feed consumption. Bulls were trained to the bunks over a 3 wk period. Upon reaching a stable DMI of approximately 2% of BW during the training period, bulls were weighed for three consecutive days to establish an initial 3 d average.

For Exp.1, bulls were stratified by age (292 ± 6.25 d) and initial BW (352 ± 19 kg and randomly assigned within strata to one of three treatment groups ($n = 14$ per treatment). Bulls received either 0.0 (**CON**), 0.22 (**MOD**), or 0.43 (**HI**) kg per head per day (DM basis) of the omega-3 based supplement. Treatment groups were randomly assigned to feed modules with 4 modules allocated to **CON** and 5 modules allocated to **MOD** and **HI** treatments. The individual bull EID numbers were assigned in the Insentec® system to their treatment group diet and the subsequent treatment diet was then assigned to the randomly allocated feed modules. Bulls were freely able to consume feed from the any of the modules assigned to their corresponding treatment. Bulls were fed a TMR diet delivered once a day to the feed modules. The treatment was then added and mixed into the basal TMR diet within the feed module before bulls had access to consume feed from the module. The feeding period was 64 d, beginning December 2nd, 2023, and ending February 4th, 2024.

For Exp. 2, bulls (332 ± 14 kg of initial BW; 291 ± 6.25 d of age) ($n = 13$ per group) were stratified by age and BW and randomly assigned within strata as assigned to the same omega-3 based supplement treatments as described for Exp. 1 (**CON**, **MOD**, **HI**). However, in Exp. 2 the diets were formulated to be isonitrogenous across treatments by adding corn germ meal (CGM) to the diet (**CON** 0.99, **MOD** 0.64, **HI** 0.59 kg per head per day (DM basis)). As in Exp. 1 Treatment groups were randomly assigned to feed bunk modules with 8 modules allocated to each treatment groups with 1-2 bulls per module. Bulls were fed a TMR diet delivered once a day to the feed modules. The treatment was then added and mixed into the basal TMR diet within the feed module before bulls had access to consume feed from the module. The feeding period was 80 d, beginning November 19th, 2024, and ending February 7th, 2025.

The supplement was a commercially manufactured blend of proprietary extruded flaxseed and lipid material algae (GreatOPlus®; NBO3 Technologies, Better Fed Foods, Manhattan, KS) formulated to supply dietary omega-3 fatty acids. The omega-3 fatty acid supplement composition for both experiment 1 and 2 are summarized in Table 2.1. The level of inclusion of the supplement was determined using the recommended inclusion amounts from the manufacturer. Each diet (Table 2.2 and 2.3) was formulated using the growing bull module of the Microsoft Excel™ based Beef Ration and Nutrition Decision Software (BRaNDS) (Iowa Beef Center, 2025) utilized by Kansas State University Research and Extension. In Exp.1, wet corn gluten feed was included as the main protein source in the diet, while dried distiller's grains with solubles (Table 2.4) were used in Exp. 2 due to product availability.

Nutrient composition of basal TMR and treatment diets for both experiments are presented in Table 2.5. In Exp. 1 basal diet TMR samples were collected during feeding once per wk and frozen in a -20 °C freezer prior to analysis. Weekly TMR samples were then composited into three periods consisting of three wk per periods, representing the first, middle, and final thirds of the feeding period. In Exp. 2 diet samples of both the basal and treatment diets after addition of the supplement to the feed bunk modules were taken once per wk and frozen at -20°C prior to analysis. Weekly diet samples were then composited into periods consisting of four wk per periods, representing the first, middle, and final thirds of the feeding period. SDK Laboratories (Hutchison, KS) for analysis. The same process was completed for both the omega 3 based supplement and CGM. All samples were sent to a commercial lab (SDK Laboratories, Hutchison, KS) for wet chemistry analysis. The analysis of feed samples for both experiments is reported as the average of the three periods in (Table 2.5).

In both experiments bulls were weighed for three consecutive days at both the beginning and end of the test period; weights were averaged to determine initial and ending BW. The Insentec® system recorded individual feed intake of each bull daily throughout each experimental period. In Exp. 1, the basal diet and omega-3 supplement were analyzed separately for DM. A composite treatment DM was calculated by combining basal and supplement values at the assigned inclusion level, and this was applied to raw as-fed intake data from the Insentec® system to derive DMI. In Exp. 2, complete treatment diets (basal + supplement) were analyzed for DM, and those values were directly applied to raw as-fed intake to calculate DMI. Average daily gain was calculated by subtracting the initial average BW from the final average BW and dividing the difference by the number of days of the feeding period. Feed efficiency was calculated by dividing the ADG by the average DMI of the feeding period. In Exp. 1, longissimus muscle area (LMA), rib fat thickness, and intramuscular fat (IMF) were measured via ultrasound by a trained technician after the end of the feeding period on d 72. In Exp. 2, ultrasound measurements were taken at d 0 and d 80 by the same technician. Scrotal circumference was measured during the BSE at the end of Exp. 1 and was measured on day 0 and day 80 in Exp. 2. In Exp. 2, an independent evaluator evaluated BCS at each measurement period using the standard 1-9 scale at the begin and end of the trial (Richards et al., 1986).

Blood samples were collected once during each 3-d BW collection period at the start and end of the test period via coccygeal venipuncture. Samples were centrifuged for 20 min at 4 °C at $1,000 \times g$. Serum was hand-pipetted into 1.5-mL tubes and stored at -20 °C.

Serum fatty acids were quantified by NBO3 Technologies using a modified long-chain fatty-acid methylation and GC protocol. A 200- μ L serum sample was freeze-dried and then combined with benzene containing an internal methyl-fatty-acid standard, and vortexed. BF₃-

methanol reagent was added, tubes were flushed with nitrogen, capped, and incubated at 60 °C for 60 min. After cooling, water and hexane were added, samples were mixed, centrifuged at $1,000 \times g$ for 10 min, and the upper hexane phase was transferred to GC vials. Fatty-acid methyl esters were separated on a Supelco SP-2560 column ($100 \text{ m} \times 0.25 \text{ mm} \times 0.20 \text{ }\mu\text{m}$) using a temperature program from 100 °C to 240 °C and identified with commercial FAME standards.

Serum was analyzed for total fatty acids, omega-3 and omega-6 fatty acids, PUFA, MUFA, SFA, EPA, DHA, and omega-6:omega-3 ratio. Laboratory personnel were blinded to treatment.

Statistical Analysis

All data were analyzed using the GLIMMIX procedure of SAS version 9.4 (SAS Institute Inc., Cary, NC). Fixed effects included treatment, and breed was included as a random effect. The individual bull was the experimental unit. Statistical significance was declared at $P \leq 0.05$ and tendencies were considered at $0.05 < P \leq 0.10$.

Results and Discussion

Experiment 1

Growth and Performance

Initial age and BW (292, 292, and 291 kg) were similar across treatment groups ($P = 0.99$ and $P = 0.98$, respectively; Table 2.6). Average daily gain was influenced ($P = 0.04$) by omega-3 supplementation. Bulls in the **HI** group gained more per day (1.93 kg) per bull than those in the **CON** (1.63 kg) and **MOD** (1.77 kg) treatments, which did not differ from one another. Ending BW did not differ ($P = 0.77$), with bulls ending at 455, 464, and 470 kg in the **CON**, **MOD**, and **HI** groups, respectively. Dry matter intake was not affected ($P = 0.64$) by dietary treatment, averaging 9.33, 9.72, and 9.96 kg/d in **CON**, **MOD**, and **HI** groups, respectively. Feed efficiency

(Table 2.6) was not impacted ($P = 0.75$) by treatment **CON** (0.176), **MOD** (0.187), and **HI** (0.184).

Omega-3 supplementation produced inconsistent effects on growth performance across the two experiments. In Exp. 1, bulls receiving the high inclusion level (**HI**; 0.43 kg/day) of the omega-3 supplement exhibited greater ADG compared to the control group (1.93 vs. 1.63 kg/day; $P = 0.04$). The higher ending body weight in **HI** bulls (470 kg vs. 455 kg in **CON**) supports the ADG response, although this difference was not statistically significant ($P = 0.77$). Despite the increase in ADG in Exp. 1, DMI was numerically higher across the treatment levels.

Ultrasound Measurements

No differences ($P = 0.50$) were observed for rib fat thickness (Table 2.7) across treatment groups **CON** (5.62), **MOD** (6.49), and **HI** (6.23 mm) but there is a numerical difference across the treatments. Intramuscular fat (Table 2.7) was effected by treatment ($P = 0.03$) to be greater in **HI** bulls (2.97%) compared to **CON** (1.64%) and **MOD** (2.92%), representing a 1.3 percentage unit increase relative to **CON**. Longissimus muscle area was tended to be affected by treatment ($P = 0.06$), with **MOD** bulls displaying a larger LMA (81.5 cm²) than **CON** (73.5 cm²) and **MOD** (77.9 cm²), which was intermediate and did not differ from **CON** or **MOD** another.

Because fewer bulls had missing ultrasound records in each treatment (**CON** = 11, **MOD** = 13, **HI** = 8), estimates for these traits have reduced precision, particularly for the **HI** group. This reduces statistical power but does not change the direction of treatment effects.

Blood Serum Fatty Acid Profiles

Serum fatty acid profiles were not affected by omega-3 supplementation (Table 2.8). No treatment effects were detected for any fatty acid class. Total fatty acid concentrations did not

differ among treatments at final sampling (1155 to 1208 $\mu\text{g/mL}$; $P = 0.76$), and net changes over the feeding period were similar among groups ($P = 0.73$).

Omega-3 related fatty acids were not altered by supplementation. Baseline omega-3 concentrations averaged 35 to 36 $\mu\text{g/mL}$ across treatments ($P = 0.99$), and final concentrations increased slightly but uniformly (39 to 42 $\mu\text{g/mL}$; $P = 0.74$). EPA+DHA followed the same pattern, with no treatment differences at baseline (4.9 to 5.9 $\mu\text{g/mL}$; $P = 0.76$), final sampling (4.0 to 4.9 $\mu\text{g/mL}$; $P = 0.17$), or in net change ($P = 0.51$).

Omega-6 concentrations increased from baseline to final sampling in all groups but did not differ among treatments at either time point (354 to 430 vs. 479 to 488 $\mu\text{g/mL}$; $P \geq 0.16$). As a result, the omega-6 to omega-3 ratio remained unchanged (baseline 10.2 to 12.4; final 11.8 to 12.3; $P \geq 0.11$).

Saturated fatty acids (SFA) increased over time but were not affected by treatment (baseline 392 to 435 $\mu\text{g/mL}$; final 480 to 495 $\mu\text{g/mL}$; $P \geq 0.60$). Monounsaturated fatty acids (MUFA) showed no treatment differences at baseline (158 to 166 $\mu\text{g/mL}$) or final sampling (159 to 168 $\mu\text{g/mL}$; $P \geq 0.62$). Polyunsaturated fatty acids (PUFA) also did not differ among treatments at baseline (392 to 469 $\mu\text{g/mL}$) or final sampling (517 to 552 $\mu\text{g/mL}$; $P \geq 0.21$).

Serum fatty-acid data were incomplete at both sampling points. At initiation, usable samples were obtained from 10 CON, 7 MOD, and 8 HI bulls; at d 64, final samples were available from 14 CON, 14 MOD, and 12 HI bulls. These unequal sample sizes increase standard errors and reduce statistical power, so treatment comparisons should be interpreted with appropriate caution.

In Exp.1, no treatment effects were observed for final serum omega-3 concentration, EPA+DHA, total FA, or any major lipid class ($P > 0.10$). Although the **HI** group had

numerically higher total FA (+199.99 $\mu\text{g/mL}$) and omega-3 (+6.39 $\mu\text{g/mL}$) concentrations relative to **CON**, high variability and a limited number of complete serum samples due to missing data at one or both sampling timepoints likely reduced the statistical power needed to detect treatment differences. Similar variability in serum and plasma ALA response has been reported in dairy cows fed extruded flaxseed, where biohydrogenation and differences in supplement handling limited consistency in omega-3 transfer (Gonthier et al., 2005). Furthermore, studies in dairy cows (Moallem et al., 2020) have shown that flax-based omega-3 supplements enriched serum ALA but did not consistently elevate long-chain derivatives like EPA and DHA, likely due to incomplete rumen protection.

Additionally, the final diets in Exp. 1 were not sampled for nutrient analysis after the omega-3 supplement was added. While the basal TMR was analyzed, the actual fatty acid profile of the **CON**, **MOD**, and **HI** diets which included additional protein and fat from the supplement remains unknown. This does not directly affect serum measurements, but it limits the confidence with which observed serum values can be linked to actual omega-3 intake, as differences in batch mixing, supplement distribution, or basal ingredient variation may have influenced nutrient delivery. The basal diet also contained wet corn gluten feed WCGF; a known source of omega-6 fatty acids. Elevated background PUFA from WCGF may have interfered with omega-3 metabolism or masked treatment effects, particularly in the absence of confirmed dietary omega-3 concentrations. This uncertainty mirrors findings by Moallem et al. (2020), who emphasized that even with well-controlled TMR composition, ingredient variability and feeding behavior may influence individual fatty acid uptake and circulating levels.

Experiment 2

Growth and Performance

There were no differences in initial age ($P = 0.99$), initial BW ($P = 0.99$), or ending BW ($P = 0.86$) among treatments (Table 2.9). Average DMI ranged from 8.98 to 9.70 kg/day and was not affected by treatment ($P = 0.39$). Average daily gain did not differ among groups ($P = 0.49$), with bulls gaining 1.41, 1.56, and 1.49 kg/day in the **CON**, **MOD**, and **HI** groups, respectively.

Gain-to-feed ratio tended to differ by treatment ($P = 0.08$). Bulls in the **MOD** group had numerically greater G:F (0.177) compared to **CON** (0.148) and **HI** (0.162), ($P > 0.05$). BCS did not differ among groups ($P = 0.28$), with bulls in the **MOD** and **HI** treatments averaging 6.15 compared to 5.85 in the **CON** group.

Experiment 2 showed no treatment effects on ADG. This lack of response is most likely due to the inclusion of CGM to equalize CP levels across treatments. This discrepancy between experiments suggests that the performance benefits observed in Exp. 1 were partially confounded by differences in overall dietary protein and energy content. A similar lack of performance effect was noted by Dokou et al. (2025), who supplemented Holstein bulls with 5% extruded linseed on a DM basis and observed no differences in ADG, or feed efficiency compared to controls when diets were isocaloric and isonitrogenous. Comparable results were observed in dairy cows fed various flaxseed forms, where effects on yield were stage- or energy-dependent (Swanepoel and Robinson, 2019).

Experiment 2 followed a similar pattern, with no significant treatment differences observed for DMI or G:F. These findings align with previous research investigating supplementation of similar feedstuffs, such as Thorn and Drouillard (2024), who fed an extruded flax-algae blend to steers and found no main effect on DMI when included at 10% of diet DM.

Barton et al. (2007), reported no change in intake or efficiency in heifers fed approximately 10% linseed on a dry matter basis. Swanepoel and Robinson (2019) found no differences in DMI when flax-based extruded linseed was fed to Holstein cows at 2.3% and 4.7% of DM, and Gonthier et al. (2005) observed no changes in DMI among flaxseed types in dairy cattle at 12.6% inclusion.

Across both experiments, the highest inclusion of the omega-3 supplement represented approximately 4.5% of dietary dry matter, and there was no evidence of the negative effects on DMI that have been reported in studies using high levels of added fat. This is consistent with Hess et al. (2008) and Zinn and Jorquera (2007), who noted that fat levels above 6-7% of dietary DM are typically required before DMI depression is observed in feedlot cattle. In both Swanepoel and Robinson (2019) and Gonthier et al. (2005), ether extract levels remained within recommended limits, supporting the interpretation that moderate fat inclusion avoids negative impacts on intake. There are other factors may have influenced intake patterns. For example, the use of the individual intake monitoring system introduces potential social and behavioral and feeding dynamics, such as competition within feeding modules, that could impact intake independently of diet composition.

Ultrasound Measurements

There were no significant treatment effects for IMF ($P = 0.61$), LMA ($P = 0.62$), or rib fat thickness ($P = 0.69$), 5.72, 6.17, and 5.90 mm across treatments (Table 2.10). LMA ranged from 81.3, 84.2, and 84.4 cm² across treatments, while IMF ranged from 2.50, 2.78, and 2.48%.

Experiment 2 showed no treatment effects on any ultrasound traits. Neither LMA ($P = 0.62$), IMF ($P = 0.61$), nor rib fat thickness ($P = 0.69$) differed among groups. The lack of response may reflect differences in dietary formulation, particularly the use of corn germ meal to

create isonitrogenous diets across treatments. By minimizing confounding protein contributions from the omega-3 supplement, the effects of fatty acid inclusion were likely more isolated in Exp. 2.

Blood Serum Fatty Acid Profiles

Serum fatty acid concentrations were partially affected by omega-3 supplementation (Table 2.11). Baseline values did not differ among treatments for total fatty acids, omega-3, EPA+DHA, omega-6, the omega-6 to omega-3 ratio, or any major fatty acid class ($P \geq 0.23$), confirming similar starting profiles across groups.

Total fatty acids at final measurements were greater in **MOD** and **HI** compared with **CON** (1432.30 and 1367.22 vs. 1207.40 $\mu\text{g/mL}$; $P = 0.03$), although net changes over the feeding period did not differ among treatments ($P \geq 0.40$). Omega-3 concentrations declined from baseline to final measurements in all groups, but **CON** had lower final values than **MOD** and **HI** (25.59 vs. 38.92 and 40.06 $\mu\text{g/mL}$; $P < 0.01$). Despite these differences at final, the magnitude of the decline did not differ among treatments ($P = 0.40$). EPA+DHA concentrations decreased similarly across treatments, with no effects detected at baseline, final, or in change values ($P \geq 0.30$).

Omega-6 concentrations increased numerically in all groups but did not differ among treatments at either measurement point ($P \geq 0.10$). However, the omega-6 to omega-3 ratio diverged over time, with **CON** exhibiting a greater final ratio than **MOD** and **HI** (22.29 vs. 16.97 and 16.10; $P < 0.01$). Change values showed a similar pattern, indicating that the ratio increased more in **CON** ($P < 0.01$).

Saturated fatty acids were greater in **MOD** and **HI** than **CON** at the end of the trial (537.50 and 512.16 vs. 456.71 $\mu\text{g/mL}$; $P = 0.03$), although changes over time were not different

among treatments ($P = 0.74$). In contrast, monounsaturated fatty acids were unaffected by treatment at either time point ($P \geq 0.33$), and change values were similar ($P = 0.84$).

Polyunsaturated fatty acids tended to be greater in **MOD** and **HI** compared with **CON** at final sampling (696.30 and 667.43 vs. 574.51 $\mu\text{g/mL}$; $P = 0.06$), but changes did not differ among treatments ($P = 0.66$).

No treatment effects were detected for the change in any fatty acid measurement from day 0 to 80 ($P \geq 0.17$). The **HI** group had the largest numerical increase in total fatty acids (+199.99 $\mu\text{g/mL}$), followed by **CON** (+155.80 $\mu\text{g/mL}$) and **MOD** (+69.56 $\mu\text{g/mL}$). Change in omega-3 followed a similar pattern, with no significant differences ($P = 0.84$).

Final serum concentrations of total fatty acids, omega-3, saturated fatty acids (SFA), and the omega-6:omega-3 ratio were significantly affected by treatment. Bulls in the **MOD** group had the greatest final total fatty acid concentration (1432.3 $\mu\text{g/mL}$; $P = 0.036$), while omega-3 concentrations were significantly higher in both **MOD** (38.92 $\mu\text{g/mL}$) and **HI** (40.06 $\mu\text{g/mL}$) compared to **CON** (25.59 $\mu\text{g/mL}$; $P < 0.0001$).

The omega-6:omega-3 ratio was lower in **MOD** and **HI** bulls (16.97 and 16.10, respectively) than in **CON** bulls (22.29; $P = 0.0075$). Final SFA concentrations were also higher in the **MOD** group than **CON** ($P = 0.031$), with **HI** intermediate.

No treatment differences were observed for change in total fatty acids, omega-3, omega-6, EPA+DHA, MUFA, or PUFA ($P \geq 0.40$). However, bulls in the **MOD** and **HI** groups exhibited significantly smaller increases in the omega-6:omega-3 ratio compared to **CON** ($P = 0.003$), suggesting that dietary omega-3 inclusion moderated the elevation in this ratio over time (Table 3.11).

Experiment 2 incorporated DDGS in the basal diet. The omega-3 supplement and CGM were added on top of the basal TMR, and diet composition for total fat content was analyzed but not the fatty acid profile. Despite the higher background n-6 from DDGS (Kerr et al., 2013), bulls in the **MOD** and **HI** groups had significantly greater final serum omega-3 concentrations compared to **CON** (38.9 and 40.1 vs. 25.6 $\mu\text{g/mL}$; $P < 0.0001$), along with a favorable reduction in the omega-6:omega-3 ratio ($P = 0.0075$). This suggests that the omega-3 supplement was absorbed and contributed to systemic lipid remodeling, even under conditions of relatively high background dietary fat. The observed increase in serum omega-3 concentration and reduction in n-6:n-3 ratio aligns with findings from large-scale dairy cow studies using extruded flaxseed supplements, which reported up to a 3.4-fold increase in plasma ALA and significant reductions in n-6:n-3 ratios (Moallem et al., 2020; Gonthier et al., 2005).

However, serum EPA+DHA concentrations declined from the start to end of the trial in both experiments, with no treatment effect observed ($P > 0.29$). This likely reflects a combination of factors, including the predominance of α -linolenic acid (ALA) in the supplement, incomplete rumen protection, and rapid metabolic turnover during the post-weaning growth period. The extrusion process used for the supplement provides only partial protection of unsaturated fats, and substantial biohydrogenation of ALA in the rumen likely limited conversion to EPA or DHA post-absorption. This is consistent with Moallem et al. (2015), who found that bulls fed flaxseed oil increased serum ALA concentrations but exhibited minimal changes in EPA and DHA, suggesting that conversion from ALA to long-chain omega-3s remains limited under typical rumen and hepatic metabolism.

Reproductive Traits

Scrotal circumference was not affected by dietary omega-3 supplementation in either experiment. In Exp. 1, SC (Table 2.6) measurements were similar ($P = 0.67$). across all treatment groups (**CON**: 34.77 cm, **MOD**: 34.48 cm, **HI**: 35.03 cm). In Exp. 2, SC (Table 2.7) was also not different ($P = 0.83$). among treatments (**CON**: 37.50 cm, **MOD**: 37.58 cm, **HI**: 37.96 cm).

Scrotal circumference, a widely accepted indicator of pubertal development and spermatogenic capacity, reflects the amount of sperm-producing tissue and is positively correlated with semen quality and fertility (Palomares and Wolfe, 2011). According to SFT guidelines, bulls under 15 months of age should have a minimum SC of 30.0 cm to be classified as satisfactory potential breeders (Hopkins and Spitzer, 1997). Across both years, SC values fell within expected ranges for bulls of this age and breed composition, and no statistical differences were detected among treatments. This suggests that omega-3 fatty acid inclusion, at the levels provided, did not alter testicular growth or physical maturation.

Conclusions

Omega-3 supplementation at inclusion levels of 0.22 and 0.43 kg/hd/day in post-weaning beef bulls influenced growth performance in the first experiment. However, these effects were not observed in a second experiment with diets formulated to be isonitrogenous, suggesting that responses were protein driven rather than from varying inclusion of omega -3 FA. Scrotal circumference and feed intake were largely unaffected. These results suggest that moderate inclusion of this omega-3 fatty acid-based supplement does not affect performance of developing bulls when diets are similar in CP content.

Table 2.1 Omega 3 fatty acid based supplement nutritional composition by Exp. % DM basis.

Item	Exp. 1	Exp. 2
DM ¹ , %	92.26	96.16
Crude Protein, %	25.96	32.26
ADF ² , %	13.52	11.28
NDF ³ , %	34.77	19.76
TDN ⁴ %	82.05	N/A ⁵
Fat (Ether Extract) %	11.53	18.85

¹DM = dry matter.

²ADF = acid detergent fiber.

³NDF = neutral detergent fiber.

⁴TDN = total digestible nutrients.

⁵N/S = not analyzed.

Table 2.2 Ingredient composition of basal diet by treatment, % DM basis Exp. 1.

Item	Basal
Corn Silage	30.50
Wet Corn Gluten Feed	29.20
Dry Rolled Corn	20.30
Brome Hay	12.50
Supplement ¹	7.50
ω -3 Fatty Acid Suppl. ^{2,3}	-

¹ Supplement includes vitamins, minerals, and rumensin

² ω -3 Fatty Acid Supplement = extruded flaxseed and algae blend.

³ Was not included in basal diet. Mixed in bunk after delivery of basal diet.

Table 2.3 Ingredient composition of basal diet by treatment, % DM basis Exp. 2.

Item	Basal
Corn Silage	34.30
DDGS ¹	22.20
Dry Rolled Corn	20.90
Brome Hay	17.70
Supplement ²	7.90
Corn Germ Meal ³	-
ω-3 Fatty Acid Suppl. ^{4,5}	-

¹ Distillers dried grains with solubles.

² Supplement includes vitamins, minerals, and rumensin.

³ Not included in basal diet until after delivery in feed module.

⁴ ω-3 Fatty Acid Supplement = extruded flaxseed and algae blend.

⁵ Was not included in basal diet. Mix in feed module after delivery of basal diet.

Table 2.4 Corn germ meal nutritional composition % DM basis.

Item	Experiment 2
DM ¹ %	91.65
Crude Protein %	27.23
ADF ² %	11.40
NDF ³ %	43.16
Fat (Ether Extract) %	5.22

¹ DM = dry matter.

²ADF = acid detergent fiber.

³NDF = neutral detergent fiber.

Table 2.5 Exp. 1 and 2 average TMR nutritional composition % DM basis

Item	Treatment Diet ¹				
	Exp. 1 Basal	Exp. 2 Basal	Exp. 2 CON	Exp. 2 MOD	Exp. 2 HI
Dry Matter	62.68	57.40	59.73	58.56	60.53
Crude Protein	15.26	12.47	13.07	12.61	13.47
ADF ² , %	17.27	18.79	17.87	18.08	17.81
NDF ³ , %	35.53	31.79	31.01	31.13	32.09
TDN ⁴ , %	71.12	72.01	72.37	72.43	73.47
Fat %	3.33	4.95	4.76	4.93	5.76
Calcium, %	0.76	0.92	0.87	0.80	0.76
Phosphorus, %	0.57	0.47	0.48	0.45	0.47
Potassium, %	1.27	1.20	1.11	1.14	1.20
Magnesium, %	0.28	0.24	0.22	0.21	0.20
Total Starch, %	--	28.53	26.93	28.13	25.60
NE _G ⁵	0.48	0.49	0.49	0.50	0.51
NE _M ⁶	0.80	0.82	0.82	0.82	0.83
DE ⁷	1.42	1.44	1.45	1.45	1.47
ME ⁸	1.17	1.18	1.19	1.19	1.21

¹ Basal diet; CON = control; MOD = 0.22 kg/hd/d omega-3 supplement; HI = 0.43 kg/hd/d omega-3 based supplement.

²ADF = acid detergent fiber.

³NDF = neutral detergent fiber.

⁴TDN = total digestible nutrients.

⁵DE = digestible energy. Mcal/lb.

⁶ME = metabolizable energy. Mcal/lb.

⁷NE_M = net energy for maintenance. Mcal/lb.

⁸NE_G = net energy for gain Mcal/lb.

Table 2.6 Effects of omega-3 supplementation on growth, feed intake, and performance on post-weaning beef bulls Exp. 1.

Item	CON	MOD	HI	SE ¹	<i>P-value</i>
Initial Age	292	292	291	6.25	0.99
Initial BW, ² kg	351	351	348	19.1	0.98
End BW, kg	455	464	470	25.0	0.77
DMI, ³ kg/day	9.33	9.72	9.96	0.97	0.64
ADG, ⁴ kg	1.63 ^a	1.77 ^a	1.93 ^b	0.14	0.04
G:F ⁵	0.176	0.187	0.184	0.01	0.75
SC ⁶ ,cm	34.77	34.48	35.03	1.14	0.67

¹ Standard Error.

² BW = body weight.

³DMI = dry matter intake.

⁴ADG = average daily gain.

⁵G:F = gain to feed ratio.

⁶SC = Scrotal circumference.

^{a-b} Within rows, means with unlike superscripts differ ($P \leq 0.05$).

Table 2.7 Effects of omega-3 supplementation on ending ultrasound measurements in post-weaning beef bulls, Exp. 1.

Item	CON ²	MOD ³	HI ⁴	SEM ¹	<i>P-value</i>
IMF ⁵ %	1.64 ^b	2.92 ^a	2.97 ^a	0.79	0.03
LMA ⁶ , cm ²	73.5 ^a	81.5 ^b	77.9 ^{ab}	4.02	0.06
Rib Fat ⁷ , mm	5.62	6.49	6.23	0.66	0.50

¹ Standard error of the mean.

² n = 11

³ n = 13

⁴ n = 8

⁵ IMF = intramuscular fat.

⁶ LMA = longissimus muscle area.

⁷ Rib Fat measured at the 12th rib.

^{a-b} Within rows, means with unlike superscripts differ ($P \leq 0.05$).

Table 2.8 Effects of omega-3 supplementation on serum fatty acid concentrations in post-weaning beef bulls (µg/mL) Exp. 1¹.

Item	CON	MOD ⁴	HI ⁵	SEM ²	<i>P-value</i>
Initial Total FA ⁶	948.84	1061.86	1019.11	147.34	0.50
Initial ω-3 ⁷	35.39	35.67	35.55	3.83	0.99
Initial EPA DHA ⁸	5.92	4.87	5.87	1.15	0.76
Initial ω-6 ⁹	353.74	430.20	390.63	59.66	0.16
Initial ω-6:ω-3	10.20	12.43	10.53	1.11	0.11
Initial SFA ¹⁰	391.60	435.31	421.68	64.25	0.60
Initial MUFA ¹¹	165.85	158.13	165.77	23.21	0.89
Initial PUFA ¹²	391.56	468.64	430.15	63.09	0.21
Final Total FA ⁶	1154.69	1207.63	1199.25	58.56	0.76
Final ω-3 ⁷	39.20	41.84	41.30	3.21	0.74
Final EPA DHA ⁸	4.01	4.94	4.37	0.39	0.17
Final ω-6 ⁹	478.91	483.15	488.08	35.75	0.97
Final ω-6:ω-3	12.25	11.79	12.33	0.66	0.81
Final SFA ¹⁰	479.54	488.34	494.73	22.79	0.87
Final MUFA ¹¹	158.73	168.24	164.92	7.53	0.62
Final PUFA ¹²	517.11	552.42	538.43	38.00	0.77
Total FA Change ⁶	155.80	69.56	199.99	194.40	0.73
ω-3 Change ⁷	2.43	4.95	6.39	6.34	0.84
EPA DHA Change ⁸	-2.12	-0.29	-1.23	1.20	0.51
ω-6 Change ⁹	100.77	31.36	110.42	99.91	0.57
ω-6:ω-3 Change	1.85	-0.92	1.74	1.67	0.18
SFA Change ¹⁰	62.98	29.18	86.51	67.82	0.68
MUFA Change ¹¹	-11.24	2.10	-1.04	25.59	0.89
PUFA Change ¹²	103.64	37.50	117.51	105.69	0.62

¹ Initial = d 0, Final = d 64, Change = difference of final from initial.

² Standard error of the mean.

³ Initial n = 10, Final n = 14

⁴ Initial n = 7, Final n = 14

⁵ Initial n = 8, Final n = 12

⁶ FA = Fatty Acid

⁷ ω -3 = omega-3 fatty acids.

⁸ EPA DHA = eicosapentaenoic acid + docosahexaenoic acid.

⁹ ω -6 = omega-6 fatty acids.

¹⁰ SFA = saturated fatty acids.

¹¹ MUFA = monounsaturated fatty acids.

¹² PUFA = polyunsaturated fatty acids.

^{a-b} Within rows, means with unlike superscripts differ ($P \leq 0.05$).

Table 2.9 Effects of omega-3 supplementation on growth, feed intake, and performance on post-weaning beef bulls Exp. 2.

Item	CON	MOD	HI	SEM ¹	<i>P-value</i>
Initial Age	292	291	291	6.20	0.99
Initial BW, ² kg	332	332	331	14.50	0.99
End BW, kg	445	458	450	17.50	0.86
DMI, ³ kg/day	9.56	8.98	9.70	0.39	0.39
ADG, ⁴ kg	1.41	1.56	1.49	0.08	0.49
G:F ⁵	0.148	0.177	0.162	0.009	0.08
SC ⁶ ,cm	37.50	37.58	37.96	0.59	0.83
BCS ⁷	5.85	6.15	6.15	0.16	0.28

¹ Standard Error.

² BW = body weight.

³DMI = dry matter intake.

⁴ADG = average daily gain.

⁴G:F = gain to feed ratio.

⁴SC = Scrotal circumference.

⁴BCS = Body Condition Score (1-9 Scale)

^{a-b} Within rows, means with unlike superscripts differ ($P \leq 0.05$).

Table 2.10 Effects of omega-3 supplementation on ending ultrasound measurements in post-weaning beef bulls, Exp. 2.

Item	CON ²	MOD ³	HI ⁴	SEM ¹	<i>P-value</i>
IMF ⁵ %	2.50	2.78	2.48	0.40	0.61
LMA ⁶ , cm ²	81.3	84.2	84.4	2.84	0.62
Rib Fat ⁷ , mm	5.72	6.17	5.90	0.37	0.69

¹ Standard error of the mean.

² n = 14

³ n = 14

⁴ n = 14

⁵ IMF = intramuscular fat.

⁶ LMA = longissimus muscle area.

⁷ Rib Fat measured at the 12th rib.

^{a-b} Within rows, means with unlike superscripts differ ($P \leq 0.05$).

Table 2.11 Effects of omega-3 supplementation on serum fatty acid concentrations in post-weaning beef bulls in (µg/mL) Exp. 2¹.

Item	CON ³	MOD ⁴	HI ⁵	SEM ²	<i>P-value</i>
Initial Total FA ⁶	1205.82	1354.30	1259.01	90.52	0.51
Initial ω-3 ⁷	87.58	96.31	90.20	9.93	0.61
Initial EPA DHA ⁸	17.46	21.06	19.06	2.93	0.30
Initial ω-6 ⁹	514.37	571.27	547.10	42.29	0.64
Initial ω-6:ω-3	6.04	5.97	6.26	0.48	0.80
Initial SFA ¹⁰	423.43	476.22	437.09	31.30	0.50
Initial MUFA ¹¹	172.11	205.47	183.36	15.03	0.23
Initial PUFA ¹²	609.80	673.77	640.76	48.37	0.65
Final Total FA ⁶	1207.40 ^b	1432.30 ^a	1367.22 ^{ab}	60.36	0.03
Final ω-3 ⁷	25.59 ^b	38.92 ^a	40.06 ^a	2.30	<0.01
Final EPA DHA ⁸	4.35	6.07	3.89	1.02	0.30
Final ω-6 ⁹	545.51	653.05	621.37	35.18	0.10
Final ω-6:ω-3	22.29 ^a	16.97 ^b	16.10 ^b	1.41	<0.01
Final SFA ¹⁰	456.71 ^b	537.50 ^a	512.16 ^{ab}	21.03	0.03
Final MUFA ¹¹	175.52	197.37	187.00	12.57	0.33
Final PUFA ¹²	574.51	696.30	667.43	36.24	0.06
Total FA Change ⁶	1.58	78.01	108.21	105.60	0.76
ω-3 Change ⁷	-62.16	-57.16	-49.61	8.70	0.40
EPA DHA Change ⁸	-13.10	-14.83	-14.96	3.12	0.76
ω-6 Change ⁹	31.15	81.77	74.27	49.65	0.74
ω-6:ω-3 Change	16.29 ^a	10.90 ^b	9.65 ^b	1.33	<0.01
SFA Change ¹⁰	33.28	61.28	75.08	38.27	0.74
MUFA Change ¹¹	3.66	-7.77	3.75	17.65	0.84
PUFA Change ¹²	-35.29	22.53	26.67	54.93	0.66

¹ Initial = d 0, Final = d 80, Change = difference of final from initial.

² Standard error of the mean.

³ Initial n = 14, Final n = 14

⁴ Initial n = 14, Final n = 14

⁵ Initial n = 14, Final n = 14

⁶ FA = Fatty Acid

⁷ ω -3 = omega-3 fatty acids.

⁸ EPA DHA = eicosapentaenoic acid + docosahexaenoic acid.

⁹ ω -6 = omega-6 fatty acids.

¹⁰ SFA = saturated fatty acids.

¹¹ MUFA = monounsaturated fatty acids.

¹² PUFA = polyunsaturated fatty acids.

^{a-b} Within rows, means with unlike superscripts differ ($P \leq 0.05$).

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Chapter 3 - Post-Weaning Feed Intake and Performance of Bulls

Developed in an Automated Feed Intake Management System

Abstract

Feed intake and performance data from spring-born purebred Angus, Hereford, and Simmental bulls across four calf crops (2021–2024; $n = 154$) were retrospectively evaluated against predicted values generated by the Growing Bull module of the BRaNDS feed formulation program (Iowa State University, Ames, IA). Following weaning, bulls were developed at the Kansas State University Precision Feed Intake Facility, Manhattan, KS where they were fed a TMR and individual DMI was recorded using Insentec® bunks for 64 to 83 d. Predictions were generated using actual diet inclusion rates, observed initial and ending BW, and either default or modified BRaNDS settings for BCS, mature BW, hair coat condition, and temperature. Across the four-year dataset, actual DMI averaged 9.29 ± 1.69 kg/d, while BRaNDS predicted 9.10 kg/d, producing a bias of -0.20 kg/d. Correlations between actual and predicted DMI were moderate ($r = 0.55$ - 0.56 ; $P < 0.01$) and stronger within year ($r = 0.71$ - 0.84). Actual ADG averaged 1.61 ± 0.34 kg/d compared to predicted values of 1.04-1.21 kg/d, yielding an underprediction bias of -0.50 to -0.57 kg/d. Correlations between observed and predicted ADG were weak overall ($r = 0.27$ - 0.29 ; $P < 0.01$) but varied by year ($r = 0.27$ - 0.74). Year-specific ADG biases were -0.76 (Yr. 1), -0.51 (Yr. 2), -0.84 (Yr. 3), and +0.07 kg/d (Yr. 4), while corresponding DMI biases were +1.23, +0.42, -1.15, and -1.18 kg/d, respectively. Adjustments for mud, temperature, body condition score, or mature BW did not meaningfully alter predictions, with outputs remaining nearly identical to the initial iteration. These findings demonstrate that while BRaNDS equations moderately predict DMI across diets, breeds, and environments, they underestimate ADG of growing bulls. Refinement of metabolizable energy

and protein equations, inclusion of bull-specific growth data, and incorporation of year-specific feed composition are needed to improve prediction accuracy.

Key words: beef bulls; dry matter intake; average daily gain; nutrient requirement models

Introduction

Post-weaning intake and its relationship to ADG is critical given the significant impact feed costs have on developing virgin bulls (Lourenco et al. 2016). In typical production systems, bulls upon weaning are often managed in pen settings in which the overall intake of the contemporary group is measured, yet variation on an individual animal basis may occur. Today systems exist allowing for individual feed consumption data to be recorded in real time with the use of individual feed intake monitoring technologies. Use of these systems, appear to have limited effects on bull performance and intake compared to traditional group pen settings. (Lundy-Woolfolk et al. 2024). The performance of growing cattle can be predicted from nutrient requirements if feed intake is measured and dietary composition is known (NASEM, 2016); however, research evaluating this with pre- and peri-pubertal bulls post-weaning is limited. (NASEM, 2016). The Beef Ration and Nutrition Decision Software (BRaNDS) (Iowa State University, Ames, IA) formulation program is used by both academia and allied industry. This program utilizes the model equations found in the *Nutrient Requirements of Beef Cattle*, 8th rev. ed (NASEM, 2016) to predict DMI and ADG of growing cattle at various ages and body weights. Data sets with both individual animal feed intake and performance data are limited and valuable for validating performance and improving accuracy of diet formulation programs. Our objectives were to report observed intake and performance data and compare expected and observed DMI and ADG of bulls in a multi-yr analysis using modeled nutrient requirement equations in the BRaNDS formulation program.

Materials and Methods

Feed intake and performance data from purebred Angus, Hereford, and Simmental bull calves across four calf crops (birth yr. 2021 (n = 38), 2022 (n = 37), 2023 (n = 40), and 2024 (n = 39) were utilized for this ongoing multi-year analysis. The first three years of this analysis were reported previously (Banks et al., 2024, Fraser et al., 2025). All calves were born at the Kansas State University Purebred Beef Unit at Manhattan, KS in the spring and raised at dam's side grazing native Flint Hills range until weaning in September each year. At weaning, bulls initially had access to native prairie hay and a commercially manufactured feed for *ad libitum* consumption for approximately 2 wk. before being transitioned to a TMR which was subsequently fed for 5-6 wk. Following the weaning and diet transition period, bulls entered the Kansas State University Precision Feed Intake Facility in mid-November each yr. Intake test periods were November 11, 2021 through February 2, 2022 (83 d), November 19, 2022 through January 30, 2023 (72 d), December 2, 2023 through February 4, 2024 (64 d), November 19, 2024 through February 7, 2025 (80 d) for yr. 1, 2, 3, and 4 respectively. During Yr. 1, feed intake data were recorded for 64 days. In all year's bulls were managed as a common group in earthen partially covered pens and fed in Insentec® feed bunk module units allowing for individual feed intake data to be recorded while on test. During Yr. 3 and 4 bulls were divided into diet treatment groups consisting of 0.0, 0.23, and 0.45 kg per head per day equivalent intake (DM basis) of an omega 3-based fatty acid supplement added onto the basal diet. The Yr. 4 bulls were divided into the same three treatment groups as the previous year, and corn germ meal was added to the treatment diet to make the diet isonitrogenous. Treatment groups were randomly assigned to bunk module units throughout the pen and individual feed intake data was recorded with bulls managed in a single pen. Ingredient composition of diets fed differed among years (Table 3.1

and 3.2). In Yr. 1 (2021-2022 test year), two different diets were fed but only diet 1 was used in the analysis as it was fed for the majority of the total days (Table 3.1). Bulls were individually weighed without feed or water restriction at both the beginning and end of the test period to calculate ADG, with G:F subsequently calculated for each bull from average individual DMI. In Yr. 3 and 4, bulls were weighed for 3 consecutive days at both the beginning and end of the test periods and averaged to determine initial and ending weight.

Projected DMI and ADG were calculated for each group of bulls by year on an individual basis using the Growing Bull module of the Excel-based BRaNDS formulation program (Iowa Beef Center, 2025) using 8 different iterations of program inputs.

The first iteration used the default settings in the module (Table 3.3). The diet values were imputed using the actual average as fed intake of each bull to retrospectively calculate the subsequent DMI value using the approximate DM of each ingredient, based on the formulated diet composition. The individual feedstuff compositions were the average tabular values from the 2016 NASEM and the default BRaNDS feed library and used for all for years. There were 7 more iterations that used the first iteration as the default parameters in the program, while only changing one parameter to see its influence on the predicted values. These iterations are found in (Table 3.4).

Intake and performance equations incorporated into BRaNDS are from the Nutrient Requirements of Beef Cattle 7th and 8th editions (NRC, 2000, NASEM, 2016). Shrunken weight gain (SWG) was calculated according to NASEM (2016) as:

$$SWG = 13.91 \times RE^{0.9116} \times SBW^{-0.6837} \quad (\text{Eq. 12-7; NASEM, 2016})$$

where SWG = shrunken weight gain (kg/d), RE = retained energy (Mcal/d), and SBW = shrunken body weight (kg).

Dry matter intake was predicted according to NASEM (2016) using the feedlot equation for steers and bulls (Eq. 19-91b):

$$\text{DMI} = \text{DMI}'' \times \text{BI} \times (\text{BFAT} \times \text{TEMP1} \times \text{MUD1})$$

where DMI = dry matter intake (kg/d), BI = breed type adjustment, BFAT = body fat adjustment, TEMP1 = temperature adjustment, and MUD1 = mud adjustment factor. The auxiliary variable DMI'' was computed as:

$$\text{DMI}'' = \text{SBW} \times (0.012425 + 0.019218 \times \text{NE}_{\text{ma}} - 0.007259 \times \text{NE}_{\text{ma}}^2) \quad (\text{Eq. 19-92})$$

where SBW = shrunk body weight (kg) and NE_{ma} = dietary net energy available for maintenance (Mcal/kg DM) (NASEM, 2016).

Using actual initial and ending BW for each bull, actual DMI of individual feedstuffs based on diet composition, and assumed average feedstuff composition values from the 2016 NASEM, projected DMI and ADG was retrospectively calculated to determine the accuracy of the program in predicting performance.

Statistical Analysis

All data were analyzed using SAS 9.4 (SAS Institute Inc., Cary, NC). The correlation procedure was used to evaluate the relationship between observed and projected DMI and ADG of all four years of data together. The correlation relationships in individual yr. were also evaluated using the correlation procedure. Bias values were calculated by predicted-observed. The individual bull was the experimental unit. *P*-values less than or equal to 0.05 were declared significant.

Results and Discussion

Across the four-year dataset bulls ($n = 154$) had an average initial BW of 353 ± 52.7 kg and reached a final BW of 473 ± 61.4 kg (Table 3.5). Actual DMI averaged 9.29 ± 1.69 kg/d,

with a range of 4.15 to 13.75 kg/d. Average daily gain was 1.61 ± 0.34 kg/d, ranging from 0.34 to 2.64 kg/d. Actual G:F 0.168 ± 0.04 ranging from 0.292 to 0.084.

When compared to BRaNDS-predicted values, actual DMI was generally similar across scenarios, but actual ADG was consistently greater (Table 3.6). For example, under the first iteration settings, bulls were expected to consume 9.10 ± 1.50 kg/d and gain 1.10 ± 0.45 kg/d, whereas actual intake was 9.29 kg/day and gain was 1.61 kg/d. This pattern held across BCS, mature BW, hair coat, and temperature adjustment settings, with BRaNDS underpredicting ADG by 0.4 to 0.7 kg/d.

Year-specific comparisons revealed consistent discrepancies (Tables 3.7-3.10). In Yr. 1, observed ADG was 1.51 ± 0.26 kg/d compared to predicted ranging from 0.72 (**iteration 2**) to 0.77 kg/d (**iterations 4-8**), while observed DMI (8.38 ± 0.95 kg/d) was lower than predicted ranging 9.15 - 9.61 kg/d for each iteration (Table 3.7). In Yr. 2, observed ADG was 1.63 ± 0.41 kg/d, exceeding predictions (1.04 -1.12 kg/d), while DMI (9.11 ± 1.67 kg/d) was similar to predicted (8.96 - 9.53 kg/d) (Table 3.8). In Yr. 3, observed ADG averaged 1.80 ± 0.35 kg/d compared to predicted ranging from 0.89 to 0.97 kg/d, with observed DMI (10.06 ± 2.05 kg/d) exceeding predictions of the iterations (8.48 - 8.91 kg/d) (Table 3.9). In Yr. 4, actual ADG (1.51 ± 0.27 kg/d) closely matched predictions in each iteration (1.50 - 1.58 kg/d) (Table 3.10), although observed DMI (9.58 ± 1.44 kg/d) was greater than predicted 8.25 (**Iteration 3**) to 8.40 kg/d (**Iterations 4-8**) (Table 3.10).

Correlation coefficients for the combined dataset (Yr. 1-4) are presented in Tables 3.11 and 3.12. Actual and predicted DMI (Table 3.11) were moderately correlated across all prediction settings ($r = 0.55$ - 0.56 ; $P < 0.01$). Actual and predicted ADG (Table 3.12) correlations were lower ranging ($r = 0.27$ - 0.29 ; $P < 0.01$) across the iterations.

Year-specific correlation coefficients are provided in Tables 3.13 to 3.16. In Yr. 1 (Table 3.13), actual and predicted DMI were strongly correlated ranging from ($r = 0.74-0.82$; $P < 0.01$) across the iterations. Correlations between actual and predicted ADG were weaker, with a R -values of 0.38 ($P = 0.02$). In Yr. 2 (Table 3.14), correlations for DMI were strong ($r = 0.84$ to 0.87 ; $P < 0.01$). Correlations for ADG were moderate to strong, ranging from $r = 0.59$ to 0.75 ($P < 0.01$). In Yr. 3 (Table 3.15), DMI correlations remained strong ($r = 0.69-0.71$; $P < 0.01$), while ADG correlations ranged from weak in **iteration 3** ($r = 0.33$; $P = < 0.01$) to moderate ($r = 0.60$; $P = < 0.01$) for all other iterations. In Yr. 4 (Table 3.16), DMI correlations were again strong ($r = 0.72-0.81$; $P < 0.01$), while ADG correlations remained weak ($r = 0.27-0.30$) and were not statistically significant ($P = 0.09$).

The NASEM growth model is based upon the NRC 1984 medium framed steer based on the work done by Garrett, 1980. There were adjustments made to equations to better account for the variation of composition, frame size and BW of cattle over time 2000 NRC there were adjustments made to better represent the changing population of beef cattle in the us by adjusting the BW of cattle to make them equivalent to the 1984 base steer. (NRC, 2000), (NASEM, 2016). This model can also factor in adjustment for carcass traits. However, these models and adjustments were created using mainly steer and heifer data found in the Literature at the time. (NASEM 2016) There is limited data for the growth and development of bulls. It is known that bulls partition energy differently post weaning through to a year of age and beyond, by using protein and energy for more lean tissue gain compared to steers and heifers. (NASEM, 2016), (Blanco et al., 2020), (Fortin et al., 1980), (Hedrick et al., 1969). Knowing the lack of growing bull data and Literature available to the authors of the NASEM growth models, the models may not accurately represent bulls that are feed in developmental programs. The factor of genetic change in beef cattle since the

adoption of the NASEM equations to calculate both feed intake and gain is also a likely sources for variation in the results. The genetic change in black angus cattle since the 1980's to 2024 has seen large increases in yearling weight and carcass weight EPDs (American Angus Association, 2025). This change is also apparent in the Hereford breed in the U.S. as there is a change in performance and growth EPDs similar to angus cattle (American Hereford Association, 2024). Both the genetic change in beef cattle and the lack of available bull data the models may not fully and accurately represent growing bulls in comparison to steers and heifers.

For the combined Yr. 1-4 (Tables 3.11 and 3.12) dataset using the default settings and NASEM feed library in the growing bull module, a moderate positive correlation ($r = 0.56$, $P < 0.01$) was found between actual and predicted DMI (Table 3.11), indicating that the BRaNDS formulation program moderately predicts DMI across varying diet compositions, breed composition, environmental conditions, and time on feed across years. However, a weak positive correlation ($r = 0.29$, $P < 0.01$) (Table 3.12) was observed between observed and predicted ADG, ADG was consistently underpredicted (-0.50 to -0.57 kg/d) predicted values. This consistent underestimation of ADG may reflect how BRaNDS handles metabolizable protein and energy balances in relation to different diets as the values in the feed library are the tabular values found in the 2016 NASEM. If all years had lab analyzed values for feedstuffs used to adjust the calculated energy values such as NE_m , NE_g , and DM for each year there would influences to the prediction of ADG as well as an effect of the prediction of DMI of each bull. With analyzed feedstuffs for each year there could be adjustments made to help eliminate the variation found for both ADG and DMI predictions.

Correlations between observed and predicted performance were consistently stronger when data were evaluated within year compared to when all years were pooled. When **Iteration**

1 was analyzed by year, correlations for DMI improved substantially ($r = 0.71$ - 0.84) (Tables 3.13-3.16) and those for ADG ranged from ($r = 0.27$ to 0.74) depending on year. Year-specific bias also varied: in Yr. 1, ADG was underpredicted by -0.76 kg/d (Table 3.13); in Yr. 2, underprediction averaged -0.51 kg/d despite strong correlations ($r = 0.74$)(Table 3.14); in Yr. 3 (Table 3.15), bias was -0.84 kg/d with weaker correlations ($r = 0.60$); and in Yr. 4 (Table 3.16), ADG predictions were nearly unbiased ($+0.07$ kg/d) but poorly correlated ($r = 0.27$). DMI predictions were similarly inconsistent, ranging from overprediction in Yr. 1 ($+1.23$ kg/d) (Table 3.13), Yr. 2 ($+0.42$ kg/d) (Table 3.14), Yr. 3 (-1.15 kg/d) (Table 3.15), Yr. 4 (-1.18 kg/d) (Table 3.15). Within a year, cattle were exposed to similar rations and management environments, allowing systematic error in model predictions to be more consistent and correlations to better capture relative differences among bulls. The stronger correlations for DMI relative to ADG suggest that intake equations are more robust across production scenarios than gain predictions, which remain influenced by type and kind of the cattle used to form the database the model equations that are used to predict gain and intake were developed on (NASEM, 2016). Variation of the predictions of gain and intake are also influenced by the feed composition in the feed library, environmental factors in the calculation of NE_m , BCS, and mature BW of bulls that may not fully be accounted for in the prediction models (NASEM, 2016).

Altering hair condition to represent mild or heavy mud coverage (**Iterations 4 and 5**) produced no measurable improvement in prediction accuracy for the multi-year analysis. When mild mud (**Iteration 4**) or heavy mud (**Iteration 5**) was applied, predicted DMI (Table 3.11) remained unchanged 9.09 kg/d vs. 9.10 kg/d (**Iteration 1**). Average daily gain predictions differed by only 0.01 kg/d (Table 3.12). Corresponding bias values (-0.20 kg/d for DMI and -0.50 kg/d for ADG) were virtually identical to **iteration 1**, demonstrating that the mud parameter

did not adjust predictions enough to reduce underprediction. In principle, the mud in hair coat adjustments in BRaNDS are designed to increase NE_m requirements by accounting for greater energy expenditures associated with thermoregulation and reduced insulation. (Fox et al. 1988, NASEM 2016.) A higher predicted maintenance requirement would typically increase modeled feed intake to meet energy demand and decrease predicted gain if intake is not sufficient to offset the added maintenance cost. In this dataset, however, the adjustments did not alter predictions, suggesting the bulls were not in conditions severe enough for the parameter to meaningfully change energy use.

Similarly, modifying temperature inputs by -2.8°C , -5.6°C , or $+2.8^{\circ}\text{C}$ (**Iterations 6 to 8**) relative to normal conditions did not improve alignment between predicted and observed values when all years were analyzed. Across these adjustments, predicted DMI (Table 3.11) stayed at 9.09 kg/d, and predicted ADG (Table 3.12) remained 1.11 kg/d, yielding the same biases as **iteration 1** (-0.20 kg/d for DMI and -0.50 kg/d for ADG). In theory, lower ambient temperatures should increase NE_m requirements through elevated heat production because of heat loss, leading the model to either raise predicted DMI or lower predicted ADG if intake is capped (NASEM, 2016). The lack of change in these results indicates that BRaNDS temperature adjustments were not large enough to elicit a change under the moderate confinement environments of these trials which track with how little of a temperature change the adjustment actually make.

Environmental adjustments in BRaNDS, including mud and temperature settings (**Iterations 4 to 8**), did not meaningfully change predictions across individual years. In Yr. 1, predicted ADG increased only slightly from 0.75 (Iteration 4) (Table 3.13) to 0.77 kg/d (**Iteration 5**) (Table 3.13) when mild or heavy mud on hair coat and temperature adjustments - 2.8°C , -5.6°C , or $+2.8^{\circ}\text{C}$ (**Iterations 6,7, and 8**) relative to normal conditions were applied,

while DMI predictions held constant at 9.60 kg/d (Table 3.13). This produced nearly identical bias values (-0.74 to -0.79 for ADG; +1.22 kg/d for DMI) (Table 3.13) and no improvement in correlation. In **Yr. 2**, DMI predictions were stable at 9.53 kg/d for **iterations 4 through 8** (Table 3.14), while ADG remained 1.12 kg/d (bias -0.52). Correlations were high for DMI ($r = 0.84$ - 0.87) and moderate to strong for ADG (Table 3.14) ($r = 0.59$ - 0.75), but adjustments did not alter these values. In Yr. 3, predicted DMI remained at 8.90 kg/d and ADG (Table 3.15) increased only 0.01 kg/d (0.96 to 0.97), leaving the underprediction bias (-0.83 to -0.88 for ADG; -1.15 to -1.16 for DMI) (Table 3.15) unchanged. In Yr. 4, predicted DMI stayed at 8.40 kg/d and ADG at 1.56 kg/d regardless of **iteration 4 through 8**, with correlations ($r = 0.27$ - 0.30 for ADG) (Table 3.16) and biases identical to **iteration 1**.

Conceptually, BRaNDS environmental adjustments are designed to raise maintenance energy requirements during thermal stress or with insulation from mud, which should increase predicted intake or reduce predicted gain. (NASEM, 2016). However, the lack of change across all four test years indicates that these adjustments were not large enough to elicit a change within the program. Thus, prediction accuracy in this study was determined primarily by year-specific diet composition and animal performance, not by modeled mud or temperature effects. This also explains why pooled data masked true prediction accuracy environmental settings did not account for variation across years, leaving diet and animal factors as the primary drivers of differences between observed and predicted values.

Changing BCS from 5 to 6 (**Iteration 2**) in the BRaNDS program had negligible impact on predicted intake and gain, both in pooled and yearly analyses. In the pooled dataset (Yr. 1-4), predicted DMI decreased slightly from 9.10 to 9.09 kg/d (Table 3.11) and predicted ADG decreased from 1.10 to 1.06 kg/d (Table 3.12), leaving correlations unchanged ($r = 0.56$ for DMI;

$r = 0.29$ for ADG) and bias nearly identical (-0.19 vs. -0.20 for DMI; -0.51 vs. -0.55 for ADG). Year-specific results confirmed the same pattern. In Yr. 1, predicted DMI (Table 3.13) was 9.60 compared to 9.61 kg/d (Iteration 1) and ADG declined from 0.75 (Iteration 1) to 0.72 kg/d, with bias remaining large (-0.76 vs. -0.79 kg/d) (Table 3.13). In Yr. 2, predicted DMI remained 9.53 kg/d and ADG (Table 3.14) decreased from 1.12 (Iteration 1) to 1.09 kg/d, producing nearly identical bias (-0.51 vs. -0.53 kg/d). In Yr. 3, predicted DMI (Table 3.15) decreased from 8.91 to 8.90 kg/d and ADG (Table 3.15) declined from 0.96 to 0.92 kg/d, with underprediction bias virtually unchanged (-0.84 vs. -0.88 kg/d). In Yr. 4, predicted DMI (Table 3.16) decreased from 8.40 to 8.39 kg/d and ADG (Table 3.16) decreased from 1.58 to 1.51 kg/d, resulting in bias estimates of 0.07 and 0.00, respectively.

Raising BCS by one compared to **iteration 1** did not meaningfully alter predicted performance. The BCS (**Iteration 2**) adjustment is designed to modify maintenance energy requirements based on body fat reserves, with cattle in greater condition expected to partition more energy toward maintenance and less toward gain. (NRC, 2000). Wagner et al. (1988), demonstrated that BCS is a stronger predictor of carcass energy reserves and winter maintenance needs than live weight. However, because the bulls in this study were maintained in moderate condition, the effect of BCS adjustments on predicted DMI and ADG was limited. In **iteration 1**, the observed differences in performance were far larger than the small numerical changes produced by altering the BCS input.

Changing mature BW (**Iteration 3**) from the medium category (875 kg) to the large category (1038 kg) in the BRaNDs program consistently reduced predicted intake and gain but did not improve agreement with observed performance. In the multi-year data set (Yr. 1-4) predicted DMI (Table 3.11) decreased from 9.10 (Iteration 1) to 8.70 kg/d (Iteration 3) and

predicted ADG (Table 3.12) decreased from 1.10 to 1.04 kg/d. Correlations remained essentially unchanged ($r = 0.55$ - 0.56), and bias increased relative to the base setting, with DMI underpredicted by -0.59 kg/d and ADG underpredicted by -0.57 kg/d.

Year-specific results confirmed this pattern. In Yr. 1, predicted DMI (Table 3.13) decreased from 9.61 to 9.15 kg/d and ADG (Table 3.13) decreased from 0.75 to 0.71 kg/d, producing biases of $+0.77$ kg/d for DMI and -0 . Yr. 2, predicted DMI (Table 3.14) decreased from 9.53 to 8.96 kg/d and ADG (Table 3.14) decreased from 1.12 to 1.04 kg/d. Although correlations for DMI were strong ($r = 0.87$) and slightly higher than the base run, the underprediction of ADG remained (-0.53 kg/d). In Yr. 3, predicted DMI (Table 3.15) decreased from 8.91 to 8.48 kg/d and ADG (Table 3.15) decreased from 0.96 to 0.89 kg/d, with correlations declining for both traits ($r = 0.69$ for DMI and $r = 0.33$ for ADG) and underprediction bias increasing (-1.58 kg/d for DMI and -0.91 kg/d for ADG). In Yr. 4, predicted DMI (Table 3.16) decreased from 8.40 to 8.25 kg/d and ADG (Table 3.16) decreased from 1.58 to 1.50 kg/d, with bias estimates of -1.33 and -0.01 , respectively.

The direction of these changes is consistent with the underlying biology. Increasing the assumed mature BW raises predicted maintenance energy requirements, which reduces the proportion of RE available for gain. (NASEM, 2016). As a result, predicted ADG decreased in every year. While this outcome is logical given the model design, the adjustment did not improve overall accuracy. The bulls in this study gained more than BRaNDs predictions even under the larger mature BW assumption, indicating that the parameter did not capture their true growth potential. In the controlled bull test environment, diet composition and year-specific performance explained more of the discrepancy than mature BW classification.

Conclusions

The BRaNDS program moderately accurately predict DMI, however, it does not predict ADG accurately with consistently lower predicted values in comparison to the observed of growing beef bulls under the constraints utilized in this retrospective analysis. Refinement of metabolizable energy and protein equations, as well as additional use of individual animal intake and performance data collected under various model input constraints are needed to improve accuracy of prediction models for ADG and DMI

Table 3.1 Ingredient composition of diets Yr. 1 and Yr. 2, % DM basis

Item	Yr.1 ¹	Yr. 1 ²	Yr. 2
Corn Silage	43.50	35.70	60.00
Wet Corn Gluten Feed	21.75	25.00	25.00
DDGS ³	--	--	--
Steam Flaked Corn	--	--	7.98
Dry Rolled Corn	23.00	10.00	--
CGM	--	--	--
Brome Hay	9.46	22.15	--
Supplement ⁴	2.29	2.15	1.74
ω -3 Fatty Acid Suppl. ⁵	--	5.00	5.28

¹ Fed from November 11 to December 29, 2021

² Fed from December 30, 2021, to February 2, 2022

³ Distillers dried grains with solubles

⁴ Supplement includes vitamins, minerals, and rumensin

⁵ ω -3 Fatty Acid Supplement = extruded flaxseed and algae blend

Table 3.2 Ingredient composition of diets by year, % DM basis

Item	Yr. 3 ¹	Yr. 3 ²	Yr. 3 ³	Yr. 4 ⁴	Yr. 4 ⁵	Yr. 4 ⁶
Corn Silage	30.50	31.10	30.80	30.90	31.40	29.00
Wet Corn Gluten Feed	29.20	27.50	26.10	-	-	-
DDGS ⁷	-	-	-	20.00	20.30	18.70
Steam Flaked Corn	-	-	-	-	-	-
Dry Rolled Corn	20.30	17.80	16.40	18.90	19.10	23.60
CGM ⁸	-	-	-	9.80	6.30	5.40
Brome Hay	12.50	14.10	14.70	13.30	13.50	12.40
Supplement ⁹	7.50	7.30	7.60	7.10	7.20	6.70
ω-3 Fatty Acid Suppl. ¹⁰	-	2.20	4.50	-	2.30	4.20

¹ Control Diet Yr. 3.

² 0.23 kg Omega 3 Fatty Acid Suppl. Inclusion Diet Yr. 3.

³ 0.45 kg. Omega 3 Fatty Acid Suppl. Inclusion Diet Yr. 3.

⁴ Control Diet Yr. 3.

⁵ 0.23 kg Omega 3 Fatty Acid Suppl. Inclusion Diet Yr. 3.

⁶ 0.45 kg. Omega 3 Fatty Acid Suppl. Inclusion Diet Yr. 3.

⁷ Distillers dried grains with solubles.

⁸ Corn germ meal.

⁹ Supplement includes vitamins, minerals, and rumensin.

¹⁰ ω-3 Fatty Acid Supplement = extruded flaxseed and algae blend.

Table 3.3 Default program inputs and subsequent parameter iterations used for BRaNDS evaluation.

Parameter	Default Value	Scale/Options
Feeding period dates	Actual feeding period of each year	Recorded start and end dates
Average BW	Actual animal average BW (start-end)	Continuous, calculated from initial and final weights
Weight range	91 kg	Fixed
Mature BW (scale 1-3)	2 = Medium (875 kg)	1 = Small (712 kg), 2 = Medium (875 kg), 3 = Large (1038 kg)
Breed type	2 = British-higher milk	1 = British-lower milk, 2 = British-higher milk, 3 = Continental-lower milk, 4 = Continental-higher milk, 5 = Zebu influence, 6 = Dairy influence, 7 = Club (Brit. × Cont.)
Condition score (1-9)	5	1 = thin, 9 = fat
Wind exposure (1-3)	1	1 = some protection, 2 = no protection, 3 = in building
Hair condition (1-4)	1 = clean, dry hair	1 = clean, dry, 2 = mild mud, 3 = heavy mud, 4 = wet/matted
Hair coat (1-4)	3 = winter	1 = summer, 2 = transition, 3 = winter, 4 = heavy winter
Temperature input	1 = normal	2 = 2.8°C colder, 3 = 5.6°C colder, 4 = 2.8°C warmer, 5 = 5.6°C warmer, 6 = in building
Breeding age	15 months	Fixed
Target empty BW gain	2.75 lb/day	Fixed

Table 3.4 Iterations applied to evaluate parameter sensitivity in BRaNDS predictions.

Iteration	Parameter Changed	Default Value	Iteration Value(s) Tested
1	Default	—	All parameters at baseline values (Table 3.3)
2	BCS	5	6
3	Mature BW	Medium (875 kg)	Large (1038 kg)
4	Hair condition	1 = clean, dry	2 = mild mud
5	Hair condition	1 = clean, dry	3 = heavy mud
6	Temperature	1 = normal	2 = 5°F colder (2.8°C colder)
7	Temperature	1 = normal	3 = 10°F colder (5.6°C colder)
8	Temperature	1 = normal	4 = 5°F warmer (2.8°C warmer)

Table 3.5 Actual bull performance means across four years

Item	Yr. 1-4 ¹			
	Mean	SD ²	Minimum	Maximum
Initial BW, ³ kg	353.39	52.73	236.02	534.33
Ending BW, ³ kg	473.29	61.41	284.40	637.75
DMI, ⁴ kg/d	9.29	1.69	4.15	13.75
ADG, ⁵ kg	1.61	0.34	0.34	2.64
G:F ⁶	0.168	0.04	0.292	0.084

¹ 2021-2025, n = 154.

² Standard deviation.

³ BW = body weight.

⁴ DMI = dry matter intake.

⁵ ADG = average daily gain.

⁶ G:F = feed to gain ratio.

Table 3.6 Predicted bull performance means across four years

Item ³	Yr. 1-4 ¹			
	Mean	SD ²	Minimum	Maximum
Iteration 1				
DMI ⁴ , kg/d	9.10	1.50	6.40	13.24
ADG ⁵ , kg/d	1.10	0.45	0.16	2.92
Iteration 2				
DMI ⁴ , kg/d	9.09	1.50	6.40	13.20
ADG ⁵ , kg/d	1.06	0.42	0.25	2.00
Iteration 3				
DMI ⁴ , kg/d	8.70	1.07	3.82	11.47
ADG ⁵ , kg/d	1.04	0.43	0.14	2.30
Iteration 4				
DMI ⁴ , kg/d	9.09	1.49	6.40	13.20
ADG ⁵ , kg/d	1.11	0.44	0.16	2.05
Iteration 5				
DMI ⁴ , kg/d	9.09	1.49	6.40	13.20
ADG ⁵ , kg/d	1.11	0.44	0.16	2.05
Iteration 6				
DMI ⁴ , kg/d	9.09	1.49	6.40	13.20
ADG ⁵ , kg/d	1.11	0.44	0.16	2.05
Iteration 7				
DMI ⁴ , kg/d	9.09	1.49	6.40	13.20
ADG ⁵ , kg/d	1.11	0.44	0.16	2.05
Iteration 8				
DMI ⁴ , kg/d	9.09	1.49	6.40	13.20
ADG ⁵ , kg/d	1.11	0.44	0.16	2.05

¹ 2021-2025, n = 154.² Standard deviation.³ Iteration details found in table (3.2).⁴ DMI = dry matter intake.⁵ ADG = average daily gain.

Table 3.7 Actual and predicted bull performance means Yr. 1

Item ³	2021 ¹			
	Mean	SD ²	Minimum	Maximum
Actual				
Initial BW ⁴ , kg	362.91	48.53	284.40	534.33
Ending BW ⁴ , kg	489.82	53.44	362.87	637.75
DMI, ⁵ kg/d	8.38	0.95	6.33	10.96
ADG, ⁶ kg	1.51	0.26	0.70	1.91
Iteration 1				
DMI, kg/d	9.61	1.43	7.57	13.24
ADG, kg/d	0.75	0.18	0.35	1.27
Iteration 2				
DMI, kg/d	9.60	1.42	7.57	13.20
ADG, kg/d	0.72	0.17	0.31	1.23
Iteration 3				
DMI, kg/d	9.15	1.05	7.57	13.20
ADG, kg/d	0.71	0.16	0.34	1.18
Iteration 4				
DMI, kg/d	9.60	1.42	7.57	13.20
ADG, kg/d	0.77	0.18	0.36	1.31
Iteration 5				
DMI, kg/d	9.60	1.42	7.57	13.20
ADG, kg/d	0.77	0.18	0.36	1.31
Iteration 6				
DMI, kg/d	9.60	1.42	7.57	13.20
ADG, kg/d	0.77	0.18	0.36	1.31
Iteration 7				
DMI, kg/d	9.60	1.42	7.57	13.20
ADG, kg/d	0.77	0.18	0.36	1.31
Iteration 8				
DMI, kg/d	9.60	1.42	7.57	13.20
ADG, kg/d	0.77	0.18	0.36	1.31

¹ n = 38² Standard deviation.³ Iteration details found in table (3.2).⁴ BW = body weight.⁵ DMI = dry matter intake.⁶ ADG = average daily gain.

Table 3.8 Actual and predicted bull performance means Yr. 2.

Item ³	2022 ¹			
	Mean	SD ²	Minimum	Maximum
Actual				
Initial BW ⁴ , kg	365.07	54.09	259.45	469.92
Ending BW, kg	482.16	71.53	284.40	608.72
DMI, ⁵ kg/d	9.11	1.67	4.15	12.21
ADG, ⁶ kg/d	1.63	0.41	0.34	2.37
Iteration 1				
DMI, ⁵ kg/d	9.53	1.62	6.40	12.25
ADG, ⁶ kg/d	1.12	0.36	0.16	1.87
Iteration 2				
DMI, ⁵ kg/d	9.53	1.62	6.40	12.25
ADG, ⁶ kg/d	1.09	0.32	0.36	1.81
Iteration 3				
DMI, ⁵ kg/d	8.96	1.09	6.40	12.25
ADG, ⁶ kg/d	1.04	0.33	0.14	1.71
Iteration 4				
DMI, ⁵ kg/d	9.53	1.62	6.40	12.25
ADG, ⁶ kg/d	1.12	0.36	0.16	1.87
Iteration 5				
DMI, ⁵ kg/d	9.53	1.62	6.40	12.25
ADG, ⁶ kg/d	1.12	0.36	0.16	1.87
Iteration 6				
DMI, ⁵ kg/d	9.53	1.62	6.40	12.25
ADG, ⁶ kg/d	1.12	0.36	0.16	1.87
Iteration 7				
DMI, ⁵ kg/d	9.53	1.62	6.40	12.25
ADG, ⁶ kg/d	1.12	0.36	0.16	1.87
Iteration 8				
DMI, ⁵ kg/d	9.53	1.62	6.40	12.25
ADG, ⁶ kg/d	1.12	0.36	0.16	1.87

¹ n = 37² Standard deviation.³ Iteration details found in table (3.2).⁴ BW = body weight.⁵ DMI = dry matter intake.⁶ ADG = average daily gain.

Table 3.9 Actual and predicted bull performance means Yr. 3.

Item ³	2023 ¹			
	Mean	SD ²	Minimum	Maximum
Actual				
Initial BW ⁴ , kg	352.05	54.09	236.02	487.76
Ending BW, kg	467.22	59.85	335.96	578.78
DMI, ⁵ kg/d	10.06	2.05	6.58	13.49
ADG, ⁶ kg/d	1.80	0.35	1.08	2.64
Iteration 1				
DMI, ⁵ kg/d	8.91	1.46	6.49	11.84
ADG, ⁶ kg/d	0.96	0.38	0.32	1.64
Iteration 2				
DMI, ⁵ kg/d	8.90	1.45	6.44	11.84
ADG, ⁶ kg/d	0.92	0.39	0.25	1.61
Iteration 3				
DMI, ⁵ kg/d	8.48	0.98	6.44	11.84
ADG, ⁶ kg/d	0.89	0.38	0.24	1.54
Iteration 4				
DMI, ⁵ kg/d	8.90	1.45	6.44	11.84
ADG, ⁶ kg/d	0.97	0.40	0.29	1.66
Iteration 5				
DMI, ⁵ kg/d	8.90	1.45	6.44	11.84
ADG, ⁶ kg/d	0.97	0.40	0.29	1.66
Iteration 6				
DMI, ⁵ kg/d	8.90	1.45	6.44	11.84
ADG, ⁶ kg/d	0.97	0.40	0.29	1.66
Iteration 7				
DMI, ⁵ kg/d	8.90	1.45	6.44	11.84
ADG, ⁶ kg/d	0.97	0.40	0.29	1.66
Iteration 8				
DMI, ⁵ kg/d	8.90	1.45	6.44	11.84
ADG, ⁶ kg/d	0.97	0.40	0.29	1.66

¹ n = 40² Standard deviation.³ Iteration details found in table (3.2).⁴ BW = body weight.⁵ DMI = dry matter intake.⁶ ADG = average daily gain.

Table 3.10 Actual and predicted bull performance means Yr. 4.

Item ³	2024 ¹			
	Mean	SD ²	Minimum	Maximum
Actual				
Initial BW ⁴ , kg	334.40	50.34	242.07	463.88
Ending BW, kg	454.98	56.09	320.39	628.98
DMI, ⁵ kg/d	9.58	1.44	6.12	13.75
ADG, ⁶ kg/d	1.51	0.27	0.97	2.33
Iteration 1				
DMI, ⁵ kg/d	8.40	1.19	6.40	12.07
ADG, ⁶ kg/d	1.58	0.37	0.79	2.92
Iteration 2				
DMI, ⁵ kg/d	8.39	1.19	6.40	12.07
ADG, ⁶ kg/d	1.51	0.31	0.76	2.00
Iteration 3				
DMI, ⁵ kg/d	8.25	0.95	6.40	12.07
ADG, ⁶ kg/d	1.50	0.33	0.73	2.30
Iteration 4				
DMI, ⁵ kg/d	8.40	1.19	6.40	12.07
ADG, ⁶ kg/d	1.56	0.31	0.79	2.05
Iteration 5				
DMI, ⁵ kg/d	8.40	1.19	6.40	12.07
ADG, ⁶ kg/d	1.56	0.31	0.79	2.05
Iteration 6				
DMI, ⁵ kg/d	8.40	1.19	6.40	12.07
ADG, ⁶ kg/d	1.56	0.31	0.79	2.05
Iteration 7				
DMI, ⁵ kg/d	8.40	1.19	6.40	12.07
ADG, ⁶ kg/d	1.56	0.31	0.79	2.05
Iteration 8				
DMI, ⁵ kg/d	8.40	1.19	6.40	12.07
ADG, ⁶ kg/d	1.56	0.31	0.79	2.05

¹ n = 39² Standard deviation.³ Iteration details found in table (3.2).⁴ BW = body weight.⁵ DMI = dry matter intake.⁶ ADG = average daily gain.

Table 3.11 Correlation coefficients for actual and predicted DMI of bulls across four years.

Item ²	Yr. 1-4 ¹				
	Actual	Predicted	r	P-value	Bias
Iteration 1	9.29	9.10	0.56	<0.01	-0.19
Iteration 2	9.29	9.09	0.56	<0.01	-0.20
Iteration 3	9.29	8.70	0.55	<0.01	-0.59
Iteration 4	9.29	9.09	0.56	<0.01	-0.20
Iteration 5	9.29	9.09	0.56	<0.01	-0.20
Iteration 6	9.29	9.09	0.56	<0.01	-0.20
Iteration 7	9.29	9.09	0.56	<0.01	-0.20
Iteration 8	9.29	9.09	0.56	<0.01	-0.20

¹ 2021-2025, n = 154.

² Iteration detail found in table 3.2.

Table 3.12 Correlation coefficients for actual and predicted ADG of bulls across four years.

Item ²	Yr. 1-4				
	Actual	Predicted	r	P-value	Bias
Iteration 1	1.61	1.10	0.29	<0.01	-0.51
Iteration 2	1.61	1.06	0.29	<0.01	-0.55
Iteration 3	1.61	1.04	0.27	<0.01	-0.57
Iteration 4	1.61	1.11	0.29	<0.01	-0.50
Iteration 5	1.61	1.11	0.29	<0.01	-0.50
Iteration 6	1.61	1.11	0.29	<0.01	-0.50
Iteration 7	1.61	1.11	0.29	<0.01	-0.50
Iteration 8	1.61	1.11	0.29	<0.01	-0.50

¹ 2021-2024, n = 154² Iteration detail found in table (3.2).

Table 3.13 Correlation coefficients for actual and predicted intake and gain of bulls by year.

Item ²	Yr.1 ¹				
	Actual	Predicted	r	P-Value	Bias
Iteration 1					
DMI ³ , kg/d	8.38	9.61	0.81	<0.01	1.23
ADG ⁴ , kg/d	1.51	0.75	0.38	0.02	-0.76
Iteration 2					
DMI ³ , kg/d	8.38	9.60	0.82	<0.01	1.22
ADG ⁴ , kg/d	1.51	0.72	0.38	0.02	-0.79
Iteration 3					
DMI ³ , kg/d	8.38	9.15	0.74	<0.01	0.77
ADG ⁴ , kg/d	1.51	0.71	0.38	0.02	-0.80
Iteration 4					
DMI ³ , kg/d	8.38	9.60	0.82	<0.01	1.22
ADG ⁴ , kg/d	1.51	0.77	0.38	0.02	-0.74
Iteration 5					
DMI ³ , kg/d	8.38	9.60	0.82	<0.01	1.22
ADG ⁴ , kg/d	1.51	0.77	0.38	0.02	-0.74
Iteration 6					
DMI ³ , kg/d	8.38	9.60	0.82	<0.01	1.22
ADG ⁴ , kg/d	1.51	0.77	0.38	0.02	-0.74
Iteration 7					
DMI ³ , kg/d	8.38	9.60	0.82	<0.01	1.22
ADG ⁴ , kg/d	1.51	0.77	0.38	0.02	-0.74
Iteration 8					
DMI ³ , kg/d	8.38	9.60	0.82	<0.01	1.22
ADG ⁴ , kg/d	1.51	0.77	0.38	0.02	-0.74

¹ 2021-2022. n = 38.² Iteration detail found in table (3.2).³ DMI = dry matter intake.⁴ ADG = average daily gain.

Table 3.14 Correlation coefficients for actual and predicted intake and gain of bulls by year.

Item ²	Yr. 2 ¹				
	Actual	Predicted	r	P-value	Bias
Iteration 1					
DMI ³ , kg/d	9.11	9.53	0.84	<0.01	0.42
ADG ⁴ , kg/d	1.63	1.12	0.74	<0.01	-0.51
Iteration 2					
DMI ³ , kg/d	9.11	9.53	0.84	<0.01	0.42
ADG ⁴ , kg/d	1.63	1.09	0.59	<0.01	-0.53
Iteration 3					
DMI ³ , kg/d	9.11	8.96	0.87	<0.01	-0.15
ADG ⁴ , kg/d	1.63	1.04	0.75	<0.01	-0.53
Iteration 4					
DMI ³ , kg/d	9.11	9.53	0.84	<0.01	0.42
ADG ⁴ , kg/d	1.63	1.12	0.74	<0.01	-0.52
Iteration 5					
DMI ³ , kg/d	9.11	9.53	0.84	<0.01	0.42
ADG ⁴ , kg/d	1.63	1.12	0.74	<0.01	-0.52
Iteration 6					
DMI ³ , kg/d	9.11	9.53	0.84	<0.01	0.42
ADG ⁴ , kg/d	1.63	1.12	0.74	<0.01	-0.52
Iteration 7					
DMI ³ , kg/d	9.11	9.53	0.84	<0.01	0.42
ADG ⁴ , kg/d	1.63	1.12	0.74	<0.01	-0.52
Iteration 8					
DMI ³ , kg/d	9.11	9.53	0.84	<0.01	0.42
ADG ⁴ , kg/d	1.63	1.12	0.74	<0.01	-0.52

¹ 2022-2023. n = 37.² Iteration detail found in table (3.2).³ DMI = dry matter intake.⁴ ADG = average daily gain.

Table 3.15 Correlation coefficients for actual and predicted intake and gain of bulls by year

Item ²	Yr. 3 ¹				
	Actual	Predicted	r	P-Value	Bias
Iteration 1					
DMI ³ , kg/d	10.06	8.91	0.71	<0.01	-1.15
ADG ⁴ , kg/d	1.80	0.96	0.60	<0.01	-0.84
Iteration 2					
DMI ³ , kg/d	10.06	8.90	0.71	<0.01	-1.16
ADG ⁴ , kg/d	1.80	0.92	0.60	<0.01	-0.88
Iteration 3					
DMI ³ , kg/d	10.06	8.48	0.69	<0.01	-1.58
ADG ⁴ , kg/d	1.80	0.89	0.33	<0.01	-0.91
Iteration 4					
DMI ³ , kg/d	10.06	8.90	0.71	<0.01	-1.16
ADG ⁴ , kg/d	1.80	0.97	0.60	<0.01	-0.83
Iteration 5					
DMI ³ , kg/d	10.06	8.90	0.71	<0.01	-1.16
ADG ⁴ , kg/d	1.80	0.97	0.60	<0.01	-0.83
Iteration 6					
DMI ³ , kg/d	10.06	8.90	0.71	<0.01	-1.16
ADG ⁴ , kg/d	1.80	0.97	0.60	<0.01	-0.83
Iteration 7					
DMI ³ , kg/d	10.06	8.90	0.71	<0.01	-1.16
ADG ⁴ , kg/d	1.80	0.97	0.60	<0.01	-0.83
Iteration 8					
DMI ³ , kg/d	10.06	8.90	0.71	<0.01	-1.16
ADG ⁴ , kg/d	1.80	0.97	0.60	<0.01	-0.83

¹ 2023-2024. n = 40² Iteration detail found in table (3.2).³ DMI = dry matter intake.⁴ ADG = average daily gain.

Table 3.16 Correlation coefficients for actual and predicted intake and gain of bulls by year

Item ²	Yr. 4 ¹				
	Actual	Predicted	r	P-value	Bias
Iteration 1					
DMI ³ , kg/d	9.58	8.40	0.72	<0.01	-1.18
ADG ⁴ , kg/d	1.51	1.58	0.27	0.09	0.07
Iteration 2					
DMI ³ , kg/d	9.58	8.39	0.72	<0.01	-1.19
ADG ⁴ , kg/d	1.51	1.51	0.28	0.09	0.00
Iteration 3					
DMI ³ , kg/d	9.58	8.25	0.81	<0.01	-1.33
ADG ⁴ , kg/d	1.51	1.50	0.30	0.06	-0.01
Iteration 4					
DMI ³ , kg/d	9.58	8.40	0.72	<0.01	-1.18
ADG ⁴ , kg/d	1.51	1.56	0.27	0.09	0.05
Iteration 5					
DMI ³ , kg/d	9.58	8.40	0.72	<0.01	-1.18
ADG ⁴ , kg/d	1.51	1.56	0.27	0.09	0.05
Iteration 6					
DMI ³ , kg/d	9.58	8.40	0.72	<0.01	-1.18
ADG ⁴ , kg/d	1.51	1.56	0.27	0.09	0.05
Iteration 7					
DMI ³ , kg/d	9.58	8.40	0.72	<0.01	-1.18
ADG ⁴ , kg/d	1.51	1.56	0.27	0.09	0.05
Iteration 8					
DMI ³ , kg/d	9.58	8.40	0.72	<0.01	-1.18
ADG ⁴ , kg/d	1.51	1.56	0.27	0.09	0.05

¹ 2024-2025. n = 39.² Iteration detail found in table (3.2).³ DMI = dry matter intake.⁴ ADG = average daily gain.

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