Comparison of ProCROSS and Holstein cows for dry matter intake, body weight, cow height, body condition score, production, feed efficiency, income over feed cost, and residual feed intake

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Brittany N. Shonka-Martin

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Dr. Leslie B. Hansen, Co-adviser

Dr. Bradley J. Heins, Co-adviser

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ABSTRACT

ProCROSS (Montbéliarde, Viking Red, Holstein) rotational crossbred cows were compared to Holstein (**HO**) cows for dry matter intake (**DMI**), body weight (**BW**), cow height, body condition score (**BCS**), production, alternative measures of feed efficiency, income over feed costs (**IOFC**), and residual feed intake (**RFI**) from 4 to 150 days in milk (**DIM**) of first, second, and third lactations. Primiparous and multiparous ProCROSS (n = 63 and n = 43, respectively) and HO (n = 60 and n = 37, respectively) cows calved from September 2014 to June 2017. Cows were fed the same total mixed ration twice daily with refusals weighed once daily, and feed was analyzed for dry matter content, net energy of lactation, and crude protein content. The BW was recorded twice weekly, and height at the withers and the hips was recorded monthly. The BCS was evaluated weekly. Daily production of milk, fat, and protein were estimated from monthly test days using Best Prediction. Measures of efficiency from 4 to 150 DIM were feed conversion efficiency (**FCE**), defined as fat plus protein production (kg) per kilogram of DMI; **ECM/DMI**, defined as kilograms of energy-corrected milk (**ECM**) per kilogram of DMI; net energy of lactation efficiency (**NE_LE**), defined as ECM (kg) per megacalorie of net energy of lactation intake; crude protein efficiency (**CPE**), defined as true protein production (kg) per kilogram of crude protein intake; and **DMI/BW**, defined as DMI (kg) per kilogram of BW. The IOFC was defined as revenue from fat plus protein production minus feed cost. The RFI from 4 to 150 DIM for each lactation was the residual error remaining from regression of DMI on milk energy output (Mcal), metabolic BW ($BW^{0.75}$), and change in body energy (Mcal). Primiparous and multiparous cows were analyzed separately. Statistical analysis for primiparous cows included the

fixed effects of year of calving and breed group, and the analysis for multiparous cows included the fixed effect of breed group and the repeated effect of cow nested within breed group. Primiparous ProCROSS cows (2,807 kg) had lower mean DMI than HO (2,948 kg) cows from 4 to 150 DIM of first lactation. Mean BW was not different for the ProCROSS (562 kg) and HO (556 kg) cows, but primiparous ProCROSS cows had mean wither height that was 4.0 cm shorter and mean hip height that was 2.0 cm shorter than the means of HO cows. Primiparous ProCROSS (3.46) had higher mean BCS compared to HO cows (3.20). Mean fat plus protein production did not differ for the primiparous ProCROSS and HO cows (331 kg vs. 329 kg, respectively). Primiparous ProCROSS cows had higher means for FCE (+5.5%), ECM/DMI (+4.0%), NE_LE (+4%), and CPE (+5.2%), but a lower mean DMI/BW (–5.3%), than primiparous HO cows. Primiparous ProCROSS cows ($875) also had higher mean IOFC than primiparous HO cows ($825). In addition, mean RFI from 4 to 150 DIM was significantly lower (more desirable) for primiparous ProCROSS cows than HO cows. Multiparous ProCROSS cows (3,360 kg) also had lower mean DMI than HO cows (3,592 kg) and did not differ (636 kg) from HO cows (644 kg) for mean BW. The ProCROSS cows had mean wither height that was 3.5 cm shorter than HO cows, but mean hip height did not differ for multiparous ProCROSS (145.2 cm) and HO cows (146.4 cm). Mean BCS was higher for multiparous ProCROSS cows (3.25) than for HO cows (3.06), and mean fat plus protein production was not different for multiparous ProCROSS (445 kg) and HO (441 kg) cows. The multiparous ProCROSS cows had higher means for FCE (+8.2%), ECM/DMI (+5.9%), NE_LE (+5.8%), and CPE (+8.1%) and a lower mean for DMI/BW (–4.8%) than multiparous HO cows. Multiparous ProCROSS cows ($1,296) also had a higher mean for IOFC than multiparous HO cows ($1,208) and a lower mean for RFI from 4 to 150 DIM than HO cows.

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CHAPTER 1. INTRODUCTION

1.1 Introduction

Over the past 20 years, the change in milk pricing toward the solids in milk, the reduction of fertility, health, and survival of Holstein (**HO**) cows, and the increase in average inbreeding of HO cows have all contributed to an increased number of crossbred dairy cows in the United States (Weigel and Barlass, 2003). Numerous studies from the 1940s to 1990s reported favorable results for crossbreds than purebreds (Touchberry, 1992); however, considerable pushback from breed associations as well as the higher mean milk volume of HO cows resulted in the global domination by the HO breed beginning in the 1980s.

The efficient utilization of feed consumed by dairy cows has grown in interest as an area of research in recent years because of heightened emphasis on agriculture sustainability. More than 50% of the expenses of dairy operations in the United States are feed cost (USDA-ERS, 2018). Therefore, feed efficiency (**FE**) of dairy cows is economically important. Modern dairy cows have higher FE than their ancestors because of increased milk production per cow resulting from genetic selection, improved nutrition, and enhanced herd management. Today's genetically-improved cows partition a higher percentage of feed to production instead of maintenance (VandeHaar et al., 2016). However, much of the potential gain in FE of dairy cows from increased production has already been exploited, so other approaches are needed to increase production per unit of feed (VandeHaar et al., 2016).

Most recent research on FE has explored the genetic control of FE for pure HO cows rather than comparing breeds of cows for FE. In order for dairy producers to make more judicious decisions on the breed composition of their cows, the FE of crossbred cows needs to be investigated. However, data on FE are costly to acquire because of the specialized labor and equipment to collect feed intake (**FI**) for individual cows. Body traits of cows such as body weight (**BW**), cow height, and body condition score (**BCS**) are also valuable for comparing crossbreds to purebreds for functionality and profitability in commercial dairies. Increased BCS is associated with improved fertility and health (Roche et al., 2009), and cows with extremely large frame size will not easily fit into modern free-stalls and milking parlors.

For high-input confinement herds with limited opportunity for grazing, a 3-breed rotational system incorporating the 3 breed groups of HO, Alpine, and Nordic Red has been recommended by Dechow and Hansen (2017). Specifically, interest is growing in an ongoing rotation including the HO, Montbéliarde (MO), and Viking Red (VR) breeds that is marketed internationally as ProCROSS by Coopex Montbéliarde (Roulans, France) and Viking Genetics (Randers, Denmark). Few studies have compared MO, VR, and HO crossbred cows with pure HO for FE and related traits such as dry matter intake (DMI), body traits, and production. Therefore, the objective of the following research was to compare HO, MO, and VR crossbred cows to pure HO cows for DMI, BW, cow height, BCS, production, and FE during the first 3 lactations.

1.2 Dissertation organization

A review of relevant literature to illustrate the need for the research of this dissertation is presented in Chapter 2. Chapters 3 and 4 were written and formatted for publication in scientific journals. Chapter 3 presents a comparison of ProCROSS and HO cows for DMI, BW, frame size, BCS, and production. Chapter 4 provides a comparison of the 2 breed groups for alternative measures of FE including ratios, income over feed cost, and residual feed intake.

CHAPTER 2. LITERATURE REVIEW

2.1 Genetic factors affecting livestock breeding decisions

2.1.1 Inbreeding depression

Inbreeding is the mating of animals more closely related to each other than random individuals in a population (Bourdon, 2000). Inbreeding of an individual is measured as an inbreeding coefficient and is the probability the 2 genes at the same locus on the chromosomes are identical by descent (Falconer and Mackay, 1996). The interaction of genes at the same locus is referred to as dominance effects, which is when one version of the gene at a locus potentially dominates over and masks the deleterious effect of a recessive gene at the same locus. Inbreeding results in an increase of homozygous genotypes, some of which will be paired deleterious recessive alleles. The consequence is inbreeding depression, which is defined as a reduction of the mean phenotype of measured traits such as production or fertility of an animal (Falconer and Mackay, 1996).

Inbreeding depression mainly affects traits that influence overall fitness and can be expressed as reduced fertility, more disease, or increased mortality from expression of paired recessive alleles (Falconer and Mackay, 1996). For domestic livestock species, the historic recommendation has been to maintain the inbreeding coefficient (a measure of inbreeding) of individuals below 6.25% to minimize the negative consequences of inbreeding (Hansen, 2000). However, inbreeding is sometimes proactively practiced by animal breeders to create inbred lines for crossing or to obtain genetic uniformity of lab animals (Falconer and Mackay, 1996; Bourdon, 2000).

2.1.2 Heterosis

Crossbreeding is defined as the crossing of unrelated lines, breeds, or populations of animals (Sørensen et al., 2008). Breeders of other livestock species such as beef, pigs, and poultry have utilized crossbreeding for decades to capitalize on heterosis (also known as hybrid vigor), which is expressed as an increase in performance of a crossbred animals above what is expected based on the parental means for a trait. Heterosis is the opposite of inbreeding depression in terms of genetic variance due to dominance effects. Unrelated breeds are less likely to have alleles that are identical by descent than related breeds; therefore, crossing unrelated breeds results in crossbred animals that are heterozygous for a larger number of allelic pairs of genes than crossing more closely related breeds (Falconer and Mackay, 1996). Heterosis typically affects the same traits that experience significant inbreeding depression, such as fertility and health, but in an opposite and positive direction (Falconer and Mackay, 1996).

The amount of heterosis expressed by crossbred animals depends on their breed composition. The first generation of offspring from the crossing 2 breeds have 100% heterosis. If the 2 breeds are alternated back and forth in successive generations, heterosis will eventually plateau at 67% of full heterosis in later generations. In other words, the crossbred animals in later generations will benefit from only 67% of the heterosis experienced by the crossbred animal in the first generation. As the number of breeds involved in a crossbreeding rotation rises, the mean level of heterosis increases across generations. However, as the number of breeds increases, more intense management is required by breeders to ensure correct matings are being implemented. For dairy cattle, a 3-breed rotational crossbreeding system has been recommended by Dechow and Hansen

(2017). The first 2 generations when crossing 3 breeds have 100% heterosis and, as generations continue, heterosis plateaus at approximately 86% of full heterosis. A 3-breed rotational system ensures a high mean level of heterosis is realized while requiring less effort to maintain than a rotational system using more than 3 breeds.

Sørensen et al. (2008) reviewed the expected heterosis of F1 cows for traits of economic importance of dairy cattle and reported heterosis was highest for traits related to fitness and functionality, such as fertility (~10%) and longevity (~10 to 15%). Also, maternal heterosis estimates for calving ease and stillbirth were 5 to 10% (Sørensen et al., 2008). They also reported heterosis was the lowest (~3%) for production traits. Similar estimates have been reported for beef cattle with heterosis being highest for cow productivity and longevity and lowest for carcass traits (Kress and Nelsen, 1988).

2.1.3 Additive genetic effects

Additive genetic effects stem from the effects of individual genes passed on from the parent breeds that were used for crossbreeding without interaction of the genes. Breeds considered for crossbreeding systems should have strong genetic selection programs and be rated highly for economically important traits. Combining the favorable attributes of multiple breeds may allow dairy producers to obtain quicker improvement of functional traits such as fertility, health, and survival than selection within breeds (Sørensen et al., 2008). Breeds must also be chosen to fit specific environments. For example, breeders with grazing systems may choose breeds that are small or intermediate for body size (Swan and Kinghorn, 1992). In general, crossbreeding increases the amount of genetic resources available to dairy producers, because the range of available genetic material becomes larger when more than a single breed is involved. This results in greater flexibility when developing a breeding program (Swan and Kinghorn, 1992).

2.2 Historic studies of crossbred dairy cows

In the early 1900s, crossbreeding experiments took place in private herds and research stations in both Europe and the United States (Touchberry, 1992). Many of these early projects were designed to study the mode of inheritance of traits such as coat color or whether there was heterosis for milk volume or fat yield. Most projects studied a small number of cows, and genetic level of the cows or sires was seldom mentioned (Fohrman et al., 1954). Therefore, firm conclusions about the benefits of crossbreeding for commercial milk production were difficult to disseminate to the public.

2.2.1 Crossbreeding at the Bureau of Dairy Industry

Dairy producers became more interested in crossbreeding after the success of hybrid corn, after the emergence of crossbreeding as a practical strategy for poultry, swine, and sheep, and after the practice of artificial insemination became routine (Fohrman et al., 1954). Increased interest in crossbreeding prompted researchers at the Bureau of Dairy Industry to initiate a crossbreeding experiment in 1939, and the goals of the experiment were to enhance knowledge regarding crossbreeding so dairy producers could make sound breeding decisions. Two-breed crosses of HO, Jersey (**JE**), Red Dane, and Guernsey were studied as were 3-breed rotational crossbred cows of those breeds. The study was unique at the time because the researchers selected only progeny-proven males based on transmitting ability and they chose dams sired by proven bulls for the study. Also, the crossbreeding plan was a rotational breeding plan using crossbred dams and purebred sires. The design of the study ensured new genes were continuously being introduced in each generation of crossbreeding (Fohrman et al., 1954).

The progress report published in 1954 had results for milk volume and fat production on 55 2-breed crosses, 58 3-breed crosses, and 23 progeny of the 3-breed crosses. For nearly all breed combinations, the crossbred cows exceeded their dams for production. Part of the increased production was explained by the high transmitting abilities of the sires and the effect of environmental improvement with study years, but the conclusion was heterosis accounted for some of the increased production. The progress report concluded both 2- and 3-breed crosses performed well and produced more milk volume and fat yield than their purebred dams. They concluded the order of breeds in a crossbreeding rotation was not as important as the individual sires used (Fohrman et al., 1954). The overall recommendation of Fohrman et al. (1954) was for dairy producers to consider crossbreeding if they were interested in obtaining high milk volume and high fat yield and increasing efficiency but to use the best sires available from each breed.

An earlier report on the experiment by Fohrman et al. (1954) was released in 1946. The results of that preliminary report were published in popular press magazines; however, significant backlash came from some in the dairy industry and rebuttal articles were published (Touchberry, 1992). Advocates of purebred cattle discounted crossbreeding after the preliminary 1946 report with claims of statistical flaws in the experiment. The 1954 report included a larger number of cows and more breed combinations but did little to sway opinions about crossbreeding despite the favorable results. Touchberry (1992) subsequently estimated heterosis in the study by Fohrman et al. (1954) was 18.8% for milk volume and 21.6% for fat yield.

2.2.2 The Illinois crossbreeding experiment

Researchers at the Illinois Agricultural Experiment Station began a long-term crossbreeding experiment in 1949 after early reports from the Bureau of Dairy Industry experiment were published. The funding for the Illinois project came from federal regional research funds to explore important problems in agriculture. The dairy industry was reluctant to embrace crossbreeding, yet researchers considered it a topic worth studying, especially because very favorable results were emerging on crossbreeding in beef cattle (Touchberry, 1992). Designers of the Illinois experiment chose to use the HO and Guernsey breeds, which were the 2 most popular breeds in the United States at that time. The design ensured crossbred cows would have purebred contemporaries for comparison instead of being compared to their dams. To create the succeeding generations, sires were used in a backcross design, which resulted in crossbred cows in generations 2 to 5 being sired by the opposite breed of her dam's sire. The same sires within breed were used on both purebred and crossbred cows in each generation (Touchberry, 1992). The backcross to purebred sires differed from the design of the Bureau of Dairy Industry study, which advocated for use of 3 breeds in a rotational mating system.

The overall goal of the Illinois experiment was to compare crossbred and purebred dairy cattle for traits important to total performance. Total performance was measured as an index weighting the traits of interest in a way that made biological, statistical, and economic sense (Touchberry, 1992). Traits were grouped into 5 categories: production, survival and reproduction, body traits, health costs, and milking traits and type. Nearly all of these traits agree with what are considered important traits for dairy cattle today. Many reports were published throughout the years of the Illinois experiment and were summarized by Touchberry (1970) and Touchberry (1992). Touchberry (1970) concluded crossbreds of HO and Guernsey were equal to or superior to purebred HO when performance was based on total monetary value of milk production, bull calves, heifers, and cull cows, as well as maintenance requirements of heifers and cows.

2.2.3 Crossbreeding at Agriculture Canada

Researchers at Agriculture Canada conducted a crossbreeding experiment from 1972 to 1986 with the goal of comparing lifetime lactational production and profitability of pure HO cows, pure Ayrshire cows, and crossbred cows of those two breeds (McAllister et al., 1994). Some of the crossbred cows were from the mating of crossbred bulls to crossbred cows, and the other cows were from a 2-breed rotational cross where only purebred sires were used on crossbred cows. Lifetime profitability was measured as annualized discount net return (**ADNR**), which encompassed the costs and returns for the complete lifetime of cows. A unique factor of ADNR was salvage value and health costs were also included. The 2-breed rotational crossbred cows were 3.2% more profitable than purebred cows. Heterosis for ADNR was estimated to be 20.6%, while heterosis for lifetime milk revenue was 17.9%. Based on preliminary reports from the Agriculture Canada study, Touchberry (1992) estimated heterosis to be 25% for a comprehensive index that included milk yield, survival, reproduction, growth, and costs associated with production. McAllister et al. (1994) concluded crossbreeding was beneficial for economic traits, but the advantage over HO cows was not glaringly obvious because the effects for individual traits were small. Also, the 2-breed rotational crossbreeding system was superior to the system using crossbred sires and to pure HO breeding because of the enhanced survival and reproduction of the 2-breed rotational crossbred cows. However, several generations were necessary to reap the benefits of crossbreeding. McAllister et al. (1994) concluded crossbreeding could exploit both additive and non-additive genetic effects, especially if the breeds used in the rotation have high genetic merit.

2.3 The deterioration of the HO breed for some traits

Fohrman et al. (1954), Touchberry (1992), and McAllister et al. (1994) all concluded crossbreeding was an economically viable mating system for commercial dairy production, yet crossbreeding did not become a standard practice for dairy breeders like it had for beef, swine, poultry breeders. During the 1980s, the HO breed became globally dominant because of its superiority for fluid milk production (Swan and Kinghorn, 1992; McAllister, 2002) and the strong promotion by purebred breeders and their breed associations (Weigel and Barlass, 2003).

2.3.1 Genetic selection within the HO breed

The HO breed has undergone extremely-intense selection over the past 35 years, and the selection emphasized production and conformation but ignored fertility and health until recently (VanRaden, 2017). For example, fertility (daughter pregnancy rate) was not included in the major selection index of the United States, Net Merit (**NM$**), until 15 yr ago in 2003 (VanRaden, 2017). Phenotypically, lactational milk production of HO cows enrolled in DHI increased approximately 116% for cows born in 2015 compared to cows born in 1957 (Council on Dairy Cattle Breeding, 2018c), and the dramatic increase was because of both genetic selection and advances in nutrition and herd management. The genetic trend for fertility of HO cows was negative during the same period from 1957 to 2015 (Council on Dairy Cattle Breeding, 2018a). The opposing directions of the two genetic trends was partially due to the underlying genetic antagonism between production and fertility.

Selection of HO cows over the past 35 yr also favored cows that were taller and had less body condition, and the result was cows that became less functional for the commercial dairy industry (Hansen, 2000). Cows in the HO breed have become taller despite the negative emphasis placed on body size in the NM$ selection index since 2000 (VanRaden, 2017). Becker et al. (2012) reported the treatment costs for health disorders of HO cows that had been selected for large versus small body size and concluded the large cows had higher total health cost in first lactation and higher costs for locomotion and displaced abomasum across the first 3 lactations. The higher health costs of large HO cows may lead to less profitability and more concerns about animal welfare (Becker et al., 2012). Furthermore, in recent years, some HO cows have become too large to comfortably fit in dairy facilities with moderate stall size. Selection for angularity or lower body condition score (**BCS**) has added to the decline in fertility of HO cows because higher BCS is associated with improved fertility and health of cows (Roche et al., 2009). Overall, the consequences of placing strong selection emphasis on higher milk production, increased tallness, and lower BCS of HO cows were cows with higher fluid milk volume but reduced fertility, increased health costs, and reduced survival to later lactations than their ancestors (Berry, 2018).

2.3.2 Inbreeding within the HO breed

The Council on Dairy Cattle Breeding (2018b) reported the mean inbreeding coefficient based on pedigree of HO females increased from 5.32% in 2007 to 7.23% just

10 yr later in 2017. Furthermore, the annual rate of increase of inbreeding accelerated after the introduction of genomic selection for dairy cattle in 2008. Genomic selection decreases the mean generation interval of a population which, in turn, increases the rate of response to selection (Bourdon, 2000). On the other hand, inbreeding depression decreases the phenotypic response to selection for many traits (Falconer and Mackay, 1996). Optimum genetic improvement should aim for a balance between increased genetic gains for economically important traits based on effects of individual genes versus the level of annual increase of inbreeding in a population. That balance may not have been applied in the HO breed over the past decade.

The negative effects of inbreeding on traits related to functionality, performance, and profitability have been extensively documented for the global HO population (Bjelland et al., 2013). In general, increase in inbreeding has been associated with decreases in production, fertility, and survival of dairy cattle, and all these traits have economic importance to dairy producers (Smith et al., 1998; Bjelland et al., 2013). The negative effects of inbreeding is often small for a single trait during a single lactation but, cumulatively, inbreeding depression is expected to result in significant reductions in phenotypic performance across the lifetimes of cows. Smith et al. (1998) reported each 1% increase in inbreeding resulted in lifetime milk volume decreasing by 177 kg, lifetime fat production decreasing by 6 kg, and lifetime protein production decreasing by 5.5 kg. González-Recio et al. (2007) found HO cows in Spain with an inbreeding coefficient of at least 6.25% had a 1.7% to 6.4% decrease in pregnancy rate per lactation.

Because inbreeding increases homozygosity of pairs of genes of animals, the potential for lethal or harmful recessive disorders increases (Falconer and Mackay, 1996).

Because of early loss of embryos that carry lethal recessive genes, genetic disorders can be difficult to detect because they may not appear in a live animal that survived as an embryo (VanRaden et al., 2011). Historically, disorders caused by recessive homozygotes were detected by the reporting of abnormal calves by breeders and, subsequently, by mating of suspected carriers to confirm the mode of inheritance (VanRaden et al., 2011). Genomic technology permits recessive disorders to be detected from the absence of homozygous haplotypes in a genotyped population when a large number of them would normally be expected based on rules of inheritance (VanRaden et al., 2011).

2.4 Renewed interest in crossbreeding

The deterioration of functional traits by HO cows has led to broader breeding goals for the HO breed with reduced emphasis on production and conformation and increased emphasis on functional traits such as fertility, health, calving ease, and longevity (Sørensen et al., 2008). To achieve productive, yet functional, cows more quickly than is permitted by selection only within a breed, some dairy producers have switched to crossbreeding, and this is reflected by the shift in breed composition of the national dairy herd (Figure 2.1). The HO breed experienced a decline from 91% to 83% of cows enrolled in DHI from 2008 to 2016 (Norman et al., 2017). Conversely, the percentage of JE increased from 6% to 9% of cows in that same period of time, and the percentage of crossbred cows increased from 2% to 5% (Norman et al., 2017). A more dramatic shift in breed composition has occurred in New Zealand. For 1996-97, 57% of cows in New Zealand were HO and 18% were HO × JE crossbreds (López-Villalobos et al., 2000). For 2016-17, HO × JE crossbred cows comprised 48% of the national herd in New Zealand (LIC and Dairy NZ, 2017). The renewed global interest in crossbreeding has led many researchers to investigate alternative breeds to determine the optimal combination of breeds for crossbreeding.

2.4.1 The state of crossbreeding in the United States in 2003

VanRaden and Sanders (2003) characterized crossbreeding in the United States using national milk recording data, and crossbred cows represented <0.5% of the total cows on milk recording in 2003. The most common combination of breeds for crossbred cows were HO and JE and the second-most common were HO and Brown Swiss (**BS**). The JE and BS were most often the breed of sire for the crossbred cows, and this suggested producers were not attempting to breed toward the HO breed. VanRaden and Sanders (2003) stated HO breeders chose to crossbreed in order to increase fat and protein percentage, to avoid deleterious recessive genes, and to avoid calving difficulty. The JE × HO and BS × HO crossbred cows had higher mean NM$ than HO cows and had positive heterosis for milk (3.4%), fat (4.4%), protein (4.1%), and productive life (1.2%). Also, these two types of crossbred cows stayed in herds at least as long as their HO herdmates.

Weigel and Barlass (2003) conducted a survey of United States dairy producers who were crossbreeding and summarized their responses. The response rate was low (9.5%) with only 50 usable surveys available for analysis. Dairy producers identified the advantages of crossbreeding to be improvements in calving ease, fertility, component percentages, longevity, and calf vitality, and results of the survey indicated JE × HO/JE matings had the highest conception rate and HO × JE cows were less likely to be culled for illness, injury, or infertility.

The disadvantages of crossbreeding noted by these dairy producers were reduced marketability of breeding stock, of slaughter animals, and of bull calves; reduced uniformity of cows in the herd; more difficulty with mating decisions; and reduced milk volume; and these disadvantages were likely because of the high percentage of JE influence in the crossbred cattle. Indeed, the most common crossbreds were JE × HO cows, followed by BS × HO, and these were the same two breed combinations reported by VanRaden and Sanders (2003). Respondents to the survey indicated pure HO breeding stock commanded higher prices than JE × HO breeding stock and cull cows of BS × HO and pure HO had higher salvage value than JE × HO cows. Furthermore, pure HO bull calves and steers had higher market value than crossbred males with JE in their pedigree. Weigel and Barlass (2003) concluded future research must focus on exploring the merit of alternative breed combinations of crossbred cows to help dairy producers exploit breed complementarity and to capitalize on heterosis.

2.4.2 Crossbreeding with HO and JE in the United States

Heins et al. (2011) compared JE × HO cows for production, mastitis, and conformation traits during their first 3 lactations. The cows were from 2 research herds at the University of Minnesota that were a low-input grazing herd and a high-input confinement herd. In first lactation, JE × HO crossbred cows did not differ from HO cows for fat plus protein production; however, the JE × HO cows had lower fat plus protein production than HO cows during second and third lactation. The JE × HO cows were not different from HO cows for SCS and mastitis incidence in first and second lactation, but the JE × HO cows had lower mastitis incidence than HO cows in third lactation. Furthermore, JE × HO cows had fewer days open than HO cows (Heins et al., 2012a) and were shorter for hip height than HO cows in all 3 lactations (Heins et al., 2011). Significantly more of the JE × HO cows were culled for udder conformation than HO cows (Heins et al., 2011). Therefore, Heins et al. (2011) concluded JE × HO crossbreds may not be well-suited for high-production confinement systems because of decreased fat plus protein production in later lactations and increased likelihood of being culled for udder conformation.

Bjelland et al. (2011) also concluded JE and HO crossbred cows may not be optimal for high-performance herds. In that study, the breed composition of the crossbred cows was ¾ HO and ¼ JE and represented a backcrossing system. Comparison of multiple generations of crossbred and purebred cows is important, because later generations are more representative of what would be expected long-term in a crossbred dairy herd. The backcross cows in Bjelland et al. (2011) had unproven HO × JE sires and HO dams and did not differ from HO cows for 305-d fat and protein production but had lower FCM than HO cows (Bjelland et al., 2011). Furthermore, the backcross cows did not differ from HO cows for fertility or health. Bjelland et al. (2011) concluded the advantages of crossbreeding with the HO and JE breeds were not substantial enough to merit widespread adoption.

2.4.3 Crossbreeding with the European breeds of Montbéliarde and Viking Red

Most dairy cows in the United States are in high-input confinement herds with limited opportunity for grazing. Dechow and Hansen (2017) recommended a 3-breed crossbreeding rotation of HO × Alpine × Red Dairy Cattle for these herds. The Alpine breed group includes BS, Montbéliarde (**MO**), and Fleckvieh cattle, while the Red Dairy Cattle group includes Viking Red (**VR**), Norwegian Red, German Angler, and Aussie

Red. The HO breed contributes milk volume to the 3-breed rotation, and the Alpine and Red Dairy Cattle groups contribute milk solids content, health, and fertility. In the United States, interest is growing in an ongoing rotation (ProCROSS) of the HO, MO, and VR breeds.

In 2016, the MO breed had 670,000 cows in France, which was 18% of the French national dairy herd (O.S. Montbéliarde , 2018b). Of these cows, 66% were enrolled in milk recording and 37% were scored for morphology (type). The mean 305-d production of MO cows was 8,520 kg of milk with 3.91% fat and 3.31% protein in 2016 (O.S. Montbéliarde , 2018b). The MO breed has been developed for the production of specialty cheeses that requires cows to graze; therefore, the modest production level of French MO cows compared to French HO cows is likely because of their different diets (Dezetter et al., 2015). Historically, the MO breed has been selected only for dairy traits but has also been selected to maintain BCS rather than to reduce BCS (O.S. Montbéliarde, 2018a,c). Furthermore, fertility and health have been included in the selection indices for the MO breed for 20 yr (Barbat et al., 2010).

The VR breed includes the subpopulations of Swedish Red, Finnish Ayrshire, and Danish Red, which have been combined for genetic improvement and marketing. In 2017, Sweden, Finland, and Denmark had 224,000 milk recorded VR cows with mean 305-d production of 9,099 kg milk, 399 kg fat (4.38%), and 318 kg protein (3.49%) according to Viking Genetics (2018a). Cows of the VR breed tend to have lower milk volume, higher fat and protein percentages in milk, and superior health and fertility than HO cows in the Nordic countries (Jönsson, 2015; Viking Genetics, 2018b). In contrast to the HO breed, the VR breed has ignored both stature and BCS for selection but has selected for fertility for over 30 yr (Pryce et al., 2014).

Because they have been selected for fertility and health for much longer than the HO breed in the United States, the MO and VR breeds may be ideal candidates for crossbreeding with the HO breed (Barbat et al., 2010; Pryce et al., 2014). Fertility, health and survival of cows are now included in U.S. selection indices, but these traits have low heritability with corresponding slow response to selection. Crossbreeding of the HO, MO, and VR breeds should permit dairy producers to achieve a quicker response in improvement of fertility, health, and survival of cows than through selection methods only within breed. In addition, the higher fat and protein percentages of milk of MO and VR cows than HO cows could compensate for lower milk volume.

Crossbreeding with HO, MO and VR in California. Crossbred cows of the HO, MO, and Nordic Red (VR and Norwegian Red) breeds were compared to HO cows for lifetime profit in commercial dairy herds in California from 2002 to 2009 (Heins et al., 2012b). In first lactation, MO × HO and Nordic Red × HO cows were less likely to be culled before their first test day (Heins et al., 2012b), and this may have resulted from improved health of the 2 crossbred groups compared to the HO cows, although differences for health were not evaluated in the study. However, the crossbred cows had less calving difficulty than HO cows (Heins et al., 2006a). Also, Heins and Hansen (2012) reported the MO × HO and Nordic Red × HO cows had 3% and 4%, respectively, lower fat plus protein production across their first 5 lactations. However, both the MO × HO and Nordic Red × HO cows had higher lifetime profit than HO cows because they had superior survival to second, third, and fourth calving (Heins et al., 2012b). Heins et al. (2012b) concluded MO × HO and Nordic Red × HO cows had 5.3% and 3.6%, respectively, more profit per day, and this would result in an additional $80 and $55 annually per cow for MO × HO and Nordic Red × HO cows, respectively, than HO cows. Therefore, at least in the first generation, crossbreeding with HO, MO, and VR cows improved cow survival and profitability.

Crossbreeding with HO, MO, and VR cows in Minnesota. Hazel et al. (2014) compared MO × HO crossbred cows to pure HO cows at the University of Minnesota in a low-input grazing herd and a high-input confinement herd for economically important traits for their first 5 lactations. In contrast to the results of Heins and Hansen (2012), the MO × HO crossbred cows were not different from HO cows for fat plus protein production in their first 5 lactations but had 39 fewer days open than HO cows (Hazel et al., 2014). Furthermore, a higher percentage of MO × HO cows survived to their third, fourth, and fifth lactations than HO cows.

A 10-yr designed study with the objective of comparing ProCROSS and HO cows for profitability was initiated in 2008 in commercial dairy herds in Minnesota. As of 2017, only production, fertility, survival, and conformation for first generation crossbred cows (MO × HO and VR × HO) in first lactation were reported. Collectively, the crossbred cows had 2% higher 305-d fat plus protein production (kg), 18% higher conception rate, and 10 fewer days open than HO cows (Hazel et al., 2017a,b). Furthermore, a higher percentage of crossbred cows (84%) survived to second calving than HO cows (80%) in agreement with Heins and Hansen (2012) and Hazel et al. (2014). In the future, the 10-yr designed study will study the subsequent generations (3-breed and beyond) to assess the benefits of an ongoing ProCROSS system.

2.5 FE in dairy cattle

Little research has been conducted on the FE of crossbred cows compared to HO cows. In order for dairy producers to make wise decisions on the breed composition of their cows, the FE of crossbred cows needs to be investigated. Multiple measures of FE have been presented in the literature, and the merit of each will be discussed herein.

2.5.1 Ratio measures of FE

The simplest definition of FE is the ability of an animal to convert feed to product (Connor, 2015). A lactating dairy cow is considered more FE than a herdmate if she produces the same amount of milk while eating less feed or if she produces more milk while eating the same amount of feed. Ratio measures of FE that compare output (production) to input (FI) are common, such as fat plus protein production/DMI and ECM/DMI. For grazing herds, achieving high FI or fat plus protein production per unit of BW is desirable and often used as a measure of FE (Buckley et al., 2007; Prendiville et al., 2009). The FI may also be described as energy intake or crude protein intake because efficiency of energy or protein utilization may be of interest (Vallimont et al., 2011). Universal agreement has not been reached on the optimum measure of FE for dairy cattle (Coleman et al., 2010; Hurley et al., 2016), and this adds to the complexity of assessing FE. For example, Hurley et al. (2016) reported relationships among 14 alternative definitions of energy efficiency expressed as a ratio. Many of the ratio measures of FE were not correlated, so alternative measures of FE may describe different aspects of FE (Hurley et al., 2016).

Limitations of ratio measures of FE. Ratio measures of FE are easy to calculate, but they have limitations. For example, Berry and Crowley (2013) pointed out ratio measures of FE are often strongly correlated with either their numerator or denominator and do not account for partitioning of energy from feed to production, body maintenance, or gain or loss of body condition (Veerkamp and Emmans, 1995). Ratio measures of FE may also identify low-producing cows with low DMI as efficient. However, these cows are likely not economically efficient, because they incur the same direct and overhead costs as high producing cows (Hazel et al., 2013). Furthermore, most measures of FE are narrow in scope because they measure only input and output without accounting for additional factors such as pregnancy status (Hazel et al., 2013). Finally, the most appropriate measure of FE may differ for production systems, such as confinement versus grazing, or fluid versus milk solids markets (Prendiville et al., 2009). For these reasons, a more holistic approach to FE beyond ratio measures may be valuable.

2.5.2 FE measured as residual feed intake

Residual feed intake (**RFI**) has become a common measure of FE for dairy cows and was first proposed for beef cattle by Koch et al. (1963). The RFI is the difference between predicted and actual FI required for production and body maintenance and is often estimated as the residual from the regression of DMI on energy sinks such as production, BW, and change in BW (**BWC**) for individual cows (Berry and Crowley, 2013; Connor, 2015). The RFI can also be estimated as actual FI minus predicted FI. The predicted FI is often derived from standardized feed tables based on a cow's production and BW. An advantage of deriving RFI from multiple regression is RFI is then independent of the energy sinks, and this allows for comparison of cows across production levels (Coleman et al., 2010). A negative RFI indicates a cow had less FI than predicted based on her energy sinks so she is, therefore, more efficient than a cow with a positive RFI. The energy sinks used to estimate RFI differ among studies (Hurley et al., 2016), and this makes comparison of RFI across studies difficult.

Limitations of RFI. Prediction of RFI becomes complicated when the population of animals is spread across multiple herds, trials within herds, or breeds. Tempelman et al. (2015) estimated RFI for HO cows from several research stations across 3 countries to better understand how partial regression coefficients of DMI on energy sinks may differ between populations. The long-term goal of the study was to better understand the genetics of FE for HO cows in order for FE to be used in the future for genetic improvement. The RFI was calculated separately for each research station to determine alternative partial regression coefficients of DMI on milk energy output (**MilkE**), metabolic BW (**MBW**), and BWC. Tempelman et al. (2015) reported heterogeneity may exist for the partial regression coefficients of DMI on MilkE and BWC among the various research stations contributing to the study. Heterogeneity of partial regression coefficients could have been caused by the high measurement error of traits and this, in turn, would result in a less accurate estimate of RFI. Davis et al. (2014) also reported heterogeneity in the partial regression coefficients among trials at the same research station. Therefore, comparisons of RFI across populations may not be appropriate.

Li et al. (2016) suggested partial regression coefficients of DMI on energy sinks may differ for breeds in the estimation of RFI because of potential differences of breeds in energy partitioning. This study estimated RFI for primiparous HO, VR, and JE cows over 44 weeks of lactation, and the model for RFI included the energy sinks of ECM, BW, and BWC. Differences in the partial regression coefficients for breeds were not formally tested; however, the standard errors for the partial regression coefficient of DMI on ECM were small enough to suggest that DMI increased more per unit increase in ECM for VR cows than HO and JE cows (Li et al., 2016). The standard errors for the partial regression coefficients of DMI on MBW and on BWC were larger, and potential differences among breeds were not as substantial as those for ECM (Li et al., 2016).

Coleman et al. (2010) determined RFI may not be an appropriate measure of FE because accounting for BWC is challenging. The BWC is often included as an energy sink in RFI models but is not a true measure of how energy is partitioned. More energy is required to deposit body fat than body protein or water, but less energy is required to maintain body fat than body protein (DiCostanzo et al., 1990). Furthermore, for estimation of RFI, Coleman et al. (2010) suggested separate regression coefficients may be necessary for BW gain and for BW loss, because the energy generated from BW loss is less than the energy required for BW gain. Also, for RFI calculated as actual minus predicted DMI, the prediction equations for DMI are based on only HO cows and may not accurately predict DMI for cows of other breeds or crossbreds. Finally, the RFI may be confusing to dairy producers because a lower (more negative) RFI is desirable (Coleman et al., 2010; Connor, 2015).

2.6 Crossbreeding and FE

2.6.1 Crossbreeding and FE in livestock species other than dairy cattle

The beef cattle industry in the United States has taken advantage of the benefits of crossbreeding (breed complementarity and heterosis) for more than 40 yr to enhance productivity through increased growth rates and female longevity that, in turn, has resulted in improved FE (Gregory and Cundiff, 1980). Historical estimates of heterosis for FE of beef cattle were generally positive but usually < 5.0% (Gregory et al., 1966;

Urick et al., 1984). Gregory and Cundiff (1980) concluded heterosis for broad measures of FE such as kilograms of calf weaned per cow exposed for breeding could be ≥ 20% because of accumulation of the small effects of heterosis for traits contributing to broad-sense FE. Capitalizing on heterosis has also been a major contributor to the commercial pig industry in the United States for more than 60 yr. Heterosis is substantial for litter size and rate of gain, and these traits influence FE (Young et al., 1976; Johnson, 1981). Heterosis for FE has not been a focus of research in recent years for either beef or dairy cattle (Berry and Crowley, 2013).

2.6.2 Crossbreeding and FE in dairy cattle

FE of JE × HO crossbred cows. In response to the increased interest in crossbreeding, researchers at the University of Minnesota compared primiparous JE × HO crossbred cows (n = 24) and pure HO cows (n = 17) for FE and related traits. The JE × HO cows had lower BW but higher BCS than HO cows in their first 150 DIM (Heins et al., 2008a). Also, the JE × HO crossbred cows tended ($P < 0.10$) to have lower milk volume than HO cows but did not differ from HO cows for fat plus protein production, ECM, or DMI (Heins et al., 2008a). Measures of FE were defined as fat plus protein production/DMI and ECM/DMI. Not surprisingly, the 2 breed groups did not differ for FE, because of a lack of difference for both production and DMI. Heins et al. (2008a) postulated JE × HO may not have differed from HO cows for DMI because of their higher BCS than HO cows. Their higher BCS may have resulted in their enhanced fertility compared to HO cows (Heins et al., 2008a,b).

Prendiville et al. (2009) also reported lower BW for JE × HO cows compared to HO cows in a grazing herd in Ireland. Like producers in the U.S., Irish dairy producers became interested in crossbreeding because of disappointing fertility of HO cows, increasing emphasis on fat and protein content in their milk payment system, and the desire to increase fat plus protein production per hectare of grazing land. The JE × HO cows had higher BCS compared to HO cows. The 2 breed groups did not differ for solids-corrected milk because the JE × HO cows had lower milk yield but higher fat and protein percentages in their milk than HO cows, and the 2 breed groups did not differ for DMI. In contrast to Heins et al. (2008a), JE × HO cows had higher fat plus protein production/DMI than HO cows (Prendiville et al., 2009), although the 2 breed groups did not differ for either fat plus protein production or DMI.

Pure JE cows were also available for comparison to crossbreds in the study by Prendiville et al. (2009), and heterosis for some traits were presented. Significant heterosis was present for fat plus protein production (+8.0%) and for fat plus protein production/DMI (+4.2%), but heterosis for DMI was not reported in the study (Prendiville et al., 2009). Estimates of heterosis for FE in dairy cattle are limited, but the results of Prendiville et al. (2009) were in line with those reported for direct measures of FE in beef cattle, which are typically < 5.0% (Gregory and Cundiff, 1980).

Researchers at Virginia Tech, the University of Kentucky, and North Carolina State University initiated a crossbreeding experiment in 2002 (Olson et al., 2009). Both HO × JE and JE × HO cows were compared to pure HO and pure JE cows for energy required for production and maintenance in first lactation by Olson et al. (2010). The JE × HO cows were not different from HO cows for energy intake during lactation. On the other hand, the reciprocal cross, HO × JE, cows had lower energy intake than HO cows (Olson et al., 2010). Both crossbred types (JE × HO and HO × JE) required less energy for maintenance than HO cows, and this was likely because they had lower BW. Also, both types of crossbred cows had higher energy intake and required more energy for maintenance than pure JE cows. No differences were reported between HO cows and the 2 crossbred types for ECM, and JE had lower ECM than all 3 of the other breed groups. Olson et al. (2010) found crossbred cows did not differ from HO cows for milk energy/energy intake.

Olson et al. (2010) also reported an unfavorable heterosis for maintenance energy of 3.02%, because crossbreds required more energy for maintenance than the mean of the parental breeds. However, both crossbred groups required less energy for maintenance than HO cows, were not different from HO cows for energy required for production, but had the same or less energy intake. Therefore, a positive heterosis for maintenance energy of JE and HO crossbred cows compared to HO cows may not be truly unfavorable. Heterosis for energy required for milk production was estimated to be a favorable 8.83% and for total energy consumed was 5.7%. The heterosis for energy required for milk production was higher than the ~3% estimate of heterosis for production given by Sørensen et al. (2008), and Olson et al. (2010) attributed the high estimate to the cumulative effects of heterosis for milk, fat, and protein production.

FE of HO, MO, and VR crossbred cows. Buckley et al. (2007) compared MO × HO crossbred cows to pure HO and pure MO for FE in a pasture-based research herd in Ireland. The MO × HO cows were not different from HO cows for milk volume, fat plus protein production, BW, and DMI (Buckley et al., 2007). The FE was defined as fat plus protein production/DMI, DMI/100 kg BW, and also fat plus protein production/100 kg BW. The MO × HO cows did not differ from HO cows for the 3 measures of FE, and this likely was because they did not differ for the contributing factors to calculate FE. For grazing cows, a high intake per unit of BW is desirable because it indicates cows have a higher capacity for FI relative to their size. The MO cows had lower fat plus protein production than HO and MO × HO cows, had lower DMI than HO cows, and did not differ from either HO or MO × HO cows for BW. Heterosis for FE was not provided but ranged from 2.2% to 2.5%.

In a research herd at the University of Minnesota, Hazel et al. (2013) reported MO × HO crossbreds did not differ from HO cows for DMI and fat plus protein production (kg) during the first 150 d of first lactation. However, the MO × HO cows had 0.58 higher mean BCS, were 36 kg heavier for mean BW than HO cows but were not different for height at the hips than HO cows (Hazel et al., 2013). The FE was not measured, but because breed groups did not differ for DMI or fat plus protein production, MO × HO likely would not have differed from HO cows for fat plus protein production/DMI. However, the higher BW of the MO × HO cows than HO cows would likely have resulted in the MO × HO having a lower DMI/BW than HO cows. For high-input confinement herds, achieving a higher DMI/BW may not be as critical as in grazing herds because cows in high-input herds are often fed to their genetic potential for production, and this is not the case in grazing herds.

2.7 Summary of key findings

Crossbreeding has been exploited by other livestock species but acceptance by dairy producers has been slow. However, interest in crossbred dairy cattle has been growing because of perceived shortcomings of the HO breed. For high-input confinement dairy herds in the United States, a 3-breed rotational crossbreeding system of the HO, MO, and VR breeds (ProCROSS) is gaining acceptance. A large-scale designed study is currently underway to study ProCROSS cows in commercial dairy herds, but economically important traits such as FE will not be evaluated in that study. Feed cost is the single largest operating cost for dairy operations. The FE is costly to measure but is an important trait to consider when evaluating crossbred and purebred animals. Therefore, the evaluation of ProCROSS and HO cows for FE and related traits is needed.

2.8 Objectives and hypotheses

The objective of this dissertation was to compare ProCROSS and HO cows in their first 3 lactations for traits that are economically important but difficult and costly to measure in a commercial setting. Traits investigated included DMI, BW, cow height (height at the withers and height at the hips), BCS, milk volume, and fat plus protein production from 4 to 150 DIM. These phenotypes were then used to compare ProCROSS and HO cows for alternative measures of FE.

The Dairy Cattle Teaching and Research Facility on the St. Paul campus of the University of Minnesota was uniquely positioned for this study because routine and systematic crossbreeding began in 2000, and the herd was approximately 45% crossbred (ProCROSS) and 55% HO when the study began. In addition, the dairy facility had the necessary design and equipment to measure individual FI, BW, cow height, and BCS.

Based on the reviewed literature, ProCROSS crossbred cows were anticipated to be more productively efficient than HO cows because they would consume less DMI but would not differ from HO cows for fat plus protein production (kg). Furthermore, ProCROSS cows were anticipated to maintain more body condition and to be smaller in frame size than HO cows. The results of the proposed study will help determine whether

ProCROSS cows are a viable alternative to HO cows for commercial dairy producers who seek more profitable cows.

2.9 Figures

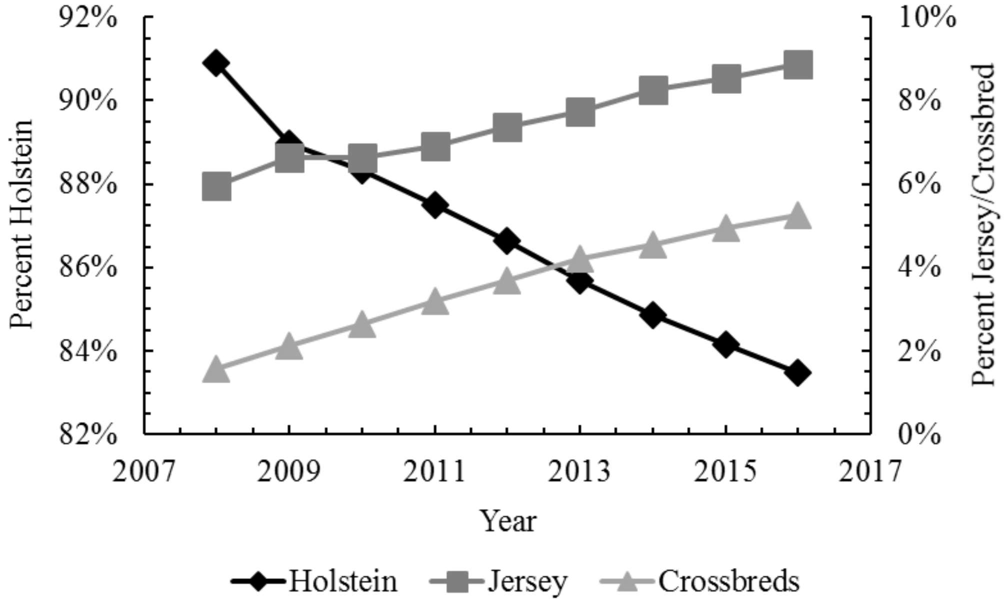

Figure 2.1. Percentage of Holstein, Jersey, and crossbred cows in the United States dairy herd from 2008 to 2016. The percentage of Holstein cows is plotted on the left axis, and the percentage of Jersey and crossbred cows are plotted on the right axis.

CHAPTER 3. COMPARISON OF PROCROSS AND HOLSTEIN COWS FOR DRY MATTER INTAKE, BODY WEIGHT, COW HEIGHT, BODY CONDITION SCORE, AND PRODUCTION

3.1 Introduction

Change in milk pricing toward the solids in milk, reduction of fertility, health, and survival of Holstein (**HO**) cows, and increase in average inbreeding of HO cows have each contributed to an increased number of crossbred dairy cows in the United States over the past 20 years (Weigel and Barlass, 2003). Research on crossbreeding was conducted in the 1940s to learn whether dairy breeders could be as successful as corn breeders at creating productive hybrids (Fohrman et al., 1954). Numerous studies from the 1940s to 1990s had favorable results for crossbreds compared to purebreds (Touchberry, 1992); however, considerable pushback from breed associations as well as the higher average milk volume of HO cows resulted in the global domination by the HO breed beginning in the 1980s.

The HO breed has undergone extremely-intense selection over the past 35 years, and the selection emphasized production and conformation but ignored fertility and health until recently (VanRaden, 2017). The result was HO cows that were less fertile, more prone to health issues, and less likely to survive to later lactations than previously (Berry, 2018). Also, selection over the past 35 yr favored larger and more angular cows, and this resulted in cows that are not optimally functional for the commercial dairy industry (Hansen, 2000). Furthermore, acceleration of the annual increase of average inbreeding within the HO breed has increased the likelihood of expression of the deleterious effects from inbreeding depression, which are mainly related to fertility and fitness (Falconer and Mackay, 1996). The Council on Dairy Cattle Breeding (2018b) reported HO females born in 2017 had a mean inbreeding coefficient of 7.23% based on pedigree compared to 5.32% just 10 years earlier in 2007.

The benefits of crossbreeding for production, health, fertility, and survival of dairy cattle have been documented (López-Villalobos et al., 2000; Heins et al., 2012; Hazel et al., 2017a,b). Data for feed intake (**FI**) of individual cows are costly to collect because of the specialized labor and equipment that is required. Therefore, little research has been conducted on the FI of crossbred versus purebred cows. Typically, feed cost accounts for more than one-half of expenses for dairy cattle production (USDA-ERS, 2018); therefore, efficient use of feed consumed by dairy cows is important for profitability. Body traits of cows such as BW, height, and BCS are also valuable for comparing crossbreds to purebreds for functionality and profitability in commercial dairies. Increased BCS is associated with improved fertility and health (Roche et al., 2009), and cows with extremely large frame size will not easily fit into modern free-stalls and milking parlors.

Heins et al. (2008a) and Olson et al. (2010) compared Jersey × HO crossbred cows to HO for FI and body traits and reported the crossbreds consumed the same or less DMI or energy compared to HO cows but did not differ for fat or protein production. Heins et al. (2008b) found Jersey × HO crossbred cows were shorter at the hips and had higher BCS than HO cows during first lactation. However, Heins et al. (2011) concluded Jersey × HO crossbreds may not be well-suited for high-production confinement systems, because they were more likely to be culled for udder conformation and had lower mean fat and protein production in second and third lactations than HO cows.

For high-input confinement herds with limited opportunity for grazing, a 3-breed rotational system using the 3 breed groups of HO, Alpine, and Nordic Red has been recommended by Dechow and Hansen (2017). Specifically, interest is growing in an ongoing rotation including the HO, Montbéliarde (**MO**), and Viking Red (**VR**) breeds that is marketed internationally as ProCROSS by Coopex Montbéliarde (Roulans, France) and Viking Genetics (Randers, Denmark). The MO breed of dairy cattle in France has been selected over time for only dairy traits but has placed selection on increasing rather than decreasing BCS (O.S. Montbéliarde, 2018a,c). The VR breed includes the subpopulations of Swedish Red, Finnish Ayrshire, and Danish Red, which have been combined for genetic improvement and marketing. Cows of the VR breed tend to have lower milk volume, higher fat and protein solids in milk, and superior health and fertility than HO cows in Nordic countries (Jönsson, 2015) due to different selection goals over time (Oltenacu and Broom, 2010).

Hazel et al. (2013) reported MO × HO crossbred cows were not different from HO cows for fat plus protein production during the first 150 d of first lactation. However, MO × HO cows had 0.58 higher mean BCS, were 36 kg heavier for mean BW than HO cows, but they were not different for height at the hips than HO cows (Hazel et al., 2013). An Irish study comparing MO × HO and HO cows in a pasture production system found DMI, BW, and fat plus protein production were not different for the two breed types (Buckley et al., 2007). The objective of this study was to compare ProCROSS crossbred and HO cows for DMI, BW, cow height, BCS, and production during the first 150 d of their first three lactations.

3.2 Materials and methods

3.2.1 Experimental design

Research with crossbreeding in the Dairy Cattle Teaching and Research Facility in St. Paul of the University of Minnesota began in the early 2000s. The initial crossbreds were Jersey × HO and MO × HO and, subsequently, 3-breed crossbreds of those breeds. The Jersey breed was later replaced with the VR breed for an ongoing 3-breed rotational system of HO, MO, and VR.

Sires of cows in this study were daughter-proven AI bulls, and 3 bulls were used as service sires annually from each of the 3 breeds. The HO bulls were chosen from among those ranking highly for the Net Merit index in the United States (VanRaden, 2017) with consideration of semen cost and were mated with both HO and ProCROSS cows. The MO and VR bulls were chosen from among those ranking highly for the French ISU index (O.S. Montbéliarde, 2018c) and the Nordic Total Merit index (Nordic Cattle Genetic Evaluation, 2018) that were available from Creative Genetics of California (Oakdale, CA), which is the United States importer. Matings of HO bulls with HO heifers and cows were assigned to minimize inbreeding coefficients. The ProCROSS heifers and cows were randomly mated to AI bulls from the appropriate breed (MO, VR, or HO) in rotation.

Cows in the study were born between 2012 and 2015, and their sires were selected between 2010 and 2013. The weighted mean birth year of all HO sires of cows was 2006, but the weighted mean birth year of the MO and VR sires of cows was 2002 and 2003, respectively. Therefore, the HO cows in this study had an advantage for genetic rank, because the HO sires of cows tended to be younger than the MO and VR sires of cows.

3.2.2 Experimental units

Cows were housed in the Dairy Cattle Teaching and Research Facility in St. Paul of the University of Minnesota. This experiment was approved by the Institutional Animal Care and Use Committee of the University of Minnesota (#1408-31736A). Cows calved seasonally between September and May. The ProCROSS and HO heifers were paired when possible prior to first calving according to age (mo) and expected calving date. First calving of cows was from September 2014 to April 2017. The cows that calved for the first time from September 2014 to May 2015 (year 1) had the opportunity for 2 subsequent lactations to be included in the study. Cows that calved for the first time from September 2015 to April 2016 (year 2) had the opportunity for 1 subsequent lactation to be included in the study. The cows that calved for the first time from August 2016 to April 2017 (year 3) had the opportunity for only a first lactation to be included in the study. Some cows were involuntarily culled, and cows that left the herd before 150 DIM were eliminated from the study for only that terminal lactation. Less than 9% of the lactations of cows were eliminated for cows that left the herd before 150 DIM (Table 3.1). The resulting number of cows analyzed are summarized in Table 3.1. Of the 63 primiparous ProCROSS cows, 14 had a HO sire, 29 had a MO sire, and 20 had a VR sire. For multiparous ProCROSS cows, 43 lactations (15 with a HO sire, 15 with a MO sire, and 13 with a VR sire) were available for this study.

An attempt was made to collect FI for the 14 d prepartum; however, a large number of cows calved earlier than anticipated, and this resulted in a limited number of prepartum records for FI. Therefore, prepartum FI is not reported in this study. Collection of FI and body trait observations of cows began 4 days postpartum and continued until 150 DIM. The objectives of this study did not include the investigation of lowly-heritable traits such as fertility and survival, because other studies with much larger sample sizes have compared ProCROSS and HO cows for those traits in commercial herds (Heins and Hansen, 2012; Heins et al., 2012; Hazel et al., 2017a).

3.2.3 Collection of FI

Each cow was assigned to a tie-stall in the barn for the duration of a lactation, and the feed mangers in front of the cows were partitioned to provide each cow an exclusive feeding space. A TMR were delivered twice daily. The diets were formulated by a professional nutritionist to meet or exceed nutritional requirements (NRC, 2001). The amount fed to each cow aimed for at least a 5% daily refusal rate, and the amount fed was adjusted daily. Feed refusals were collected and weighed daily before the first feed delivery. Feed delivered and reclaimed was recorded electronically using Feed Supervisor software (Dresser, WI). Recording errors caused by computer malfunction or human error were removed, but they accounted for a small proportion (2.6%) of daily FI data. Missing daily FI were estimated by extrapolation using the mean from 2 d before and 2 d after the missing daily FI observation.

Samples of the diets were collected twice weekly and stored in a freezer at –20°C. The two weekly samples were pooled into a single weekly sample and dried in an oven at 105°C for at least 16 hours to determine dry matter content. Weekly samples were pooled into monthly samples and analyzed commercially (Rock River Laboratory, Watertown, WI) for nutrient analysis and energy calculations. Ingredient and nutrient composition of the TMR for the duration of the study is in Table 3.2. The daily DMI (kg) was calculated by multiplying daily FI by the dry matter content of the TMR. Daily DMI observations were summed from 4 to 150 DIM to determine 150-d DMI for each lactation.

3.2.4 Body traits

The BW was recorded twice weekly with a digital scale when cows exited the milking parlor. Cow height was measured once monthly and was height from the ground to the withers (**WH**) and from the ground to the sacrum (hip height; **HH**). The WH and HH were recorded in increments of 0.5 cm. The BCS was evaluated on all cows once per week by a single trained evaluator and was scored on a five-point scale with 0.25 increments with 1 = thin and 5 = obese (Wildman et al., 1982). The means of BW, WH, HH, and BCS observations from 4 to 150 DIM were analyzed.

3.2.5 Production

Cows were milked twice daily at 0400 h and 1600 h. Milk volume and fat and protein percentages from monthly DHI (Minnesota DHIA, Buffalo, MN) were used to estimate production for complete lactations with Best Prediction (**BP**), which is used for national genetic evaluation in the United States (Cole and VanRaden, 2009). Each test day was required to have an observation for milk volume and fat and protein percentage, and test day observations were excluded if milk was below 4.54 kg, fat percentage was outside the range of 1.0 to 9.0%, and protein percentage was outside the range of 1.0 to 6.0%, and this affected a small number (< 1%) of test days. The BP adjusted for age at calving and previous days open. Daily estimates of milk volume (kg) and fat plus protein production (kg) from BP were summed from 4 to 150 DIM for each lactation.

3.2.6 Statistical analysis

Lactational analysis of DMI, BW, cow height, BCS, and production. Exploratory data analysis revealed primiparous cows decreased significantly ($P < 0.01$) by year for mean age at first calving as the study progressed (25.5 ± 2.4, 24.2 ± 2.4, and 22.9 ± 1.3 mo for years 1, 2, and 3, respectively) because of changes in heifer rearing and herd management policies regarding age at calving. Also, preliminary analysis indicated a covariable for age at calving (mo) did not consistently explain variation for the dependent variables beyond what was explained by year of calving. Consequently, primiparous and multiparous cows were analyzed separately because lactation curves differ substantially for traits such as DMI, BW, and production. Therefore, for primiparous cows, breed group (ProCROSS or HO) and year of calving (1, 2, or 3) were the fixed effects for statistical analysis of DMI, BW, WH, HH, BCS, milk volume (kg), and fat plus protein production (kg) from 4 to 150 DIM, and the GLM procedure of SAS (release 9.4, SAS Institute, Inc., Cary, NC) was used to conduct the ANOVA and obtain solutions. For multiparous cows, breed group (ProCROSS or HO) was a fixed effect, and cow nested within breed group was a repeated effect because some cows had both second and third lactations included in the study. The MIXED procedure of SAS was used to conduct the ANOVA and obtain solutions for the multiparous analysis.

Weekly analysis of DMI, BW, cow height, BCS, and production. A separate analysis was used to delineate differences of the ProCROSS and HO cows for intervals of time within the 4 to 150 DIM. Means for 21 periods of 7 d each (4 to 10 DIM, 11 to 17 DIM, etc.) within 4 to 150 DIM were analyzed for all traits except WH and HH. Analysis of weekly mean DMI, BW, BCS, milk volume, and fat plus protein production was with the same models described previously but with 7-d period (1 to 21) nested within breed group added as a repeated effect. Again, primiparous and multiparous cows were analyzed separately, and the MIXED procedure of SAS was used to conduct the ANOVA and obtain solutions of weekly observations for traits.

Data were from a single herd, so the number of ProCROSS cows sired by bulls from each of the 3 breeds was not large. Therefore, breed of sire of ProCROSS cows was not included in the statistical analysis. The goal of this study was to compare a mixture of generations and sire breeds representing the 3-breed rotational (ProCROSS) system to the HO cows and was not to compare breeds of sire within ProCROSS.

3.3 Results

3.3.1 Lactational DMI, BW, cow height, BCS, and production

Effect of year of calving for primiparous cows. Year of calving significantly ($P <$ 0.01) explained variation of lactational DMI, BCS, milk volume, and fat plus protein production for primiparous cows. The cows that calved for the first time in year 1 had the oldest mean age at calving (Table 3.3) but had less milk volume and less fat plus protein production ($P < 0.01$) than the cows that calved for the first time in years 2 and 3, and these differences likely resulted from their lower mean BW (Table 3.3). Primiparous cows that calved in year 3 had higher DMI ($P < 0.01$) and had higher BCS ($P < 0.05$) than cows that calved in years 1 and 2 (Table 3.3). The effect of year of calving was not significant ($P = 0.50$) for explaining variation of WH for primiparous cows; however, primiparous cows that calved in year 2 were taller ($P < 0.05$) for HH than cows that calved in year 1 (Table 3.3). Both the ProCROSS and the HO heifers that calved in year 1 were grown on pasture when available with little energy supplementation. On the other hand, the heifers that calved in years 2 and 3 were reared at a different location and were provided energy supplementation in addition to seasonal pasture access prior to first calving.

Primiparous ProCROSS cows consumed 141 kg less ($P < 0.01$) DMI than HO cows from 4 to 150 DIM, but mean BW did not differ ($P = 0.59$) for the 2 breed groups (Table 3.4). Primiparous ProCROSS cows were 4.0 cm shorter ($P < 0.01$) for mean WH than HO cows and were 2.0 cm shorter ($P < 0.01$) for mean HH than HO cows (Table 3.4). Primiparous ProCROSS cows had higher ($P < 0.01$) mean BCS (+0.26) than the HO cows (Table 3.4). Primiparous ProCROSS cows produced 206 kg less mean milk volume ($P < 0.01$) but were not different ($P = 0.73$) for fat plus protein production (Table 3.4) from the HO cows.

Multiparous ProCROSS cows consumed 232 kg less ($P = 0.02$) mean DMI than HO cows (Table 3.4). Mean BW did not differ ($P = 0.53$) between the two breed groups (Table 3.4), but ProCROSS cows were 3.5 cm shorter ($P < 0.01$) than HO cows for mean WH. Multiparous ProCROSS cows were not different ($P = 0.16$) from HO cows for mean HH (Table 3.4). Mean BCS was 0.19 higher ($P < 0.01$) for multiparous ProCROSS cows than HO cows. The multiparous ProCROSS cows produced 372 kg less mean milk volume ($P = 0.02$) but were not different ($P = 0.68$) for fat plus protein production from the multiparous HO cows (Table 3.4).

3.3.2 Weekly DMI, BW, cow height, BCS, and production

Dry matter intake. Year of calving, breed group, and 7-d period nested within breed group all significantly ($P < 0.01$) explained variation of mean weekly DMI for primiparous cows. Primiparous ProCROSS cows had less ($P < 0.05$) mean DMI than the

HO cows for a majority of the 7-d periods beginning in period 6 (Figure 3.1). Both the ProCROSS and HO cows increased in DMI from 4 to 150 DIM, and the statistical contrast between primiparous ProCROSS and HO cows for DMI became more significant with time and the least squares means differed more in the 7-d periods.

For multiparous cows, both breed group and 7-d period nested within breed group significantly ($P < 0.01$) explained variation in mean weekly DMI. Similar to primiparous cows, multiparous ProCROSS cows consumed less mean DMI ($P < 0.05$) during a majority of 7-d periods than multiparous HO cows beginning with period 6 (Figure 3.1). However, the largest difference in mean weekly DMI for breed groups occurred in periods 10 to 14 based on the strength of the contrasts for breed groups. Contrary to the DMI lactation curve for primiparous cows, the difference in mean weekly DMI for ProCROSS and HO cows became less pronounced in periods 15 to 21. For both the primiparous and multiparous cows, breed groups rapidly increased in DMI during early lactation because cows required increased DMI to cope with the energy demands for production.

Body weight. For weekly BW, year of calving and 7-d period nested within breed group significantly ($P < 0.05$) explained variation for primiparous cows. However, none of the contrasts between breed groups for the 7-d periods differed ($P > 0.49$) for BW. Primiparous ProCROSS and HO cows both reached their lowest BW in period 3, and cows in both breed groups increased ($P < 0.05$) for mean BW in periods 3 to 21. The means of 7-d periods indicated cows in both breed groups lost BW at the beginning of lactation ($P < 0.01$ for contrast of period 1 to period 3 within breed group), and this was expected because cows often mobilize body tissue to gain energy for production (Figure

3.2). Both ProCROSS and HO cows had greater (P < 0.01) mean BW in the last 7-d period than in the first 7-d period, and this reflected continued growth toward mature BW.

For multiparous cows, only 7-d period nested within breed group significantly (P < 0.01) explained variation of BW. Like the primiparous cows, the 7-d periods for multiparous ProCROSS and HO did not differ (P > 0.29) for mean BW (Figure 3.2), and both ProCROSS and HO cows lost BW at the beginning of lactation (P < 0.01). Multiparous ProCROSS and HO cows reached their lowest mean BW in periods 3 to 6.

Body condition score. Year of calving, breed group, and 7-d period nested within breed group significantly (P < 0.01) explained variation of weekly BCS for primiparous cows. Primiparous ProCROSS cows had higher (P < 0.01) mean BCS in every 7-d period than the HO cows (Figure 3.3). Both ProCROSS and HO primiparous cows lost BCS (P < 0.01) at the beginning of lactation. The ProCROSS cows had BCS of 3.41 to 3.48 in periods 3 to 21, with their lowest mean BCS in period 10. The primiparous HO cows reached lowest mean BCS in period 6, but they were relatively constant (P > 0.05) for BCS in periods 5 to 21 with a mean BCS of 3.14 to 3.24 in those periods.

Breed group and 7-d period nested within breed group significantly (P < 0.01) explained variation of weekly BCS for multiparous cows. Multiparous ProCROSS cows had higher mean BCS (P < 0.05) than HO cows in every 7-d period except period 5, when the ProCROSS cows tended (P = 0.10) to have higher BCS than HO cows (Figure 3.3). Like the primiparous cows, multiparous ProCROSS and HO cows both lost BCS (P < 0.01) at the beginning of lactation (Figure 3.3). In periods 7 to 21, multiparous

ProCROSS cows had BCS of 3.17 to 3.25 and multiparous HO cows had BCS of 2.97 to 3.07.

Production. For primiparous cows, year of calving, breed group, and 7-d period nested within breed group all significantly ($P < 0.01$) explained variation of weekly milk volume. Primiparous ProCROSS cows produced less milk volume ($P < 0.05$) than HO cows in every 7-d period (Figure 3.4). The ProCROSS cows had their highest mean milk volume near 33.0 kg/d in periods 12 to 15, whereas HO cows had their highest mean milk volume (34.4 to 35.5 kg/d) in periods 12 to 14.

Breed group and 7-d period nested within breed group significantly ($P < 0.05$) explained variation of milk volume for multiparous cows. ProCROSS and HO cows did not differ ($P > 0.06$) for mean milk volume until period 8, when HO cows began to have higher ($P < 0.05$) milk volume than ProCROSS cows through 150 DIM (Figure 3.4). Multiparous ProCROSS cows had highest milk volume of 45.2 to 45.3 kg/d in periods 7 to 9, and multiparous HO cows had highest milk volume of 47.7 to 47.8 kg/d in periods 9 to 11. Multiparous cows reached peak milk volume earlier within lactation than they reached peak DMI. Multiparous cows of both breed groups also reached highest milk volume sooner within lactation than primiparous cows.

For primiparous cows, year of calving, and 7-d period nested within breed group significantly ($P < 0.01$) explained variation for fat plus protein production. However, the ProCROSS cows did not differ ($P > 0.49$) from HO cows for mean fat plus protein production for any of the 21 weekly 7-d periods. In comparison to milk volume, primiparous cows increased ($P < 0.01$) for fat plus protein production at the beginning of lactation and then plateaued until 150 DIM (Figure 3.5). Primiparous ProCROSS cows plateaued at 2.34 to 2.35 kg of fat plus protein production/day in periods 14 to 21, and, similarly, primiparous HO cows plateaued at 2.32 to 2.33 kg of fat plus protein production/day in periods 13 to 21.

For multiparous cows, only 7-d period nested within breed group significantly ($P < 0.01$) explained variation of fat plus protein production. Like the primiparous cows, multiparous ProCROSS cows did not differ ($P > 0.65$) from HO cows for fat plus protein production for any of the weekly 7-d periods (Figure 3.5). Multiparous ProCROSS cows increased for fat plus protein production at the beginning of lactation, plateaued in periods 5 to 9 at 3.11 to 3.13 kg fat/day plus protein/day, and then decreased for fat plus protein production through 150 DIM. Multiparous HO cows were similar to ProCROSS cows, but plateaued at 3.08 to 3.10 kg fat/day plus protein/day in periods 5 to 10.

3.4 Discussion

Differences in DMI between ProCROSS and HO cows may reflect differences of the pure breeds of HO, MO, and VR for DMI of cows. Ntallaris et al. (2017) compared pure VR cows to pure HO cows for DMI, production, and energy balance in a Swedish confinement herd and reported primiparous VR cows consumed 9.3% less DMI, produced 14% less ECM, had more BCS, and mobilized less body condition than HO cows from calving to 120 DIM, although sample sizes were small. Furthermore, Ntallaris et al. (2017) suggested the HO cows in their study prioritized production over fertility and health more than did the VR cows and, perhaps, HO cows required more DMI than VR cows because of higher production and because of a lower baseline BCS at calving.

Buckley et al. (2007) and Walsh et al. (2008) compared pure HO, pure MO, and MO × HO crossbred cows in a grazing system, and they reported pure MO cows had

5.7% lower DMI, 13% lower milk volume, 15.6% lower fat plus protein production (kg), and 0.38 higher BCS than HO cows. Also, both studies found MO × HO cows were not different from HO cows for DMI, milk volume, or fat plus protein production, but MO × HO cows had 0.23 higher BCS than HO cows (Buckley et al., 2007; Walsh et al., 2008). In our study, both primiparous and multiparous ProCROSS and HO cows did not differ for fat plus protein production; however, ProCROSS cows had lower DMI and lower milk volume, but higher BCS, than HO cows. Differences in milk volume and BCS, despite no difference for fat plus protein production, may have accounted for some of the difference in DMI of the breed groups in this study. The HO cows in this study may have required more DMI in order to produce more fluid carrier (water) in their milk compared to the ProCROSS cows. Heterosis of crossbreds for DMI could also explain at least some of the difference in DMI from HO cows in addition to breed differences for additive genetic effects. However, heterosis could not be estimated in this study because pure MO and VR cows were not available for comparison.

Composition of refusals was not analyzed in this study, and breed groups potentially could have sorted TMR differently, which also could have influenced differences in DMI. Furthermore, the higher DMI of the HO cows could have led to reduced digestibility of the diet because of a higher rate of passage through the digestive system (Colucci et al., 1982). Differences in the microbiome of cows in this study may also have played a role in breed group differences for DMI. Gonzalez-Recio et al. (2018) reported differences in the microbiome of Holstein and Brown Swiss cows fed the same diets, and this suggested genetics of cows may explain differences of the microbiome they harbor. The MO and VR breeds have been genetically improved in northern Europe based on diets with emphasis on rye grass. On the other hand, the HO breed has been genetically improved in North America based on TMR diets with emphasis on legumes and corn silage.

The ProCROSS and HO cows in this study did not differ for BW, and this was likely because the ProCROSS cows had smaller mean WH but higher mean BCS than the HO cows. The differences in WH and BCS were anticipated because of different selection goals for the HO, MO, and VR breeds. For the HO breed, a positive genetic trend for body size composite, which placed 50% emphasis on stature until 2016 (Holstein Association USA, Inc, 2016), has resulted in HO cows that are taller in the front (WH), despite a negative weight on body size composite in the Net Merit index (VanRaden et al., 2014; VanRaden, 2017). Furthermore, the HO breed has strongly selected for lower BCS and continues to do so with the negative weight on body weight composite in the Net Merit index (Holstein Association USA Inc, 2017; VanRaden, 2017). The MO breed has historically selected for cows to maintain BCS and has selected for fertility and survival for 20 years (Barbat et al., 2010). The VR breed has ignored both stature and BCS for selection but has selected for fertility for over 30 years in their selection indices (Pryce et al., 2014).

In commercial herds in the United States, primiparous MO × HO and VR × HO crossbred cows were shorter for mean WH and had 0.38 higher BCS than HO cows (Hazel et al., 2017a), and these results are similar to those in this study for primiparous ProCROSS and HO cows. However, the cows in Hazel et al. (2017a) were only scored once for BCS in early lactation, and BW was not available. Like this study of ProCROSS and HO cows, Walsh et al. (2008) found no differences in BW for mixed-parity MO ×

HO crossbred cows compared to HO cows, and their cows reached nadir BW between 5 and 8 weeks of lactation. In contrast, Hazel et al. (2013) reported primiparous MO × HO cows had 36 kg higher BW compared to primiparous HO cows, but this was likely because MO × HO cows had much higher BCS (+0.58) and similar HH in the first 150 DIM compared to HO cows. Both Hazel et al. (2013) and Walsh et al. (2008) found both MO × HO and HO cows lost body condition in early lactation but, similar to ProCROSS cows in this study, the MO × HO crossbred cows maintained higher BCS during the first half of lactation.

The DMI and BCS of growing heifers were not evaluated. Also, DMI and BCS was not available for cows after 150 DIM or during the dry period; therefore, the DMI and BCS of ProCROSS and HO cattle during those periods of time are unknown. However, results from this study suggest both primiparous and multiparous ProCROSS cows maintained a higher baseline BCS compared to HO cows over time, and this was supported by Hazel et al. (2014) who observed BCS from calving to 300 DIM and across the first 5 lactations was higher for MO-sired crossbred cows than HO cows.

The ProCROSS cows in this study had lower milk volume than HO cows, but the ProCROSS and HO cows were not different for fat plus protein production (kg). Fluid milk volume is too frequently used as the sole measure of productivity of cows on dairy farms; however, most dairy producers in the United States are paid primarily for the fat and protein solids in milk rather than the fluid carrier of milk. The HO breed has a documented advantage over other breeds for fluid milk volume. However, pure MO (Dezetter et al., 2015) and pure VR cows (Jönsson, 2015) have higher fat and protein percentages in their milk than HO cows. The MO and VR breeds have not historically placed selection emphasis on milk volume but, rather, both breeds have selected for fat and protein production (kg), for fertility, and for cow health or survival (Oltenacu and Broom, 2010).

Other studies, like this study, have reported lower milk volume (–2.1% to –6.1%) for 2-breed and 3-breed crosses of the HO, MO, and VR breeds (Heins et al., 2006b; Malchiodi et al., 2011; Hazel et al., 2017b). Heins et al. (2006b) found primiparous MO × HO cows had 3.8% less fat plus protein production (kg) than HO cows while Nordic Red × HO cows had no differences for fat plus protein production from HO cows. Malchiodi et al. (2011) reported ProCROSS cows from a single herd in northern Italy had 5.5% less fat production and no difference for protein production than HO cows during their first 2 lactations. More recently, Hazel et al. (2017b) reported MO × HO and VR × HO primiparous crossbreds collectively had 1.9% more fat plus protein production than their HO herdmates. Conflicting results for fat plus protein production for cows in the various studies could have resulted from genetic level of sires of cows within breeds or from differences in herd management.

3.5 Conclusions

During the past decade, interest in crossbreeding has grown for dairy cattle because the deficiencies of pure HO cows for fertility, health, and survival became more pronounced. Because most crossbred cows have higher BCS and lower milk volume than HO cows, some may have assumed crossbred dairy cows must have lower fat plus protein production than HO cows. However, the ProCROSS cows in this study did not differ from HO cows for fat plus protein production (kg) from 4 to 150 DIM their first 3 lactations. Also, the ProCROSS cows consumed less DMI than HO cows, did not differ for BW from HO cows, were shorter for WH than HO cows, and had higher BCS than HO cows. Therefore, the lower DMI of ProCROSS than HO cows resulted in less feed cost without lost revenue from fat plus protein production.

Furthermore, higher BCS is documented to have a positive relationship with improved fertility and reduced health disorders of cows. The comparison of ProCROSS and HO cows in this study suggests ProCROSS cows may have advantages for profitability over HO cows for commercial milk production.

3.6 Acknowledgements

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3.7 Tables

Table 3.1. Number of cow-lactations available for analysis by parity group and breed group

	Lactation number					
	1		2		3	
	Holstein	ProCROSS	Holstein	ProCROSS	Holstein	ProCROSS
Calved	63	70	31	38	9	11
Involuntarily culled before 150 DIM	3	7	3	4	0	2
Completed 150-d study	60	63	28	34	9	9

Table 3.2. Mean TMR diet composition and nutrient density across the 3 years of the study

Item	Diet
Ingredient (% of DM)	
Alfalfa hay	7.7
Grass hay	1.0
Alfalfa haylage	8.3
Corn silage	30.0
Corn gluten feed	9.8
Corn grain, ground	13.1
Cottonseed, fuzzy	5.0
Molasses, liquid	3.2
Protein mix	20.8[1]
Energy Booster 100	1.1[2]
Nutrient composition	
DM (%)	54.6
CP (% of DM)	16.6
ADF (% of DM)	19.7
NDF (% of DM)	30.2
NE_L (Mcal/kg DM)	1.62

[1] Protein mix included fine rolled corn (29.7%), soybean meal (17.5%), canola meal (12.5%), AminoPlus (8.75%; Ag Processing Inc., Omaha, NE), blood meal (6.25%), calcium (5.5%), dry distillers grain (5.0%), sodium bicarbonate (5.0%), microminerals (2.5%), Ultramet (2.0%; Vita Plus Corp., Madison, WI), potassium carbonate (2.0%), white salt (2.0%), urea (1.25%), and Rumensin (0.03%; Elanco Animal Health, Greenfield, IN) on a DM basis

[2] Hydrogenated fat (Milk Specialties, Eden Prairie, MN)

Table 3.3. Least square means and standard errors of means for the effect of year (1, 2, or 3) for DMI, BCS, BW, wither (WH), hip height (HH), milk volume, and fat plus protein production from 4 to 150 DIM for primiparous cows

	Year[1]					
	1 (n = 48)		2 (n = 37)		3 (n = 38)	
Trait	LSM	SE	LSM	SE	LSM	SE
DMI (kg)	2,823[a]	41.3	2,744[a]	47.0	3,067[b]	46.4
BW (kg)	544[a]	7.9	562[ab]	9.0	570[b]	8.9
WH (cm)	137.0	0.6	138.0	0.7	137.1	0.7
HH (cm)	142.6[a]	0.6	144.3[b]	0.6	143.0[ab]	0.6
BCS	3.25[a]	0.03	3.31[a]	0.04	3.43[b]	0.04
Milk (kg)	4,508[a]	53.8	4,731[b]	61.2	4,762[b]	60.4
Fat + protein (kg)	317[a]	3.7	338[b]	4.2	335[b]	4.1

[1] Mean age at calving of 25.5 ± 2.4 mo (year 1), 24.2 ± 2.4 mo (year 2), and 22.9 ± 1.3 mo (year 3).

[a,b] LSM are significantly different ($P < 0.05$) when superscripts differ across columns.

Table 3.4. Least square means and standard errors of means for DMI, BCS, BW, wither height (WH), hip height (HH), milk volume, and fat plus protein production from 4 to 150 DIM by parity and breed group

	Primiparous				Multiparous			
	Holstein (n = 60)		ProCROSS (n = 63)		Holstein (n = 37)		ProCROSS (n = 43)	
Trait	LSM	SE	LSM	SE	LSM	SE	LSM	SE
DMI (kg)	2,948	36.9	2,807**	36.3	3,592	68.1	3,360*	63.1
BW (kg)	556	7.1	562	7.0	644	10.2	636	9.4
WH (cm)	139.4	0.5	135.4**	0.5	143.7	0.7	140.2**	0.6
HH (cm)	144.3	0.5	142.3**	0.5	146.4	0.7	145.2	0.6
BCS	3.20	0.03	3.46**	0.03	3.06	0.04	3.25**	0.04
Milk (kg)	4,770	48.1	4,564**	47.2	6,636	111.2	6,264*	103.1
Fat + protein (kg)	329	3.3	331	3.2	441	7.0	445	6.5

**$P < 0.01$, *$P < 0.05$ for differences from Holstein within parity group

3.8 Figures

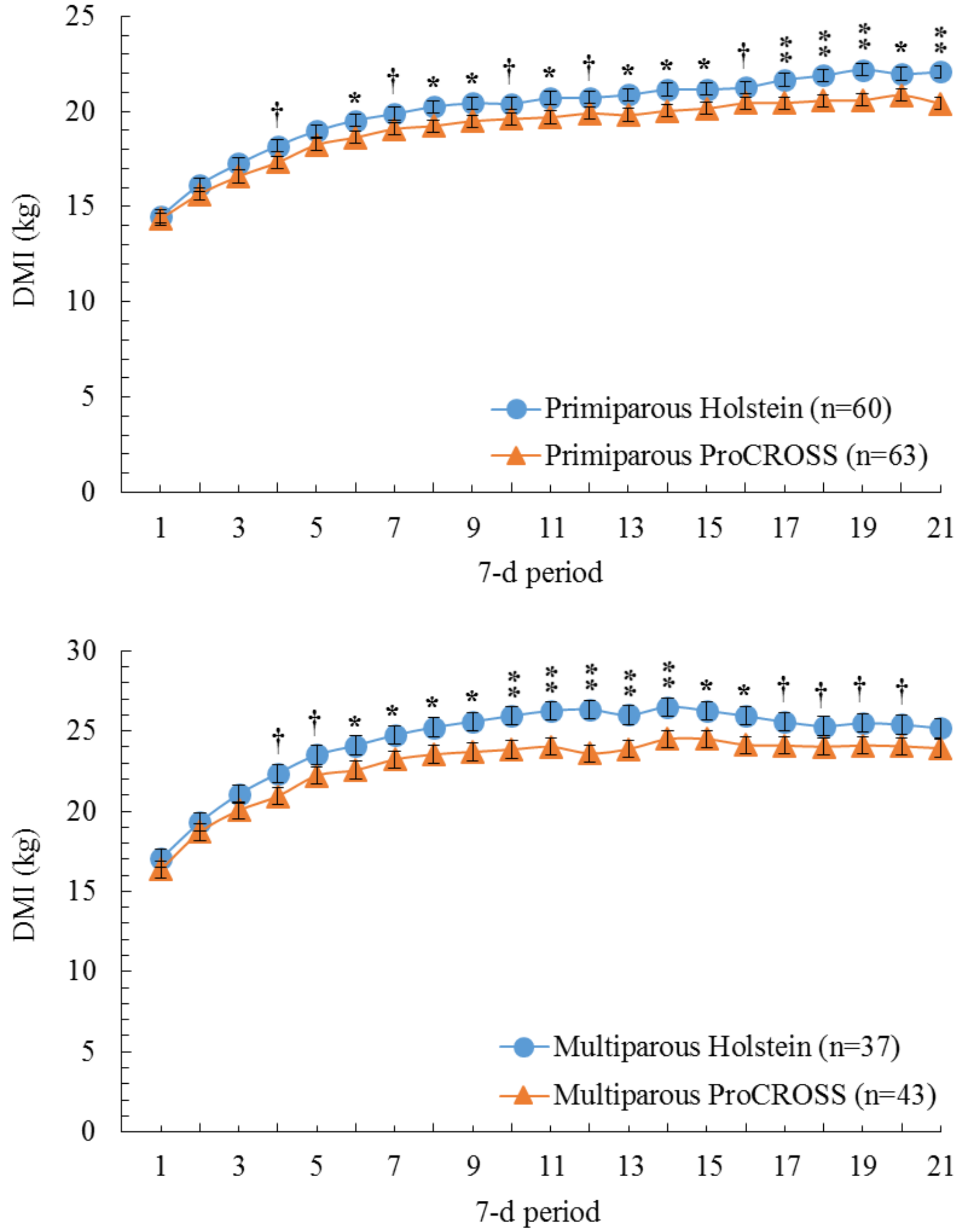

Figure 3.1. Least square means of weekly DMI (kg) for primiparous and multiparous Holstein and ProCROSS cows. Error bars represent SEM of weekly DMI. Symbols above means represent differences between breed groups for weekly least square means of DMI (†$P < 0.10$, *$P < 0.05$ and **$P < 0.01$). The 7-d periods correspond to DIM: 1 (4 to 10), 2 (11 to 17), 3 (18 to 24), 4 (25 to 31), 5 (32 to 38), 6 (39 to 45), 7 (46 to 52), 8 (53 to 59), 9 (60 to 66), 10 (67 to 73), 11 (74 to 80), 12 (81 to 87), 13 (88 to 94), 14 (95 to 101), 15 (102 to 108), 16 (109 to 115), 17 (116 to 122), 18 (123 to 129), 19 (130 to 136), 20 (137 to 143) and 21 (144 to 150).

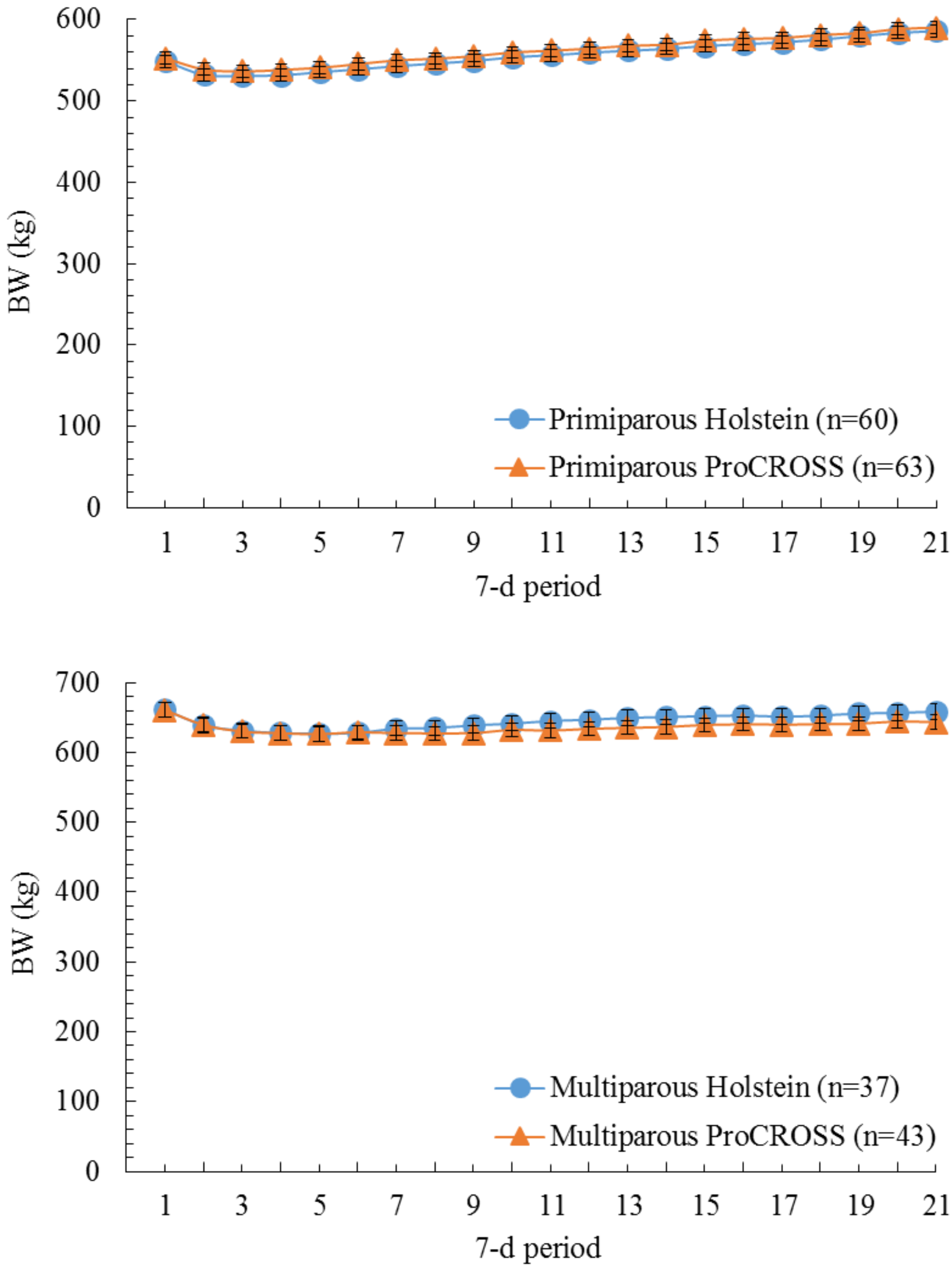

Figure 3.2. Least square means of weekly BW for primiparous and multiparous Holstein and ProCROSS cows. Error bars represent SEM of weekly BW. Breed groups did not differ for weekly BW. The 7-d periods correspond to DIM: 1 (4 to 10), 2 (11 to 17), 3 (18 to 24), 4 (25 to 31), 5 (32 to 38), 6 (39 to 45), 7 (46 to 52), 8 (53 to 59), 9 (60 to 66), 10 (67 to 73), 11 (74 to 80), 12 (81 to 87), 13 (88 to 94), 14 (95 to 101), 15 (102 to 108), 16 (109 to 115), 17 (116 to 122), 18 (123 to 129), 19 (130 to 136), 20 (137 to 143) and 21 (144 to 150).

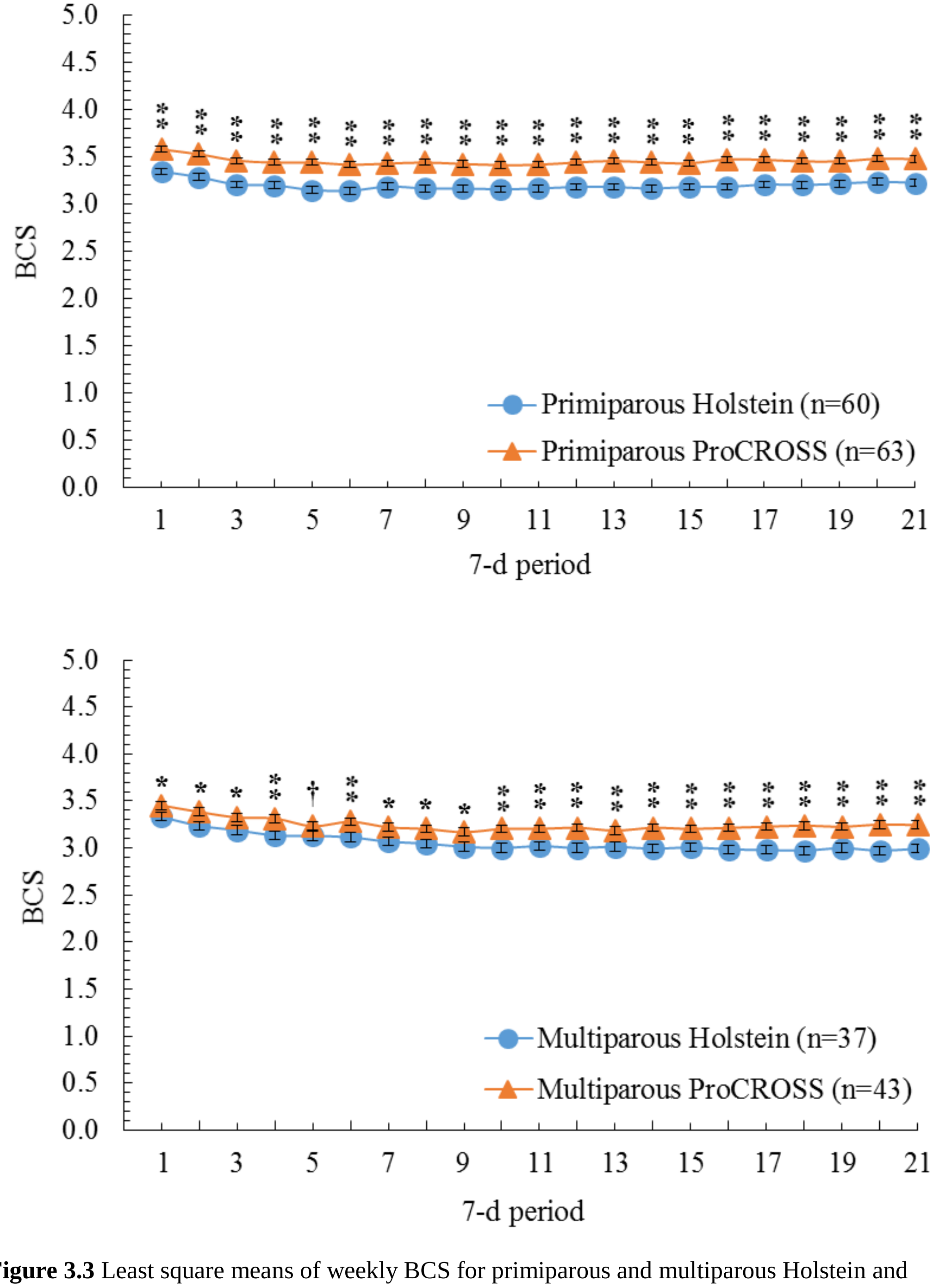

Figure 3.3 Least square means of weekly BCS for primiparous and multiparous Holstein and ProCROSS cows. Error bars represent SEM of weekly BCS. Symbols above means represent differences between breed groups for weekly least square means of BCS (†$P < 0.10$, *$P < 0.05$ and **$P < 0.01$). The 7-d periods correspond to DIM: 1 (4 to 10), 2 (11 to 17), 3 (18 to 24), 4 (25 to 31), 5 (32 to 38), 6 (39 to 45), 7 (46 to 52), 8 (53 to 59), 9 (60 to 66), 10 (67 to 73), 11 (74 to 80), 12 (81 to 87), 13 (88 to 94), 14 (95 to 101), 15 (102 to 108), 16 (109 to 115), 17 (116 to 122), 18 (123 to 129), 19 (130 to 136), 20 (137 to 143) and 21 (144 to 150).

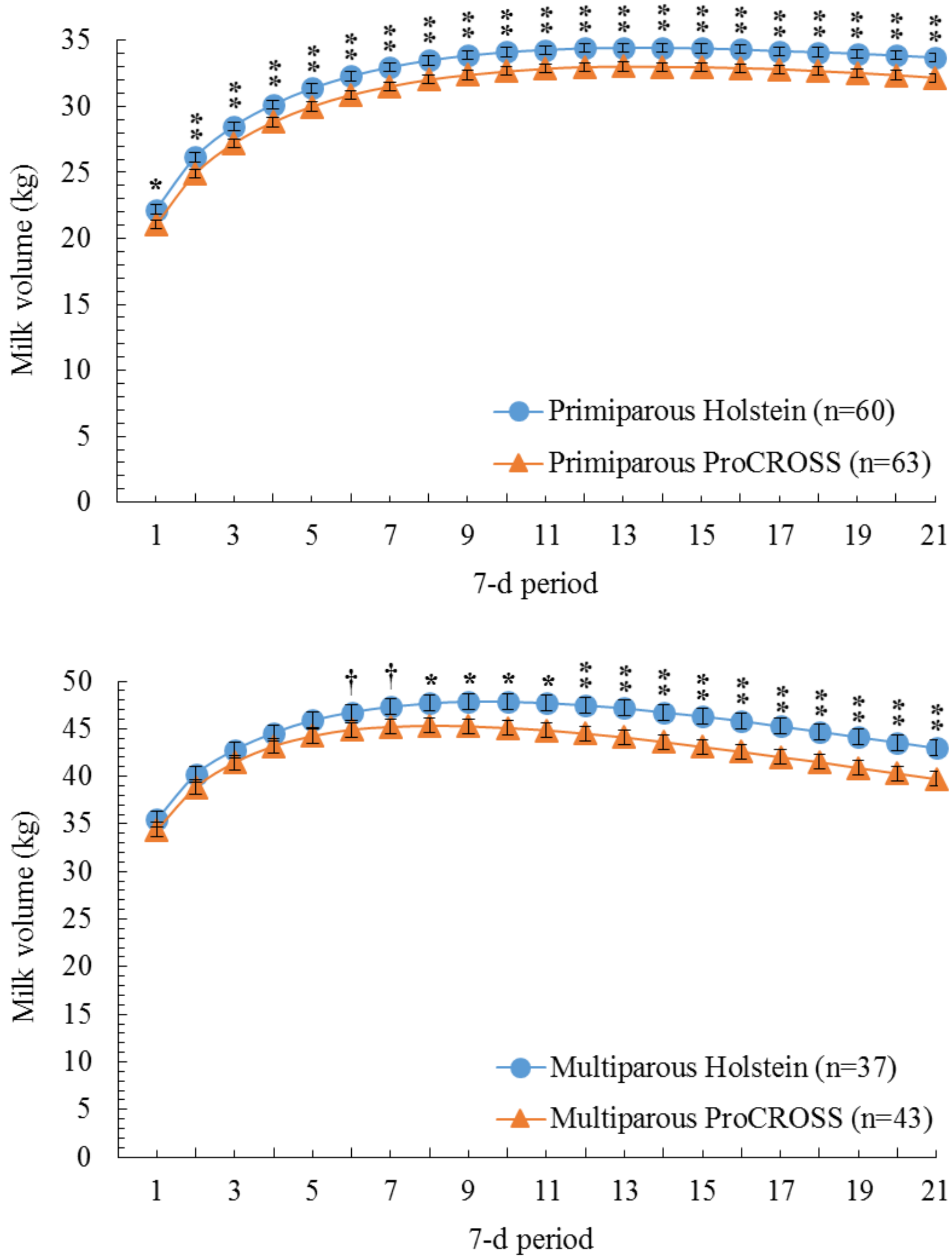

Figure 3.4 Least square means of weekly milk volume (kg) for primiparous and multiparous Holstein and ProCROSS cows. Error bars represent SEM of weekly milk volume. Symbols above means represent differences between breed groups for weekly least square means (†$P < 0.10$, *$P < 0.05$ and **$P < 0.01$). The 7-d periods correspond to DIM: 1 (4 to 10), 2 (11 to 17), 3 (18 to 24), 4 (25 to 31), 5 (32 to 38), 6 (39 to 45), 7 (46 to 52), 8 (53 to 59), 9 (60 to 66), 10 (67 to 73), 11 (74 to 80), 12 (81 to 87), 13 (88 to 94), 14 (95 to 101), 15 (102 to 108), 16 (109 to 115), 17 (116 to 122), 18 (123 to 129), 19 (130 to 136), 20 (137 to 143) and 21 (144 to 150).

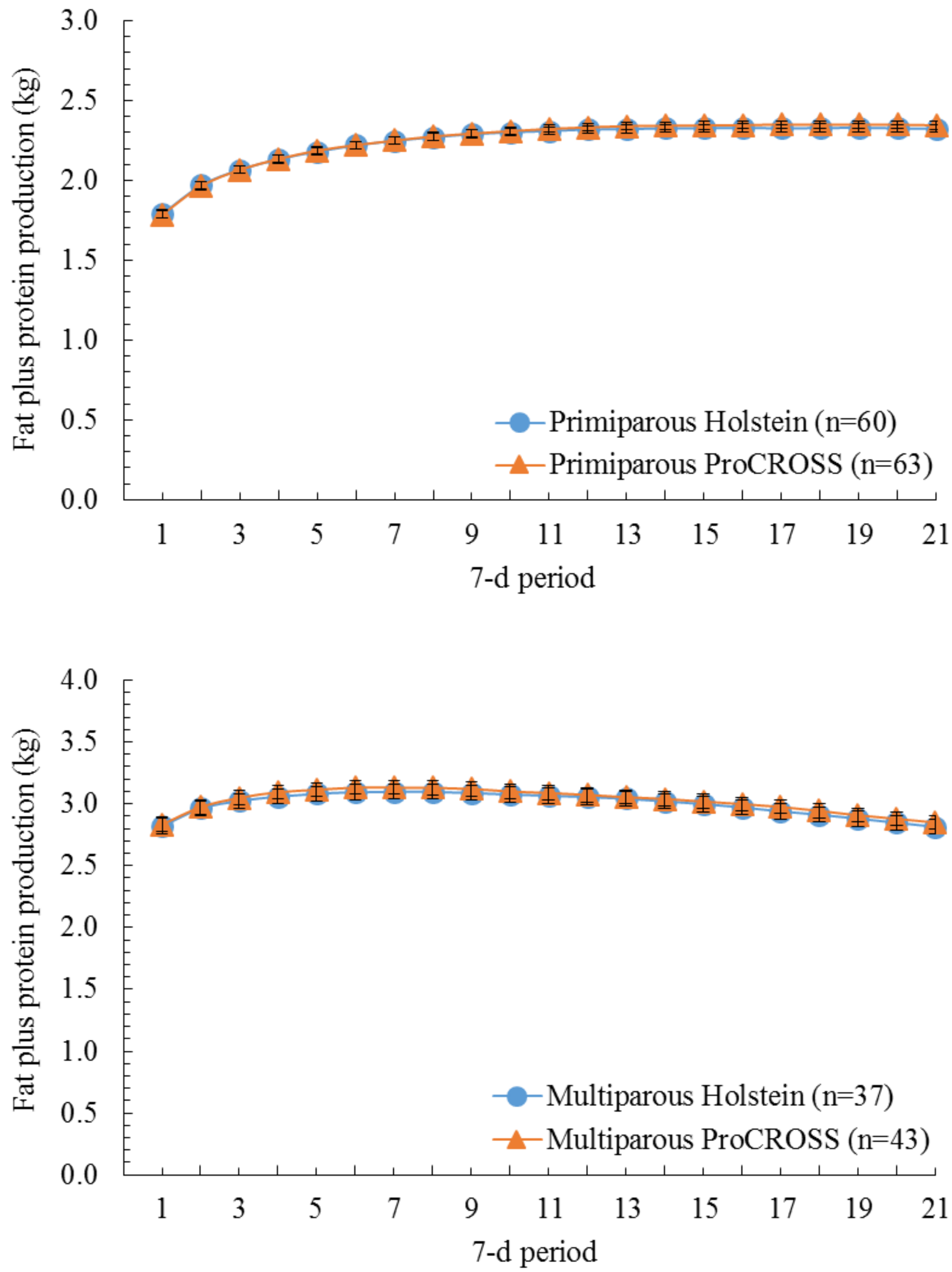

Figure 3.5. Least square means of weekly fat plus protein production (kg) for primiparous and multiparous Holstein and ProCROSS cows. Error bars represent SEM of weekly fat plus protein production. Breed groups did not differ for weekly fat plus protein production. The 7-d periods correspond to DIM: 1 (4 to 10), 2 (11 to 17), 3 (18 to 24), 4 (25 to 31), 5 (32 to 38), 6 (39 to 45), 7 (46 to 52), 8 (53 to 59), 9 (60 to 66), 10 (67 to 73), 11 (74 to 80), 12 (81 to 87), 13 (88 to 94), 14 (95 to 101), 15 (102 to 108), 16 (109 to 115), 17 (116 to 122), 18 (123 to 129), 19 (130 to 136), 20 (137 to 143) and 21 (144 to 150).

CHAPTER 4. COMPARISON OF PROCROSS AND HO COWS FOR FEED EFFICIENCY, INCOME OVER FEED COST, AND RESIDUAL FEED INTAKE

4.1 Introduction

The efficient utilization of feed consumed by dairy cows has grown in interest as an area of research in recent years because of heightened emphasis on agriculture sustainability. More than 50% of the expenses of dairy operations in the United States are feed cost (USDA-ERS, 2018). Therefore, feed efficiency (**FE**) of dairy cows is economically important and is defined as the ability of an animal to convert feed to product (Connor, 2015). Modern dairy cows have higher FE than their ancestors because of increased milk production per cow resulting from genetic selection, improved nutrition, and enhanced herd management. Today’s genetically-improved cows partition a higher percentage of feed to production instead of maintenance (VandeHaar et al., 2016). However, much of the potential gain in FE from increased production has already been exploited, so other approaches are needed to further increase production per unit of feed (VandeHaar et al., 2016).

The number of crossbred dairy cows in the United States has risen over the past decade because of the decline in fertility, health, and survival and the increase of average inbreeding of Holstein (**HO**) cows (Council on Dairy Cattle Breeding, 2018a,b). In addition, most milk pricing systems in the United States favor high fat and protein solids production rather than the fluid carrier of milk and crossbreds have higher fat and protein content in their milk than HO cows (López-Villalobos et al., 2000; USDA-AMS, 2018b). Many studies have reported favorable results of crossbred cows compared to HO cows for production, fertility, heath, and survival (López-Villalobos et al., 2000; Heins et al., 2012; Hazel et al., 2017a,b), but little research has been conducted on the FE of crossbred compared to HO cows. In order for dairy producers to make more judicious decisions on the breed composition of their cows, the FE of crossbred cows needs to be investigated. However, data on FE are costly to acquire because of the specialized labor and equipment to collect feed intake (**FI**) for individual cows.

Universal agreement on the optimum measure of FE for dairy cattle has not been achieved (Coleman et al., 2010; Hurley et al., 2016), and this adds to the complexity of assessing FE. For example, Hurley et al. (2016) reported relationships among 14 alternative definitions of energy efficiency. Ratio traits that compare output (production) to input (intake) are common, but they don't adequately account for differences in cows for energy partitioning toward milk production, body maintenance, or mobilization of body tissue (Veerkamp and Emmans, 1995; Berry and Crowley, 2013). Many of the ratio measures of FE in the study by Hurley et al. (2016) were not correlated, which suggested the alternative measures of FE may describe different aspects of FE.

Residual feed intake (**RFI**) has become a common measure of FE for dairy cows, especially for genetic evaluation. The RFI is the difference between the predicted and actual FI required for production and body maintenance and is often estimated as the residual from the regression of DMI on energy sinks such as production, BW, and change in BW for individual cows (Berry and Crowley, 2013; Connor, 2015). An advantage of deriving RFI from multiple regression is RFI becomes independent of the energy sinks, which allows for comparison of cows across production levels. (Coleman et al., 2010). A negative RFI indicates a cow had less FI than predicted based on her energy sinks and thus is more efficient. The regression variables used to estimate RFI also differ among studies (Hurley et al., 2016); therefore, comparison of RFI across studies is somewhat difficult.

The beef cattle industry in the United States has taken advantage of the benefits of crossbreeding (breed complementarity and heterosis) for more than 40 yr to enhance productivity through increased growth rates and female longevity which, in turn, has resulted in improved FE (Gregory and Cundiff, 1980). Historical estimates of heterosis for FE of beef cattle have generally been positive but usually < 5%; however, heterosis varied depending on the breed composition of the crossbred cattle and differences in herd management (Gregory et al., 1966; Urick et al., 1984). Capitalizing on heterosis from crossbreeding has been a major contributor to the commercial pig industry for more than 60 yr in the United States, because heterosis is substantial for litter size and rate of gain and these traits have large impact on FE (Young et al., 1976; Johnson, 1981). However, heterosis for FE from crossbreeding has not been a focus of research in recent years for either beef or dairy cattle (Berry and Crowley, 2013).

Most recent research on FE has explored the genetic control of FE for pure HO cows rather than comparing breeds of cows for FE. Research on FE of crossbred cows has mostly focused on Jersey × HO crossbreds, and the results have been mixed. Schwager-Suter et al. (2001) reported Jersey × HO crossbreds in a confinement system had more FE than pure HO cows because of a higher ratio of ECM to net energy intake. Prendiville et al. (2009) found Jersey × HO crossbreds had a higher ratio of milk solids to DMI over a total lactation in a pasture system. In contrast, Heins et al. (2008) reported Jersey × HO crossbreds were not different than HO cows for the ratio of ECM to DMI through 150 DIM. Olson et al. (2010) found neither Jersey × HO nor HO × Jersey crossbreds were different from HO for FE defined as the ratio of energy required for milk production to total energy consumed. Buckley et al. (2007) reported MO × HO crossbreds were not different from HO for milk solids production per unit of DMI or for DMI per unit of BW.

Rotational crossbreeding, usually with 3 distinct breeds, has grown in global popularity over the past decade. In particular, the 3-breed rotation of the HO, Montbeliarde (**MO**), and Viking Red (**VR**) breeds has broad interest for dairying in temperate climates and is marketed internationally as ProCROSS. The MO breed was developed in France and has based selection only on dairy traits but with a goal of increasing BCS unlike most other breeds of dairy cattle (O.S. Montbéliarde, 2018a,c). The VR breed includes the subpopulations of Swedish Red, Finnish Ayrshire, and Danish Red, and VR cows tend to have lower milk volume but higher fat and protein content of milk than HO cows (Jönsson, 2015). Furthermore, the VR breed has been selected for health and fertility for over 30 yr (Pryce et al., 2014). The objective of this study was to compare three-breed rotational crossbred cows of the HO, MO, and VR breeds to pure HO for alternative measures of FE.

4.2 Materials and methods

4.2.1 Experimental units

Research with crossbreeding at the University of Minnesota began in the early 2000s. The initial crossbreds were Jersey × HO and MO × HO and, subsequently, 3-breed crossbreds of those breeds. The Jersey breed was later replaced with the VR breed for an ongoing 3-breed rotational system of HO, MO, and VR. A description of the crossbreeding design and genetic level of cows in this study was reviewed in Chapter 3.

Cows were housed at the Dairy Cattle Teaching and Research Facility of the University of Minnesota, St. Paul, and animal use was approved by the Institutional Animal Care and Use Committee of the University of Minnesota (#1408-31736A). The ProCROSS and HO cows were paired prior to first calving according to age (mo) and expected calving date. The cows that calved for the first time from September 2014 to May 2015 (year 1) had the opportunity for 2 subsequent lactations to be included in the study. Cows that calved for the first time from September 2015 to April 2016 (year 2) had the opportunity for 1 subsequent lactation to be included in the study. The cows that calved for the first time from August 2016 to April 2017 (year 3) had the opportunity for only a first lactation to be included in the study.

Some cows were involuntarily culled, and cows that left the herd before 150 DIM were eliminated from the study for only the terminal lactation (Chapter 3). Less than 9% of the lactations of cows were eliminated for cows that left the herd before 150 DIM. In total, 63 ProCROSS and 60 HO cows were available for analysis. Of the 63 primiparous ProCROSS cows, 14 had a HO sire, 29 had a MO sire, and 20 had a VR sire. The multiparous analysis had 43 lactations (15 with a HO sire, 15 with a MO sire, and 13 with a VR sire) of ProCROSS cows and 37 lactations of HO cows. More details about the cows in this study were reviewed in Chapter 3.

4.2.2 Data collection

A TMR was delivered twice daily to cows housed in the tie-stall barn for the duration of study period. The amount fed to each cow had a target of at least a 5% daily refusal rate, and the amount fed was adjusted daily. Recording errors caused by computer malfunction or human error were removed, but they accounted for a small proportion (2.6%) of daily FI data. Missing daily FI were estimated by extrapolation using the mean from 2 d before and 2 d after the missing daily FI observation. The DM content of the TMR was determined from weekly samples and the NE_L and CP density of the TMR was determined from monthly samples. The TMR had a mean DM of 54.6%, a mean NE_L of 1.62 Mcal per kilogram of DM, and a mean CP of 16.6% on a DM basis. The daily DMI (kg) was daily FI multiplied by the respective weekly DM content of the TMR, the daily NE_L intake (**NEI**) was daily DMI multiplied by the respective monthly NE_L density of the diet, and the daily CP intake (**CPI**) was DMI multiplying by the respective monthly CP content of the diet.

The BW was recorded twice weekly with a digital scale at the time cows exited the milking parlor. The BCS was evaluated on all cows once per week by a single trained evaluator and was scored on a 5-point scale with 0.25 increments with 1 = thin and 5 = obese (Wildman et al., 1982). Additional details about the FI, BW, and BCS of individual cows, as well as the ingredients and nutritional composition of the diet, are presented in Chapter 3.

Cows were milked twice daily at 0400 h and 1600 h. Milk volume and fat, protein, and lactose percentages from monthly DHI (Minnesota DHIA, Buffalo, MN) were used to estimate production for complete lactations with Best Prediction (**BP**) from Cole and VanRaden (2009). Edits applied to test-day observations for milk volume and fat and protein percentages were described in Chapter 3. Daily lactose production could not be estimated with BP; therefore, percentage of lactose was assigned for each DIM from 4 d to 150 d based on the test day closest to that DIM for each cow.

4.2.3 Measures of FE

Ratio measures. Both FI and production were the sums of daily observations from 4 to 150 DIM. The FI was quantified as DMI (kg), NEI (Mcal), or CPI (kg). Production was quantified as fat plus protein production (kg), true protein production (kg), or ECM (kg) calculated with the equation of Tyrrell and Reid (1965):

$$\text{ECM} = 0.327 \times \text{milk (kg)} + 12.95 \times \text{fat (kg)} + 7.20 \times \text{protein (kg)}$$

with daily milk, fat, and protein of a cow estimated by BP. The BW was the mean BW from 4 to 150 DIM. The FE for 4 to 150 DIM was defined as

1) Feed conversion efficiency (**FCE**):

$$\text{FCE} = \frac{\text{Fat plus protein production (kg)}}{\text{DMI (kg)}}$$

2) ECM per unit of DMI (**ECM/DMI**):

$$\text{ECM/DMI} = \frac{\text{ECM (kg)}}{\text{DMI (kg)}}$$

3) Net energy of lactation efficiency (**NE_LE**):

$$\text{NE}_\text{L}\text{E} = \frac{\text{ECM (kg)}}{\text{NEI (Mcal)}}$$

4) Crude protein efficiency (**CPE**):

$$\text{CPE} = \frac{\text{True protein production (kg)}}{\text{CPI (kg)}}$$

5) DMI per unit of BW **(DMI/BW)**:

$$\text{DMI/BW} = \frac{\text{DMI (kg)}}{\text{BW (kg)}}$$

Income over feed cost. Feed cost was estimated as $0.2936/kg of DM reported by FINBIN (Center for Farm Financial Management, 2017), which summarizes financial data from dairy producers in the Upper Midwest region of the United States. Feed cost per cow from 4 to 150 d of lactation was calculated by multiplying the feed cost per kilogram ($0.2936) by the total DMI (kg) consumed. The value of fat and protein production was derived from Federal Milk Marketing Order component prices (USDA-AMS, 2018a) from September 2014 to December 2017, and resulted in a mean price of fat of $5.3471/kg and a mean price of protein of $4.8674/kg. Income from fat and protein production was obtained by multiplying the fat and protein produced by a cow by the respective fat and protein price and summing the two components. Income over feed cost (**IOFC**) was then calculated as revenue ($) from fat plus protein production minus feed cost ($) from 4 to 150 DIM.

Residual feed intake from 4 to 150 DIM. Fat, protein, and lactose production, as well as BW and BCS, were used to assess the major energy sinks of cows. Energy expended in milk (**MilkE**) was calculated according to the NRC (2001) with the use of true protein as:

$$\text{MilkE} = 9.29 \times \text{fat (kg)} + 5.63 \times \text{true protein (kg)} + 3.95 \times \text{lactose (kg)}$$

with fat, protein, and lactose production of each cow from 4 to 150 DIM. Metabolic BW (**MBW**) was used to estimate maintenance requirements of each cow as $BW^{0.75}$ from mean BW from 4 to 150 DIM. The BW change (**BWC**) from 4 to 150 DIM was estimated by regressing BW on week of observation within each lactation of a cow. Energy gained or lost for BWC (**BWCE**) from 4 to 150 DIM when BW increased was:

$$\text{BWCE (Mcal/d)} = \text{BWC (kg/d)} \times (2.88 + 1.026 \times \text{BCS}) \times 0.85$$

and when BW decreased was:

$$\text{BWCE (Mcal/d)} = \text{BWC (kg/d)} \times (2.88 + 1.026 \times \text{BCS}) \times 0.82$$

(NRC, 2001; Hardie et al., 2015). In both situations, BCS was the mean BCS recorded from 4 to 150 DIM. Energy required for physical activity was not taken into consideration, because cows were housed in a tie-stall barn for the duration of the study. In addition, energy required for pregnancy was considered negligible, because none of the cows in the study had reached 100 d of gestation by 150 DIM (NRC, 2001).

The RFI was explored separately for the primiparous and multiparous cows because their lactation curves differed substantially for DMI, BW, and production (Chapter 3). Consequently, the phenotypic RFI for the ith cow was defined as the error term (ε_i) from the regression model for primiparous cows:

$$\text{DMI}_i = \beta_0 + \beta_1 \times \text{MilkE}_i + \beta_2 \times \text{MBW}_i + \beta_3 \times \text{BWCE}_i + \text{year}_i + \varepsilon_i$$

where DMI_i is the total DMI from 4 to 150 DIM for the ith cow; β_0 is the intercept; β_1, β_2, and β_3 are the partial regression coefficients associated with the MilkE, MBW, and BWCE from 4 to 150 DIM, respectively, and year_i is year of study (1, 2, or 3) to reflect differences in heifer rearing for the 3 yr. For multiparous cows, the phenotypic RFI for the ith cow was defined as the error term (ε_i) from the regression model:

$$\text{DMI}_i = \beta_0 + \beta_1 \times \text{MilkE}_i + \beta_2 \times \text{MBW}_i + \beta_3 \times \text{BWCE}_i + \text{cow}_i + \varepsilon_i$$

where all variables are defined the same as for primiparous cows and cow_i is the repeated effect for cows with both second and third lactations.

Residual feed intake for 28-d intervals. Previous research has suggested DMI and RFI may be regulated by different genes during alternative stages of lactation (Tetens et al., 2014; Li et al., 2017). Also, research has suggested the partial regression coefficients of DMI on the various energy sinks may differ by stage of lactation, especially in early lactation, when body condition is mobilized and large changes in BW are most likely to occur (Li et al., 2017). Therefore, RFI was estimated separately for 5 stages of lactation (28-d intervals) to compare ProCROSS and HO cows from 11 to 150 DIM, and primiparous and multiparous cows were again analyzed separately within each 28-d interval. The energy sinks were again based on the mean MilkE, MBW, and BCS but only within each 28-d interval for each cow. The BWC within each 28-d interval was estimated using a regression coefficient from weekly BW observations and converted to BWCE. The RFI for 28-d intervals were estimated with the same model that was previously used for estimation of RFI from 4 to 150 DIM.

4.2.4 Statistical analysis

Variables contributing to measures of FE and RFI. Least square means of breed groups for DMI, fat plus protein production, and BW of cows in this study were previously reported (Chapter 3). The other variables contributing to measures of FE (NEI, CPI, ECM, and true protein production) and to RFI (MilkE, MBW, and BWCE) were also analyzed to assess breed group differences. For primiparous cows, year of calving (1, 2, or 3) and breed group (ProCROSS or HO) were the fixed effects for the statistical analysis for all variables contributing to FE and RFI, and the GLM procedure of SAS (release 9.4, SAS Institute, Inc., Cary, NC) was used to conduct the ANOVA and obtain solutions. For multiparous cows, breed group (ProCROSS or HO) was a fixed effect, and cow nested within breed group was a repeated effect because some cows had both second and third lactations included in the study. The MIXED procedure of SAS was used to conduct the ANOVA and obtain solutions for the multiparous analyses.

Ratio measures of FE and IOFC. For primiparous cows, independent variables for the statistical analysis of FCE, ECM/DMI, NE_LE, CPE, DMI/BW, and IOFC included the fixed effects of year of calving (1, 2, or 3) and breed group (ProCROSS or HO), and the GLM procedure of SAS was used to conduct the ANOVA and obtain solutions. For multiparous cows, the independent variables for the analysis of all of the ratio measures of FE, as well as IOFC, were breed group (ProCROSS or HO) and repeated cow within breed group to account for cows that had both second and third lactations. The MIXED procedure of SAS was used for analysis of multiparous cows to conduct the ANOVA and obtain solutions.

Residual feed intake from 4 to 150 DIM. For primiparous cows, breed group (ProCROSS or HO) was the only independent variable, and the GLM procedure of SAS was used for the analysis of RFI to conduct the ANOVA and obtain solutions. For multiparous cows, effects were breed group (ProCROSS or HO) and repeated cow within breed group, and the MIXED procedure of SAS was used for the analysis of RFI from 4 to 150 DIM to conduct the ANOVA and obtain solutions.

Residual feed intake for 28-d intervals. Ten separate analyses of RFI were conducted because each 28-d interval was analyzed separately by parity group (primiparous and multiparous). Like RFI from 4 to 150 DIM, breed group (ProCROSS or HO) was the only fixed effect for the analysis of RFI for 28-d intervals for the primiparous cows, and the GLM procedure of SAS was used to conduct the ANOVA and obtain solutions. Breed group (ProCROSS or HO) and repeated cow within breed group were the effects in the statistical model to analyze RFI for 28-d interval for the multiparous cows, and the MIXED procedure of SAS was used to conduct the ANOVA and obtain solutions.

4.3 Results and Discussion

4.3.1 Ratio measures of FE

The least square means and standard errors of means for the variables contributing to ratio measures of FE from 4 to 150 DIM are summarized in Table 4.1. Both the primiparous and multiparous ProCROSS cows had lower ($P < 0.05$) means for DMI, NEI, and CPI than HO cows but were not different ($P > 0.50$) from HO cows for all measures of production (mean fat plus protein production, mean ECM, and mean true protein production). Furthermore, both primiparous and multiparous ProCROSS cows were not different ($P > 0.53$) from HO cows for mean BW.

FCE and ECM/DMI. Year of calving significantly ($P < 0.01$) explained variation of both FCE and ECM/DMI for primiparous cows. Primiparous ProCROSS cows had higher ($P < 0.01$) mean FCE than HO cows (Table 4.2), and this was likely because ProCROSS cows consumed significantly less DMI than HO cows but were not different from HO cows for fat plus protein production (Chapter 3). Likewise, multiparous ProCROSS cows had higher ($P < 0.01$) mean FCE than multiparous HO cows (Table 4.2). The estimates of mean FCE for HO cows in this study were slightly higher than the FCE of 0.09 reported for HO cows in the same herd as this study from 4 to 150 DIM (Heins et al., 2008) and for North American HO cows in Irish grazing systems from 21 to 288 DIM (Coleman et al., 2010), and the departure is likely a reflection of differences in diet, management, genetic selection, or a combination of these factors. Contrary to the results from this study of ProCROSS and HO cows, Buckley et al. (2007) reported MO × HO crossbreds (0.142) and HO cows (0.146) did not differ for FCE in the first 8 weeks of lactation in a grazing environment, likely because the breed groups did not differ for either fat plus protein production or DMI.

Both primiparous and multiparous ProCROSS cows had higher ($P < 0.05$) ECM/DMI than HO cows (Table 4.2). The higher ECM/DMI for the ProCROSS cows was not surprising because the ProCROSS and HO cows were not different ($P > 0.50$) for ECM but ProCROSS cows had lower DMI than HO cows (Table 4.1). The ECM/DMI for both primiparous and multiparous HO cows in this study was higher than the estimates of 1.43 to 1.66 for HO cows with mixed parities and diets (Heins et al., 2008a; Potts et al., 2017).

NE_LE and CPE. Year of calving significantly ($P < 0.01$) explained variation of both NE_LE and CPE for primiparous cows. Primiparous ($P = 0.02$) and multiparous ($P = 0.02$) ProCROSS cows both had higher NE_LE than HO cows (Table 4.2). Vallimont et al. (2011) reported a mean 305-d lactational NE_LE (using FCM instead ECM) of 0.98 for HO cows housed in commercial tie-stall barns, and this was slightly lower than the estimates of 1.05 and 1.16 for HO cows from 4 to 150 DIM in this study. Like FCE and ECM/DMI, NE_LE was anticipated to be superior for both the primiparous and multiparous ProCROSS cows than the HO cows, because ProCROSS cows consumed less NEI ($P < 0.01$) than HO cows but were not different ($P > 0.50$) from HO cows for ECM (Table 4.1).

Primiparous ProCROSS cows had higher ($P < 0.01$) CPE than HO cows (Table 4.2), and this was likely because ProCROSS cows had less ($P = 0.01$) CPI than HO cows but did not differ ($P = 0.92$) from HO cows for true protein production. Likewise, multiparous ProCROSS cows had higher ($P < 0.01$) CPE than HO cows. Again, this was likely because multiparous ProCROSS cows had less ($P = 0.01$) CPI than HO cows but did not differ ($P = 0.57$) from HO cows for true protein production (Table 4.1). The CPE of HO cows in this study was comparable to the 305-d lactational CPE of 0.32 reported by Vallimont et al. (2011). Protein is often an expensive component of TMR diets, so efficient use of protein is economically important for milk production.

DMI/BW. For primiparous cows, both year of calving and breed group significantly ($P < 0.01$) explained variation for DMI/BW, and ProCROSS cows had lower ($P < 0.01$) mean DMI/BW than HO cows (Table 4.2). Multiparous ProCROSS cows also had a lower ($P = 0.03$) mean DMI/BW than multiparous HO cows (Table 4.2). The HO cows in this study had a mean daily DMI/BW of 0.036 and 0.038 for primiparous and multiparous cows, respectively. The DMI/BW for HO cows in this study was comparable to the estimates reported by Coleman et al. (2010) ranging from 0.030 to 0.034 daily DMI/kg BW for alternative strains of HO cows in grazing systems. Buckley et al. (2007) reported MO × HO and HO cows did not differ for DMI per 100 kg of BW, because the two breed groups did not differ for either DMI or BW. The lower DMI, but equivalent BW, of ProCROSS cows compared with HO cows in this study (Table 4.1) resulted in ProCROSS cows having a lower DMI/BW than HO cows.

In a review paper, Grainger and Goddard (2004) suggested higher FCE could be achieved, all other things being equal, if cows have a higher DMI/BW, especially in grazing systems. However, contrary to the suggestion of Grainger and Goddard (2004), ProCROSS cows had a higher mean FCE despite a lower DMI/BW than HO cows. Also, Grainger and Goddard (2004) reviewed studies that indicated Jersey cows have a higher DMI/BW and a higher mass to the digestive system per unit of BW and, therefore, have more capacity for intake per unit BW than HO cows. Furthermore, Grainger and Goddard (2004) reviewed studies that indicated Jerseys have a higher rate of passage of feed, and Colucci et al. (1982) reported higher passage rates are associated with less digestion of feed compared to lower passage rates. The lower DMI/BW of ProCROSS cows than HO cows in this study may suggest ProCROSS cows have enhanced ability to extract nutrients from the diet.

4.3.2 Income over feed cost

For primiparous cows, year of study significantly ($P < 0.01$) explained variation for IOFC. Primiparous ProCROSS cows (\$875 ± 13) had higher ($P < 0.01$) IOFC from 4 to 150 DIM than primiparous HO cows (\$825 ± 14). The \$50 advantage of primiparous ProCROSS cows over HO cows is the equivalent of \$0.34/d, with \$0.06/d from more fat plus protein production and \$0.28/d from lower feed costs than HO cows. Multiparous ProCROSS cows (\$1,296 ± 29) also had higher ($P = 0.04$) IOFC than multiparous HO cows (\$1,208 ± 31). The \$88 difference is the equivalent of \$0.60/d, with \$0.14/d from more fat plus protein production and \$0.46/d from lower feed cost than HO cows.

Fat plus protein production was chosen as the measure of income in this study because a majority of milk in the United States is priced based on the fat and protein solids in milk rather than on the fluid volume of milk. Like ratio measures of FE, higher IOFC of ProCROSS cows than HO cows was anticipated because both primiparous and multiparous ProCROSS cows had lower DMI than HO cows but were not different from HO cows for fat plus protein production (Chapter 3). The IOFC is an informative measure of profit (Heins et al., 2012b), but IOFC ignores longevity, fertility, and health of cows. Crossbred livestock usually have an advantage over purebreds for fertility and health because of heterosis (Falconer and Mackay, 1996), and lower cost for fertility and health disorders of crossbred dairy cows would be in addition to their advantage for IOFC.

4.3.3 Residual feed intake

Residual feed intake from 4 to 150 DIM. The least square means and standard errors of means for variables used to estimate RFI from 4 to 150 DIM are in Table 4.3. ProCROSS and HO cows were not different ($P > 0.07$) for MilkE, MBW, and BWCE in either parity group.

For primiparous cows, partial regression coefficients of DMI on MilkE, mean MBW, and BWCE from 4 to 150 DIM were 0.75, 8.45, and 0.62, respectively, and all significantly ($P < 0.01$) explained variation for DMI. For multiparous cows, the partial regression coefficients were 0.51, 23.2, and 0.40, respectively, for DMI on MilkE, mean MBW, and BWCE from 4 to 150 DIM, and all of the partial regression coefficients were significant ($P < 0.05$). The positive regression coefficients were intuitive, because a cow is expected to require more DMI as production, maintenance, or BWCE increases.

Primiparous ProCROSS cows (–65.5 kg) had significantly lower ($P < 0.01$) mean RFI from 4 to 150 DIM than HO cows (+68.8 kg); however, the breed groups overlapped substantially for RFI (Figure 4.1). A majority of the lowest 10% (most favorable) of primiparous cows for RFI were ProCROSS (7 of 12 cows), and a majority of the highest

10% (least favorable) of primiparous cows for RFI were HO (10 of 12 cows). Multiparous ProCROSS cows (–64.5 kg) had significantly lower (*P* = 0.02) mean RFI from 4 to 150 DIM than HO cows (+75.0 kg). Like the primiparous cows, significant overlap of the breed groups existed for the multiparous cows (Figure 4.1). Again, for multiparous cows, a majority of the lowest 10% (most favorable) of cows for RFI were ProCROSS (7 of 8 cows), and a majority of the top 10% (least favorable) of cows for RFI were HO (5 of 8 cows).

Potts et al. (2017) reported MilkE, MBW, and BWCE were not different for HO cows stratified by high or low RFI at approximately 120 DIM. In addition, the low RFI cows had significantly lower DMI and higher ECM/DMI than the high RFI cows (Potts et al., 2017). The ProCROSS cows in this study had lower mean RFI than HO cows but did not differ from HO cows for MilkE, mean MBW, and BWCE (*P* > 0.07), and the ProCROSS cows had higher ECM/DMI than HO cows. Coleman et al. (2010) provided associations between RFI and various measures of FE for different strains of HO cows in a grazing system. The cows with low (more efficient) RFI consumed less DMI, had higher FCE, and had lower DMI/BW than cows with high RFI from 21 to 288 DIM (Coleman et al., 2010). In this study, ProCROSS cows had lower mean RFI and consumed less DMI, had higher FCE, and had lower DMI/BW than HO cows. Heterosis for RFI of crossbred dairy cows has not been well documented (Berry and Crowley, 2013), but the cumulative effects of heterosis for the variables contributing to RFI could explain some of the differences in RFI in this study for the breed groups.

By definition, RFI should be independent of model effects; therefore, inclusion of breed group in the model for RFI would have resulted in no breed group difference for

RFI. Li et al. (2016) suggested breed differences for the partial regression coefficients of DMI on energy sinks may exist when estimating RFI, because of potential differences of breeds in partitioning of energy. Therefore, partial regression coefficients for RFI from 4 to 150 DIM were calculated for ProCROSS and HO cows separately by parity group. A simple *z*-test was used to compare breed groups for specific partial regression coefficients as described by (Tempelman et al., 2015) and, for primiparous cows, no differences ($P > 0.11$) were found between the two breed groups for the partial regression coefficients of DMI on MilkE or BWCE (Figure 4.2). On the other hand, the partial regression coefficient of DMI on MBW was significantly ($P = 0.02$) lower for ProCROSS cows than HO cows (Figure 4.2), so DMI for primiparous HO cows increased more per unit increase of MBW than DMI for primiparous ProCROSS cows. However, partial regression coefficients for multiparous cows were not different ($P > 0.24$) for any of the three energy sinks (Figure 4.2).

The mean BCS of cows was initially included in the analysis as an energy sink in the estimation of RFI from 4 to 150 DIM. However, when RFI was estimated with the primiparous ProCROSS and HO cows combined, the partial regression coefficient for BCS was significant ($P = 0.02$) and negative, which was illogical and counter to biological expectation. Also, when RFI was estimated separately for primiparous ProCROSS and HO cows, the partial regression coefficients for DMI on BCS were nearly equal in magnitude but opposite in direction (negative for ProCROSS cows and positive for HO cows) and not significant ($P > 0.70$). The multiparous cows behaved in a similar fashion to the primiparous cows for relationship of DMI and BCS. This outcome may have resulted because ProCROSS cows in this study consumed significantly less DMI than HO cows but had significantly higher BCS than HO cows (Chapter 3). Because of the incongruous relationship of DMI and BCS for the breed groups, the model for RFI did not include BCS for either primiparous or multiparous cows. However, inclusion of BWCE rather than BWC permitted BCS to be indirectly taken into account, because BCS contributed to the calculation of BWCE for cows.

Residual feed intake for 28-d intervals. Unadjusted means and standard deviations for the variables contributing to the estimation of RFI in each 28-d interval are in Table 4.4. Primiparous cows had their highest numerical DMI in interval 5 (123 to 150 DIM). The MilkE increased numerically with time until intervals 3 to 5, and the MBW increased numerically in intervals 1 to 5 (Table 4.4). The BWCE of primiparous cows was lowest in interval 1 (11 to 38 DIM). Typically, cows lose BW after calving and slowly regain BW as lactation progresses. For multiparous cows, DMI was numerically highest in interval 4 (95 to 122 DIM) and MilkE was numerically highest in interval 2 (39 to 66 DIM). Like primiparous cows, BWCE of multiparous cows was lowest in interval 1 and was negative, which indicated cows lost BW.

The partial regression coefficients for DMI on MilkE and MBW were all positive and significant in each interval ($P < 0.01$) for primiparous cows (Figure 4.3). The partial regression coefficient for DMI on BWCE was positive for all intervals and was significant ($P < 0.05$) in intervals 1, 2, and 4, tended to be significant ($P = 0.09$) in interval 3, and was not significant in interval 5 ($P = 0.14$) for primiparous cows (Figure 4.3). The partial regression coefficients for DMI on MilkE and MBW were positive and significant ($P < 0.01$) for all intervals for multiparous cows (Figure 4.3), and the partial regression coefficient of DMI on BWCE was positive for all intervals and significant (*P* < 0.05) in intervals 1, 2, 3, and 5.

Estimated partial regression coefficients of DMI on MilkE for both primiparous and multiparous cows were lowest in interval 1 followed by an increase and then a plateau (Figure 4.3). This pattern was akin to that reported by Li et al. (2017) for primiparous Danish HO for entire lactations, although ECM was used as the measure of production instead of MilkE in that study. In general, the partial regression coefficients of DMI on MilkE by 28-d interval in this study were higher than those estimated in recent studies during comparable DIM (Tempelman et al., 2015; Li et al., 2017; Potts et al., 2017). The partial regression coefficients for DMI on MBW were comparable to those reported by Tempelman et al. (2015), Li et al. (2017), and Potts et al. (2017). On the other hand, the partial regression coefficients for DMI on BWCE were similar to those reported by Tempelman et al. (2015) but they were lower than those of Li et al. (2017) for DMI on BWC and higher than those of by Potts et al. (2017) for DMI on BWCE. Partial regression coefficients often differ between locations and between trials within a single location (Davis et al., 2014; Tempelman et al., 2015), so comparison of coefficients across studies is difficult.

Primiparous ProCROSS cows had significantly lower (*P* < 0.05) RFI in each 28-d interval than primiparous HO cows (Table 4.5) and, for both breed groups, RFI became larger in magnitude from interval 1 to interval 5. Multiparous ProCROSS cows had significantly lower (*P* < 0.05) RFI than HO cows in intervals 1, 3, and 4. In interval 2, multiparous ProCROSS cows tended (*P* = 0.09) to have lower RFI than HO cows. However, the ProCROSS cows were not different (*P* = 0.26) from HO cows for RFI in interval 5 (Table 4.5), and this likely reflects a lack of difference for DMI for multiparous breed groups in interval 5 of the observation period (Chapter 3). Conclusions about RFI after 150 DIM cannot be made from this study, and further investigation is needed to compare ProCROSS and HO cows during the remainder of lactation and during the dry period.

4.3.4 Limitations for measures of FE for crossbred versus HO cows.

Ratio measures of FE are easy to calculate and are readily interpreted. However, Berry and Crowley (2013) pointed out ratios are often strongly correlated with either the numerator or denominator and do not take into account the partitioning of energy from FI. Furthermore, most measures of FE are narrow in scope and measure only input and output without accounting for additional factors such as pregnancy status (Hazel et al., 2013). ProCROSS cows have been documented to have superior fertility to HO cows (Malchiodi et al., 2014); therefore, measures of FE in this study are conservative from a comprehensive perspective.

Coleman et al. (2010) suggested RFI may not be an appropriate measure of FE because accounting for BWC is challenging. The BWC is often included as an energy sink in RFI models but does not adequately explain how energy is partitioned. More energy is required to deposit fat than protein or water, but protein requires more energy to maintain than fat (DiCostanzo et al., 1990). Differences of ProCROSS and HO cows for percentages and location of muscle versus fat in the body were not investigated in this or other studies but could explain some of the differences for FE found in this study. Coleman et al. (2010) also suggested separate regression coefficients for BW gain versus BW loss may be necessary to estimate RFI because the energy generated from BW loss is less than the energy required for BW gain. Furthermore, prediction equations for DMI used for RFI are often based on HO cows and may not be appropriate for application to cows of other breeds or crossbreds.

4.4 Conclusions

A growing number of dairy producers globally are implementing crossbreeding systems; therefore, the FE of crossbred versus purebred cows requires investigation. The ProCROSS cows in this study had higher mean FE for every measure of production per unit of intake (FCE, ECM/DMI, NE_LE, and CPE) than the HO cows, and the ProCROSS cows also had lower mean DMI/BW than the HO cows. Furthermore, the ProCROSS cows had higher mean IOFC than HO cows. The mean RFI of ProCROSS cows was lower (more favorable) than the mean RFI of HO cows. Consequently, this study suggests ProCROSS cows should have greater profitability than HO cows because of enhanced FE without loss of fat plus protein production. Furthermore, the measures of FE reported in this study may be conservative because they do not account for the gain in FE from the enhanced fertility and longevity of ProCROSS cows.

4.5 Acknowledgements

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4.7 Tables

Table 4.1. Least square means and standard errors of means for the variables contributing to the ratio measures of feed efficiency from 4 to 150 DIM by parity group and breed group. Means are for feed intake (DMI, NEI, and CPI), production (fat + protein, ECM, protein) and mean BW from 4 to 150 DIM.

	Primiparous				Multiparous			
	Holstein (n = 60)		ProCROSS (n = 63)		Holstein (n = 37)		ProCROSS (n = 43)	
Trait	LSM	SE	LSM	SE	LSM	SE	LSM	SE
DMI[1] (kg)	2,948	36.9	2,807**	36.3	3,592	68.1	3,360*	63.1
NEI[2] (Mcal)	4,790	61.9	4,563**	60.7	5,867	108.9	5,487*	101.0
CPI[3] (kg)	491	6.6	467*	6.5	605	11.2	565*	10.4
Fat + protein[1] (kg)	329	3.3	331	3.2	441	7.0	445	6.5
ECM (kg)	4,985	48.9	4,939	48.0	6,759	105.9	6,676	98.2
Protein (kg)	146	1.4	146	1.3	194	2.9	196	2.7
BW[1] (kg)	556	7.1	562	7.0	644	10.2	636	9.4

**$P < 0.01$, *$P < 0.05$ for differences from Holstein within parity group

[1]From Chapter 2

[2]NEI = net energy of lactation intake

[3]CPI = crude protein intake

Table 4.2. Least square means and standard errors of means for ratio measures of feed efficiency from 4 to 150 DIM by parity group and breed group.

	Primiparous				Multiparous			
	Holstein (n = 60)		ProCROSS (n = 63)		Holstein (n = 37)		ProCROSS (n = 43)	
Ratio	LSM	SE	LSM	SE	LSM	SE	LSM	SE
FCE[1]	0.113	0.001	0.119**	0.001	0.124	0.002	0.134**	0.002
ECM/DMI	1.704	0.020	1.773*	0.019	1.894	0.034	2.006*	0.032
NE_LE[2]	1.048	0.013	1.091*	0.013	1.159	0.020	1.226*	0.019
CPE[3]	0.300	0.004	0.322**	0.004	0.324	0.006	0.350**	0.005
DMI/BW	5.314	0.069	5.035**	0.068	5.574	0.090	5.306*	0.083

**$P<0.01$, *$P<0.05$ for differences from Holstein within parity group

[1]FCE = feed conversion efficiency

[2]NE_LE = net energy of lactation efficiency

[3]CPE = crude protein efficiency

Table 4.3. Least square means and standard errors of means for variables in addition to DMI used to estimate RFI from 4 to 150 DIM by parity group and breed group. Means are for total milk energy output (MilkE), mean metabolic BW (MBW), and change in body weight energy (BWCE) from 4 to 150 DIM.

	Primiparous				Multiparous			
	Holstein (n = 60)		ProCROSS (n = 63)		Holstein (n = 37)		ProCROSS (n = 43)	
Component	Mean	SE	Mean	SE	Mean	SE	Mean	SE
MilkE (Mcal)	3,460	34.2	3,431	33.6	4,656	73.1	4,606	67.8
MBW ($kg^{0.75}$)	114	1.1	115	1.1	128	1.5	126	1.4
BWCE (Mcal)	302	24.1	316	23.7	131	35.4	41[†]	32.8

[†] *P* < 0.10 for differences from Holstein within parity group

Table 4.4. Unadjusted means and standard deviations for the variables contributing to the estimation of RFI for 28-d intervals from 11 to 150 DIM by parity group and breed group. Means are for DMI, milk energy output (MilkE), metabolic BW (MBW), and change in body weight energy (BWCE) for each interval.

	Primiparous				Multiparous			
	Holstein (n = 60)		ProCROSS (n = 63)		Holstein (n = 37)		ProCROSS (n = 43)	
Interval[1]	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DMI	––––––––––––––––––– (kg/d) –––––––––––––––––––							
1	17.6	1.8	16.9	1.9	21.6	3.1	20.5	3.0
2	20.0	2.4	19.1	2.4	24.9	3.2	23.3	3.3
3	20.7	2.9	19.7	2.8	26.1	3.2	23.8	3.5
4	21.3	2.8	20.2	2.8	26.1	3.2	24.3	3.5
5	22.0	2.6	20.6	2.6	25.3	3.6	24.0	3.3
MilkE	–––––––––––––––––– (Mcal/d) ––––––––––––––––––							
1	21.7	1.8	21.4	2.1	31.8	4.5	31.6	3.8
2	23.8	1.8	23.5	2.1	32.9	3.7	32.7	3.2
3	24.4	1.9	24.2	2.0	32.6	3.2	32.1	2.9
4	24.5	2.0	24.3	2.1	31.6	3.0	31.1	2.9
5	24.3	2.0	24.1	2.2	30.2	3.0	29.8	3.2
MBW	––––––––––––––––––– ($kg^{0.75}$) –––––––––––––––––––							
1	111	7.8	111	9.2	126	8.1	126	10.9
2	112	7.5	113	9.4	126	7.7	125	10.7
3	115	7.6	115	9.5	128	7.4	126	10.6
4	116	7.2	117	10.0	129	7.3	127	10.4
5	118	7.4	119	10.2	130	7.3	127	10.6
BWCE	–––––––––––––––––– (Mcal/d) ––––––––––––––––––							
1	0.9	3.7	0.7	4.2	-2.9	4.1	-3.0	4.1
2	2.5	2.3	2.4	3.1	2.5	4.6	-0.3	3.6
3	2.1	2.7	2.1	2.6	2.0	2.9	0.9	3.6
4	2.0	3.2	2.1	3.1	0.3	3.5	0.8	4.3
5	2.7	2.5	2.5	3.0	1.3	2.8	0.9	3.1

[1]Intervals correspond to DIM: 1 (11 to 38), 2 (39 to 66), 3 (67 to 94), 4 (95 to 122), and 5 (123 to 150).

Table 4.5. Least square means and standard errors of means of residual feed intake (RFI) for 28-d intervals by breed group and parity group.

	Primiparous				Multiparous			
	Holstein		ProCROSS		Holstein		ProCROSS	
Interval[1]	LSM	SE	LSM	SE	LSM	SE	LSM	SE
	– – – – – – – – – – – – – – – – – – –			(kg/d)	– – – – – – – – – – – – – – – – – – –			
1	0.34	0.18	– 0.33**	0.18	0.51	0.34	– 0.44*	0.32
2	0.42	0.21	– 0.40**	0.20	0.47	0.38	– 0.41†	0.35
3	0.43	0.25	– 0.41*	0.24	0.75	0.38	– 0.65**	0.36
4	0.53	0.24	– 0.50**	0.24	0.63	0.37	– 0.54*	0.34
5	0.70	0.23	– 0.66**	0.23	0.33	0.39	– 0.28	0.36

†$P < 0.10$, *$P < 0.05$ and **$P < 0.01$ for differences from Holstein within parity group
[1]Intervals correspond to DIM: 1 (11 to 38), 2 (39 to 66), 3 (67 to 94), 4 (95 to 122), and 5 (123 to 150).

4.8 Figures

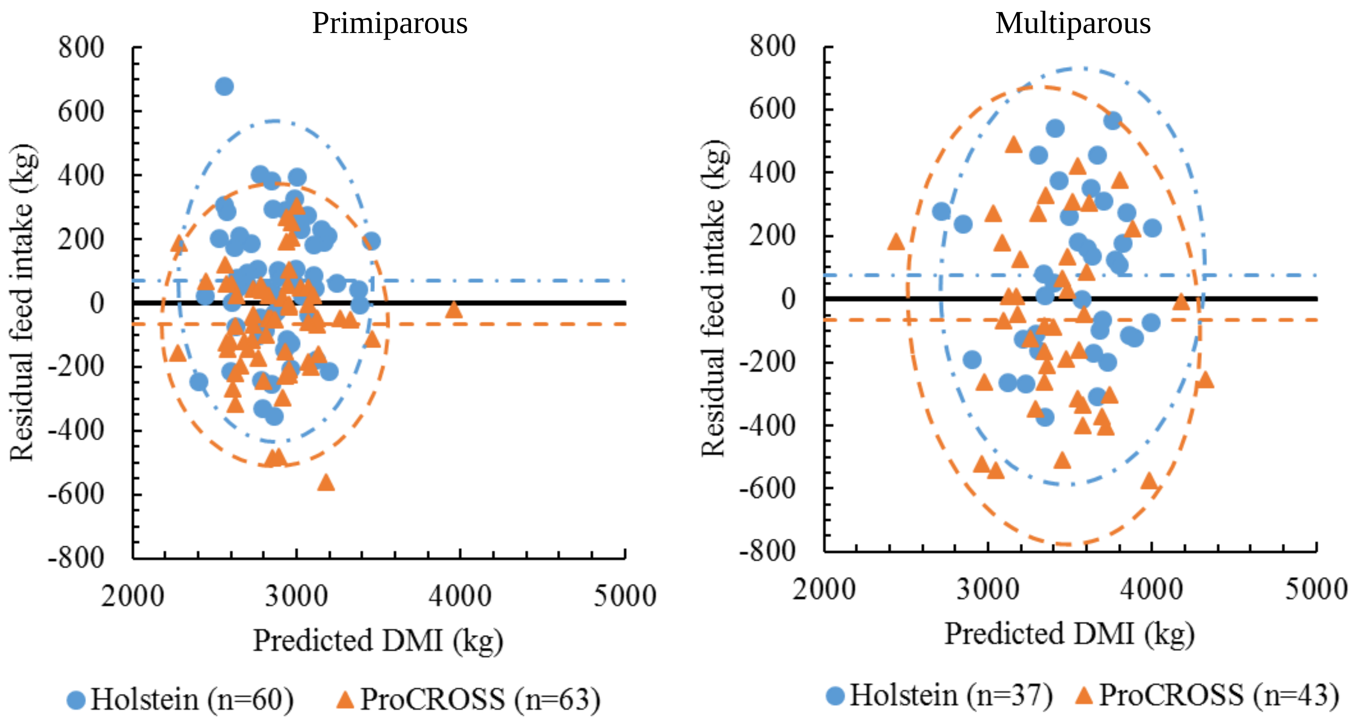

Figure 4.1. Residual feed intake (RFI) plotted against predicted DMI from 4 to 150 DIM for primiparous and multiparous cows by breed group. The solid black line references mean RFI (0 kg). The dotted-dashed line in each panel represents the mean RFI of primiparous (68.8 kg) and multiparous (75.0 kg) Holstein cows, and the dotted-dashed ovals represent 95% prediction ellipses for Holstein cows. The dashed line in each panel represents the mean of primiparous (– 65.5 kg) and multiparous (–64.5 kg) ProCROSS cows, and the dashed ovals represent 95% prediction ellipses for ProCROSS cows. Color version available online**.**

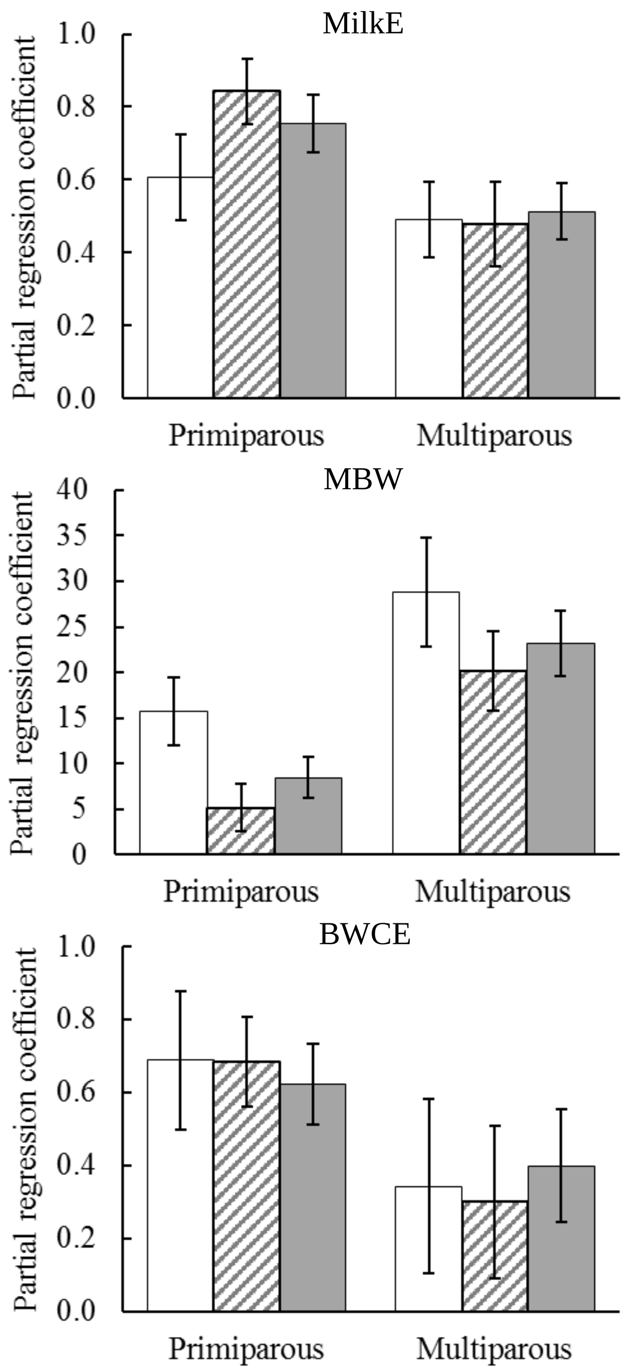

Figure 4.2. Partial regression coefficients from estimation of residual feed intake (RFI) from 4 to 150 DIM for Holstein (white bars), ProCROSS (diagonal striped bars), and breed groups combined (grey bars). Coefficients are from the regression of DMI on MilkE (milk energy output), mean MBW (metabolic BW), and BWCE (change in body weight energy).

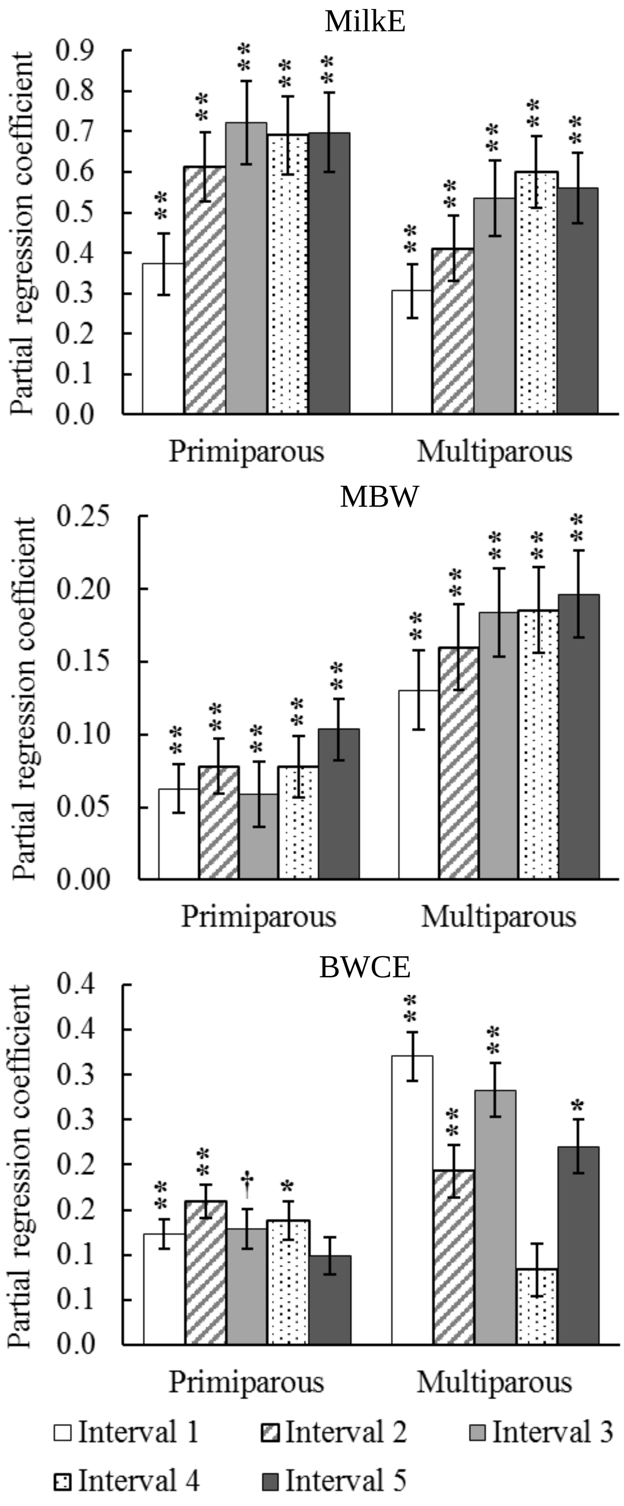

Figure 4.3. Partial regression coefficients of DMI on mean MilkE (milk energy output), mean MBW (metabolic BW), and BWCE (change in body weight energy) for estimates of residual feed intake (RFI) by 28-d interval and parity group. Symbols above partial regression coefficients represent energy sinks that were significant in explaining variation in DMI (†$P < 0.10$, *$P < 0.05$ and **$P < 0.01$). Intervals correspond to DIM: 1 (11 to 38), 2 (39 to 66), 3 (67 to 94), 4 (95 to 122), and 5 (123 to 150).

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