Associations between herd-level feeding and housing management practices, ration characteristics and production of free-stall housed dairy cows

By

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ABSTRACT

ASSOCIATIONS BETWEEN HERD-LEVEL FEEDING AND HOUSING MANAGEMENT PRACTICES, RATION CHARACTERISTICS AND PRODUCTION OF FREE-STALL HOUSED DAIRY COWS

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A cross sectional study of 22 commercial free stall farms was conducted to investigate associations between feeding and housing practices, ration variability, and measures of productivity of group-housed dairy cows. Farms were visited for 7 consecutive days in both summer and winter to collect measures related to management, milk production, environment, and ration characteristics. Feeding 2x/d compared to 1x/d was associated with greater group-average milk yield, DMI and less sorting against long particles. Provision of increased feed bunk space was associated with increased milk fat% and lower group-average SCC. Higher daily variability in energy content and % long particles in the ration was associated with lower group-average milk yield and efficiency of milk production. Overall, these results suggest that herd-level feeding and housing practices which increase access to consistent feed can improve group-level productivity and ultimately improve herd profitability.

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CHAPTER 1: INTRODUCTION

Dairy producers are concerned with the efficient conversion of nutrients to milk components. Feed costs account for a large proportion of expenses associated with milk production and can be extremely variable (Britt et al., 2003; USDA-ERS, 2013). Therefore, factors which reduce efficiency of feed utilization can greatly impact the profitability of a dairy herd. Total mixed rations (TMR) were adopted by producers as an efficient means of delivering a consistent ration to dairy cows (Coppock et al., 1981). Unfortunately, cows do not always consume the ration as formulated for them. Additionally, the ration delivered may not always reflect the ration formulated and may vary in composition from day-to-day. There are a number of factors which may prevent cows from consuming the intended ration. Feed sorting behaviour can affect nutrient intakes, resulting in variability within cows within a day, between cows, as well as between days (Leonardi and Armentano, 2003; DeVries et al., 2008). Dairy cows sort TMR in favor of starch-rich short particles and against fiber-rich long particles (Leonardi and Armentano, 2003). This causes concerns for health and production, as over-consumption of the starch-rich concentrate component and decreased long forage particle intake can lead to depressed rumen pH and sub-acute ruminal acidosis (SARA; Garrett et al., 1998; DeVries et al., 2008). Excessive feed sorting can result in inefficiency of feed use of group-housed cows as the NDF content of the ration in the hours following delivery increases (DeVries et al., 2005), thus subjecting cows to a ration that might not meet their lactational demands. This is especially important for socially subordinate cows with reduced success at the feed bunk as it has been shown that subordinate cows may access the bunk during off-peak times if feed access is reduced as a result of competition (Huzzey et al., 2006).

There is a growing body of knowledge suggesting that management factors can greatly impact the feeding behaviour of dairy cows. Feed bunk attendance is greatest following the delivery of fresh feed (DeVries and von Keyserlingk, 2005) and competition for feed bunk access can increase the frequency of aggressive displacements. This can have implications for variability in nutrient intake between cows because cows with lower success at the feed bunk may access feed later, after it has been extensively sorted (DeVries et al., 2007). Factors which help to improve overall feed access, such as increased feeding frequency, have been shown to reduce feed sorting and distribute feeding events more evenly throughout the day (DeVries et al., 2005). Improvements to feed access, especially for subordinate cows, have been reported as a result of providing increased feed bunk space and using headlocks at feeders (Huzzey et al., 2006). Competition at the feed bunk can alter feeding patterns and impact the consistency of the ration consumed by cows within the group.

Variability in nutrient intakes can also be attributed to inconsistencies in ration composition day-to-day and inaccuracies in relation to the diet formulated by the nutritionist. Significant variability in commercial rations has been reported (Silva-del-rio and Castillo, 2012) and evidence exists to suggest that deviations in daily batch weight can impact production (James and Cox, 2008). Commonly reported sources of variation in TMR composition include improper mixing order of ingredients, high variability in nutrient and dry matter (DM) composition of forages, poor education of operators and over-mixing (Stone, 2008; Mikus, 2012).

This review will outline those ration and management factors that influence the consistency with which nutrients are delivered and consumed by cows and consider the consequences for feed efficiency and milk production.

1.1 Ration Characteristics

Health and productivity of dairy cows have significantly increased over the past two decades as a result of a substantial amount of research dedicated to nutritive aspects of the diet (Eastridge, 2006). Ration formulation plays a large role in influencing health and milk production parameters. As such, routine monitoring of ration characteristics is essential to reduce potential variability in nutrient intakes experienced between cows and throughout the day. Significant variability between cows in feed intake and nutrient consumption is commonly observed in group-housed dairy cows as a result of feed sorting behaviour (Leonardi and Armentano, 2007). Cows generally preferentially consume less long forage particles than predicted and as such, may be at increased risk of depressed rumen pH (DeVries et al., 2008), posing further risks for reduced productivity. Feed sorting behaviour is an inherent component of dairy cow feeding patterns but efforts to reduce this behaviour can be mediated through changes in dietary composition. Specifically, particle size distribution, DM content, and fiber content can influence how dairy cattle may sort the diet and, thus, the consistency of feed they consume.

Increasing particle length is correlated to physically effective fiber (peNDF) and is important for promoting chewing and rumination (NRC, 2001). However, increasing the amount of long forage particles in the ration may exacerbate selective consumption of short particles (Leonardi and Armentano, 2003) because cows are better able to discriminate between particle sizes when a higher proportion of long particles is offered. DeVries et al. (2007) also reported an effect of particle size on sorting, with cows increasing selection for short particles when fed a diet high in concentrates. These results suggest that extreme distributions of particle sizes influence selective consumption of short particles by enabling the cow to easily distinguish between forage and concentrate components. Leonardi and Armentano (2003) used alfalfa silages, however similar conclusions for corn-based diets have been reported (Kononoff et al., 2003). This tendency to sort against long particles can result in reduced NDF intake (DeVries et al., 2007) and may increase risk of SARA due to reduced rumen pH (DeVries et al., 2008). However, it has also been shown that providing diets with greater chop length and higher effective fiber content can negatively impact microbial protein synthesis and efficiency (Yang and Beauchemin, 2006).

Moisture content of the ration is easily manipulated through the addition of water. Water can functionally alter particle size distribution such that more short particles are stuck to the longer fractions (Leonardi et al., 2005; Fish and DeVries, 2012). This change in distribution can also alter starch content of the various fractions resulting in greater starch content of the long particle fraction (Fish and DeVries, 2012). Addition of water to dry rations causes finer particles to adhere to longer particles; it has been theorized that cows are less able to sort out those fine particles, thus increasing consumption of the intended ration and reducing nutrient consumption variability throughout the day. This theory is supported by the findings of Leonardi et al. (2005) as addition of water tended to increase NDF intake. However, researchers have reported the opposite effect when water was added to wetter rations (Miller-Cushon and DeVries, 2009; Felton and DeVries, 2010). This increase in sorting was attributed by Felton and DeVries (2010) to the increased potential for wet rations to heat and possibly cause secondary fermentation. Leonardi et al. (2005) used a hay-based diet that was much drier (81%) than the average commercial ration. Other researchers (Miller-Cushon and DeVries, 2009; Felton and DeVries, 2010) fed much wetter (range: 44 to 58 %) haylage and silage-based diets. Overall, these changes in moisture content had little impact on milk yield and efficiency (Leonardi et al., 2005; Fish and DeVries, 2012). Other researchers (Miller-Cushon and DeVries, 2009; Felton and DeVries, 2010) reported increased efficiency of milk production as a result of reduced DMI, likely associated with increased gut fill, and similar milk yields. Interestingly, greater sorting against long particles was associated with reductions in milk fat (Leonardi et al., 2005; Fish and DeVries, 2012), perhaps as a result of lower rumen pH. These four studies were all conducted on individually housed cows in a controlled setting. More work is needed to understand how addition of water can impact the consistency with which group-housed cows consume the ration.

1.2 Feeding Management

Past work on feeding management practices has emphasized implications for feed intake and milk yield (Gibson, 1984; Nocek and Braund, 1985). However, an emergent stream of research suggests that feeding management practices may also impact feeding behaviour of dairy cows, especially between cows with different social status within a group (DeVries et al., 2004; Huzzey et al., 2006). Cows generally synchronize behaviours, even in intensive systems (Curtis and Houpt, 1983), which can be problematic if insufficient access to resources or barriers to these resources exist. Albright (1993) suggested that ensuring good access to feed may outweigh the importance of the amount of nutrients presented to dairy cattle. Non-dietary factors such as feeding frequency, feeding amount, frequency of feed push-up, feeder design and feed bunk space may impact feeding patterns, feed intake, and their variability between cows. Recent work has shown that delivery of identical rations to 47 herds in Spain resulted in significantly different milk production, which was attributed to differences in management factors (Bach et al, 2008). These researchers attributed 56% of the variability in milk production to non-dietary factors (Bach et al., 2008). This illustrates the importance of management as it relates to milk production and herd profitability.

Frequency of feed delivery is a component of feeding management that must be considered due to the implications for stimulating feed intake. Dairy cattle are crepuscular creatures that are stimulated to eat at dawn and dusk (Shabi et al., 2005). However, for group-housed dairy cattle fed a conserved ration indoors, this intake stimulation is primarily driven by the provision of fresh feed (DeVries and von Keyserlingk, 2005), regardless of the time of day. There is limited research to determine the effect of feeding frequency on group-housed cows. Gibson (1984) reviewed the effect of feeding frequency of individually housed cows on intake and milk yield but reported inconsistent findings due to variability in methods. More recently, DeVries et al. (2005) investigated the impact of increased feeding frequency (2x vs. 1x/d) on feeding behaviour of group-housed dairy cows. They reported increased daily feeding time, less sorting and more evenly distributed feeding events throughout the day as a result of increased feeding frequency (DeVries et al., 2005). These results were especially important for subordinate cows as increased feeding frequency increased their success during the peak hour following fresh feed delivery (DeVries et al. 2005). Cows in a competitive environment may alter their feeding patterns to avoid social interactions, therefore it follows that increased frequency of provision of fresh feed should provide increased opportunities to access a consistent (i.e unsorted) ration, thus increasing the consistency in nutrient intakes between cows and within a day.

Access to feed can impact feeding behaviour of dairy cattle and the consistency of feed consumed. Dairy cattle housed under commercial settings are typically delivered feed with the intention of ad libitum intake. However, in recent years there is a growing trend whereby producers target zero feed refusal in order to minimize costs associated with wasted feed (Silva-del-Rio et al., 2010). It has been shown that feed restriction can result in reductions in feed intake and milk yield (Martinsson and Burstedt, 1990) as well as altered feeding patterns (Collings et al., 2011). Collings et al. (2011) investigated the impact of 14 and 24 hour feed access and reported lower daily feeding times, increased feeding rates and increased feed bunk competition when feed access was restricted. Their results suggest that dairy cows modify feeding patterns in times of reduced feed access by increasing their rate of consumption, especially in cases of overstocking (Collings et al., 2011). Less extreme limitations to feed access have also been shown to impact feeding behaviour. French et al. (2005) also reported reductions in daily feeding time and increases in feeding rate as a result of targeting lower feed refusal (2.5 % refusal at 18 h vs. 5 % refusal at 23h). Over-feeding can also impact the consistency of feed consumed with higher feeding amounts resulting in increased sorting activity (Leonardi and Armentano, 2007; Miller-Cushon and DeVries, 2010).

The synchronous behaviour of dairy cows may be problematic in commercial settings, especially when accompanied by high stocking density at the feed bunk. The current recommendation for feed bunk space is 0.6 m/cow (Grant and Albright, 2001). However, that space only allowed for 70% of the group to feed simultaneously (DeVries et al., 2003). Feeding is often accompanied by aggressive interactions as cows are competing for resources (Jezierski and Podluzny, 1984). It follows that the frequency of aggressive displacements at the feed bunk is highest in the hour following fresh feed delivery (Huzzey et al., 2006), potentially altering feeding patterns of cows with low feeding success. Some research suggests that reducing feed bunk space to as little as 0.2 m/cow will have no negative implications for feed intake or milk yield (Friend et al., 1977), but more recent research suggests that increasing stocking density at the feed bunk is negatively correlated with feeding time and displacements, especially for subordinate cows (Huzzey et al., 2006). Researchers have also found that competition for feed access can result in increased rate of consumption, resulting in fewer, larger meals (Hosseinkhani et al., 2008); which may increase risk of SARA (Stone, 2004). DeVries et al. (2004) reported a 57% reduction in aggressive displacements as well as increases in feeding time of group-housed dairy cows in response to increased feed bunk space (1.0 vs. 0.5 m/cow). Similarly, Huzzey et al. (2006) reported that the proportion of cows feeding during the 60 minutes following feed delivery increased quadratically as stocking density increased. Given that the NDF content of the ration increases in the hours following delivery (DeVries et al., 2005), this may be problematic for subordinate cows who may be forced to access the feed bunk in the later hours as the ration consumed may not meet their lactational demands (Krause and Oetzel, 2006). These findings show that limiting feed bunk space may alter feeding patterns and interactions between cows within a group, potentially impacting the quality and consistency of the ration consumed.

Cows are separated from the feed in the bunk by a barrier. Commercial farms commonly use post and rail or headlock feeder designs, the latter providing physical divisions between cows. It has been suggested that individual headlocks may increase feeding success as cows are less easily displaced from the feed bunk. Huzzey et al. (2006) found that individual headlocks, compared to post and rail feed bunk designs, resulted in reductions in daily feeding time and displacements from the feed bunk. This suggests that cows have more success at the feed bunk but are perhaps increasing their rate of consumption in order to avoid negative social interactions. A similar study by Endres et al. (2005) reported a reduction in aggressive displacements with the use of headlocks, but feeding time was unaffected. DeVries and von Keyserlingk (2006) evaluated the use of individual partitions ('feed stalls') at the feed bunk and found a reduction in cow displacements from the bunk as well as increased feeding time. Regardless of these differences in findings, barriers that reduce aggression between cows should theoretically increase feeding time, increase access to consistent feed (i.e. unsorted TMR) and reduce variability in feed bunk access among cows.

Sorting behaviour by dairy cows may reduce feed access as feed is pushed beyond reach. Feed push-up increases feed bunk occupancy, albeit it to a lesser degree than fresh feed delivery (DeVries et al., 2003), and it has also been associated with greater milk yield (Bach et al., 2008). In theory, more frequent feed push-up will ensure access to a mixed ration, which might more closely resemble that originally delivered, especially for those cows accessing feed hours after fresh feed delivery. DeVries et al. (2003) investigated the impact of increased feed push-up frequency (2 vs.4x/d) on feed bunk attendance. No significant differences in feed bunk attendance were noted with the addition of two extra feed push-ups. Regardless, consistent access to feed is important for maintaining a stable rumen microbial population (Nocek and Braund, 1985) to support high milk production.

1.3 Accuracy and precision of TMR

Variability in nutrient intake may be influenced by a variety of factors in addition to feed sorting behaviour of individual cows. It is widely known that the ration delivered may not reflect the ration formulated by the nutritionist, nor will it be identical day-to-day. The aim of TMR feeding programs is to deliver a consistently balanced supply of nutrients to the rumen to maximize nutrient utilization and conversion to milk components (Coppock et al., 1981). However, variability in TMR composition can impact herd production as a result of errors in TMR mixing (Tylutki et al., 2005; Stone, 2008). Efforts to improve both accuracy (defined as the delivery of nutrients reflective of that formulated) and precision day-to-day is needed to maximize milk production and to get the most value out of the ration.

Quality control of TMR is important with respect to uniformity between batches as well as within a batch. Potential sources of variability in TMR composition include variability in individual feed ingredients, inadequate DM monitoring, poor education of feeders, improper mixing order and poor mixer wagon maintenance (Stone, 2008; Mikus, 2012). Regular sampling of individual feed ingredients to recognize the variability in nutrient composition and DM content of ingredients is necessary to ensure consistent TMR composition.

There is evidence to suggest that errors in batch preparation can affect production. One study found that switching to manual feed sheets from automated software technology, during software upgrading, resulted in increased variability in milk yield between cows (Tylutki et al., 2005). They detected errors in estimating DM to construct these manual feed sheets which likely accounted for the increased variability in milk yield. Other researchers reported a negative correlation between milk yield and deviations in batch size (James and Cox, 2008). They found that loading accuracy was impacted by unreliability in silo unloaders, inclusion of ingredients with low DM, operator diligence, and poor layout of feed storage facilities.

There is limited research to quantify the degree of agreement between fed and formulated rations, but it is clear that variability exists. Ration evaluation on 7 commercial dairy farms in California indicated that the variability between fed and formulated rations was extensive, especially for fat and calcium (Silva-del-rio and Castillo, 2012). Those researchers also noted that consistency between days was much greater than that observed between the fed and formulated rations, indicating that producers were consistently feeding a ration that differed from recommended. Cox (2007) also reported significant differences between the ration fed and formulated for phosphorous content. More research regarding the impact of these nutrient deviations is needed to determine impacts on production.

The use of particle size distribution has been evaluated as an inexpensive tool for monitoring TMR consistency. It has been suggested that less than 10% coefficient of variation (CV) between days is an acceptable level of variation (Behnke, 1996). Extensive variation in particle size distribution has been reported, especially for particles retained on the top sieve, with average CV exceeding 20% for more than half the herds observed (Rippel et al., 1998). The variability in particles retained on the bottom screen is generally lower, but is dependent on mixing procedures (Rippel et al., 1998). To date, the majority of research regarding particle size and TMR uniformity relates to changes to mixing order and mixing time. Rippel et al. (1997) investigated the effect of altering mixing order of feed ingredients on particle retention on a 2 screen separator (3 fractions). The distribution of particles on the top screen could be altered by 30% by switching the mixing order of alfalfa hay from first to third (Rippel et al., 1998). Over-mixing the batch can also affect particle size distribution, resulting in more particles in the bottom pan and less on the top sieve (Possin et al., 1994; Rippel et al., 1998). Possin et al. (1994) classified herds into risk categories for laminitis and reported that herds with high risk were fed diets with lower proportion of long particles. There are no data investigating the impact of daily variability in particle size on production measures. However, given the relationship between chewing time, buffering capacity, and fiber (Mertens, 1997), it seems likely that particle size could impact intake and ultimately efficiency of milk production. Particle size distribution is greatly affected by mixing practices and so has the potential to impact disease susceptibility, thus care should be taken to ensure delivery of a ration to maximize health and productivity.

Overall, variability in TMR composition is evident and has implications for rumen health and milk production. More research is needed to determine the extent, causes, and impacts of ration variability on commercial farms as a means of reducing the disparity between expected and actual levels of production.

1.4 Objectives and Hypotheses

The overall objective of this thesis was to investigate the relationship among feeding and housing management factors, ration characteristics, and measures of productivity of group-housed dairy cows. A cross-sectional study of commercial free-stall farms was conducted to describe average herd-level feeding and housing management practices, ration composition, and group-average measures of productivity. Our first objective (Chapter 2) was to determine associations among herd-level housing and feeding management factors, feed sorting and group-average milk production parameters. It was hypothesized that feeding management factors to improve feed access, including increased frequency of feed delivery and increased feed bunk space would improve group-average milk production, efficiency and DMI and reduce group-level feed sorting. Our second objective (Chapter 3) was to determine the degree of agreement between the fed and formulated rations, determine daily variability in ration composition, and examine associations between ration variability and measures of group-average milk production parameters. We hypothesized that measures of milk production and efficiency would be improved with increased consistency in day-to-day ration composition.

CHAPTER 2: ASSOCIATIONS BETWEEN HERD-LEVEL FEEDING MANAGEMENT PRACTICES, FEED SORTING, AND MILK PRODUCTION IN FREE-STALL DAIRY FARMS

2.1 INTRODUCTION

The efficiency of nutrient conversion to milk components substantially influences the profitability of a dairy herd. Costs associated with feed are continually rising and, on average, can account for greater than 50% of all operating costs of dairy production systems (USDA-ERS, 2013). As a result, producers have adopted the use of TMR delivery as a means of reducing labor costs and ensuring that a homogenous supply of nutrients is delivered to the rumen for optimal digestive function (Coppock et al., 1981). While this method of feed delivery should theoretically ensure consumption of a balanced ration, cows have been shown to sort the ration such that nutrient intakes are variable both day-to-day and between cows within a pen (Leonardi and Armentano, 2003; DeVries et al., 2008).

Several lines of evidence exist to suggest that herd-level feeding management factors can decrease feed sorting and improve bunk access, thus reducing variability in nutrient intake across the herd. Feed bunk attendance is observed to be highest following practices that increase feed availability, such as feed delivery and feed push-up (DeVries et al., 2003), but most notably, delivery of fresh feed (DeVries and von Keyserlingk, 2005). Further, it has been shown that increasing frequency of feed delivery from once to twice daily reduced TMR sorting and resulted in more equal bunk access for all cows, especially in the peak hour following feed delivery (DeVries et al., 2005). Competition for feed bunk access may also impact feeding behavior and access to a consistent ration. Huzzey et al. (2006) reported decreased displacements at the feed bunk, especially for subordinate cows, as a result of increasing feed bunk space per cow. In the same study, Huzzey et al. (2006) reported favorable decreases in displacements of subordinate cows from the bunk when headlock feeders were used; suggesting that feed bunk design affects success at the feed bunk. Competition at the feed bunk can alter feeding patterns and meal characteristics observed between dominant and subordinate cows and, as a result, negatively impact the consistency of ration consumed within the group (Hosseinkhani et al., 2008). Excessive sorting of the ration, as well as exposure to an inconsistent ration, can lead to depressed rumen pH and increased risk of ruminal acidosis (DeVries et al., 2008).

The vast majority of research in the area of feed sorting and feeding behavior has been in controlled experiments. While this research has been central to understanding the relationship between feeding behaviour and feeding management practices, there is a paucity of data on how these practices influence productivity at a herd level under commercial settings. Herd-level feeding practices, such as increased frequency of feed delivery, reduce the extent of change in ration NDF throughout the day (Endres and Espejo, 2010). Furthermore, Bach et al. (2008) reported that 50% of the variability in milk yield of herds fed an identical ration were attributed to differences in nondietary factors, such as stall density and feed push up. The results of these previous two studies illustrate the importance of feeding management factors as they relate to variability in intake and milk production, but these studies have limitations. Endres and Espejo (2010) were limited to using change in NDF as a proxy for determining feed sorting, rather than evaluating changes in consumption of different ration particles. Furthermore, those researchers limited their data collection to a single day of data per herd. Bach et al. (2008) enrolled farms that fed an identical ration, so conditions in that study may not have reflected the typical variability in nutritional programs that occurs between commercial farms. Thus, the objectives of this cross-sectional observational study were: 1) to describe the feeding, housing, and management practices on commercial free-stall herds and 2) to examine the associations between herd-level feeding, housing, and management practices, and measures of feed sorting and productivity. It was hypothesized that herds with improved feed access, including increased feed bunk space, frequency of feed delivery and feed push-up, would have greater group-average milk production parameters and exhibit less sorting behavior at the group level.

2.2 Materials and Methods

2.2.1 Farm Selection

Twenty-four commercial dairy farms in Eastern Ontario, Canada were recruited for participation in this study. Sample size was determined through power analysis using the Power Analysis and Sample Size software program (PASS, Kaysville, Utah, USA; Hintze, 2008). Estimates of variation for the primary response, dependent variables (including DMI, milk production, efficiency of milk production, and feed sorting) were based on previously reported values (average CV = 12%) from similar herd-level studies (Britt et al., 2003; Endres and Espejo, 2010) and group-level estimates of feed sorting (Leonardi and Armentano, 2007). An estimated sample size of 24 herds was determined sufficient to detect a prevalence of 10% greater production (as well as DMI, efficiency, and sorting) with 95% confidence. A list of prospective producers was identified by CanWest DHI (Guelph, Ontario, Canada) based on herd size greater than 50 cows, primarily Holstein genetics, free-stall housing, and geographic location (within 150 km of Kemptville, Ontario, Canada). Initial questionnaires to assess suitability for participation were prepared and mailed by CanWest DHI to those prospective producers. Farms were enrolled through a combination of mail and telephone contact. Farms meeting the previous criteria and expressing willingness to participate were enrolled. Ten farms were enrolled through mail and an additional 14 through telephone. One farm withdrew from the study during the first data collection period due to time commitments. One farm was included in the study, however, excluded from statistical analysis as sampling and recording protocols were not met. Thus, data from 22 herds were included in this study and its analysis.

Participating farms were visited for 7 consecutive days in both summer (June to September) and winter (December to March) periods. Distribution of data collection was split over 2 summers. Nine farms were studied in the summer of 2011 and the remaining 13 were studied in the summer of 2012. All 22 farms were visited in one winter period (December 2011 to March 2012).

2.2.2 Within-Herd Group Selection

Data collection was limited to one focal pen per farm. In cases where multiple cow groups existed, the highest producing group with an even distribution of DIM and parity and a size of greater than 50 cows (or >40% of the total lactating herd population) was selected for study. Effort was made to exclude groups consisting primarily of fresh cows and first lactation cows.

2.2.3 Cow Measures

The timing of data collection during each summer and winter period was scheduled to coincide with a regular DHI milk test date (+/- 3 days). DHI records from the coinciding test date were accessed to acquire milk production data, including milk yield, fat, protein, MUN, and SCC, as well as cow characteristics including DIM and parity. Data were collected only for those cows in the focal group in each herd. For each cow, using DHI data, 4% FCM was calculated as follows: 4% FCM = (0.4 × test day milk yield) + (15.0 × fat yield) (NRC, 2001). Similarly, energy-corrected milk was calculated for each cow as follows: ECM = (0.327 × test day milk yield) + (12.95 × kg of milk fat) + (7.2 ×kg of milk protein) (Tyrrell and Reid, 1965). Body condition score (BCS) was evaluated for all cows in the focal group during both 7-d data collection periods and was based on a 5 point scale (Wildman et al., 1982). Cows were scored by two individuals and averaged to obtain one BCS per cow per period. Inter- and intra-observer reliability was established prior to scoring to ensure validity of results by calculating the correlation coefficient between different days of validation scoring. Average Pearson correlation coefficients for each observer were 0.89 and 0.83 and between observers was 0.84.

2.2.4 Housing and Feeding Management

Information on housing, milking, and feeding management was obtained through a questionnaire administered to the herd manager during the first week of data collection. The questionnaire covered aspects of ration formulation, stall management, milking, and feeding practices. Producers kept a daily log of timing of milking, feed delivery, and feed push-up. Linear bunk and water trough measurements were recorded by researchers. Pen group population size was recorded daily to calculate daily feed bunk space, water trough space, and stall stocking density. Minimum, maximum and average barn temperature and humidity were recorded daily in the focal pen using a hygrometer (BIOS, Thermor Ltd, Newmarket, Ontario, Canada) in each 7 day observation period.

2.2.5 Feed Sampling Analysis

Farms were visited daily during each 7-d observation period at time of first feed delivery. Amount of feed offered, based on amount dispensed to each group by a TMR mixer wagon, was recorded daily at time of feeding. This was calculated by recording the initial scale weight on the TMR mixer and subtracting any balance after feed was delivered to the focal group. Additional feeding events, including timing and amount, were recorded by the farm manager. Daily feed refusal amount was recorded 24 h after delivery of the first feeding event using a portable scale (OHAUS ES50R, Dundas, Ontario, Canada). Daily DM offered and refused were calculated by multiplying the daily as-fed amount of TMR offered and refused by the DM% of that feed (as determined through daily samples taken of that offered and refused feed), respectively. Daily pen-level DMI was recorded by subtracting DM refused from total DM offered.

Samples of the fresh and refusal TMR, respectively, were taken at time of delivery and 24-h post-delivery. Duplicate samples were collected at these times to assess particle size and DM/chemical content of the ration. Fresh feed was sampled from 5 different areas of the feed bunk, at the beginning, middle and end of TMR delivery, within minutes of delivery to ensure accurate representation of the TMR. Refusals were sampled subsequent to bunk clean up and were mixed to obtain a representative sample. All samples were frozen at -20°C until processing.

Samples for particle size separation were thawed and separated using the 3-screen (19, 8, and 1.18 mm) Penn State Particle Separator (PSPS; Kononoff et al., 2003). This separated the particles into 4 fractions: long (>19 mm), medium (<19, >8 mm), short (<8, >1.18 mm) and fine (<1.18 mm) particles. After separation, the DM of each separated fraction was determined by oven drying at 55°C for 48 h. Particle size distribution (%) was calculated on a DM basis by dividing each dried fraction weight by the total dried sample weight. Samples taken for DM and chemical analysis were oven-dried at 55°C for 48 h and then ground to pass through a 1-mm screen (Brinkmann Mill, Brinkmann Instruments Co., Westbury, NY). Both fresh DM samples plus the dried TMR particle fractions, were sent to Cumberland Valley Analytical Services Inc. (Maugansville, MD) for analysis of DM (135°C; AOAC, 2000; method 930.15), ash (535°C; AOAC, 2000; method 942.05), ADF (AOAC, 2000; method 973.18), NDF with heat-stable α-amylase and sodium sulfite (Van Soest et al., 1991), CP (N × 6.25; AOAC, 2000; method 990.03; Leco FP-528 Nitrogen Analyzer, Leco, St. Joseph, MI) and minerals (AOAC, 2000;

method 985.01). Dried refusal samples were analyzed at University of Guelph-Kemptville Campus using an Ankom^{2000} Fiber Analyzer (Ankom Technology, Macedon, NY) for NDF with heat-stable α-amylase and sodium sulfite (Van Soest et al., 1991).

2.2.6. Calculations and Statistical Analysis

Sorting for each particle fraction of the PSPS was calculated as the actual intake of each fraction expressed as a percentage of the predicted intake of that fraction (Leonardi and Armentano, 2003). The predicted intake of an individual fraction was calculated as the product of the group-level DMI of the total diet multiplied by the DM percentage of that fraction in the fed TMR. Values equal to 100% indicate no sorting, <100% indicate selective refusals (sorting against), and >100% indicate preferential consumption (sorting for). The physical effectiveness factor (pef) was determined as the DM proportion of particles retained by the top 2 sieves of the PSPS (Yang and Beauchemin, 2006). The physically effective NDF (peNDF) was calculated by multiplying the NDF content of the feed by the pef.

Prior to analyses, data outcomes were screened for normality using the UNIVARIATE procedure of SAS (SAS Institute, 2009). Log transformation was performed to normalize somatic cell count. Data were summarized by farm and period (summer and winter) to obtain group averages for the outcomes of interest and all possible explanatory variables. Associations between group-average productivity measures (milk yield, milk fat %, milk protein %, DMI, feed efficiency and feed sorting) and group-level feeding management and ration characteristics were analyzed with multivariable linear mixed models using the MIXED procedure of SAS (SAS institute Inc., 2009), treating period as a repeated measure. Farm within period was included in the model as the subject of the repeated statement. The covariance structure used in the repeated statement was compound symmetry, chosen due to best fit according to Schwarz's

Bayesian information criterion. All independent variables were screened in univariable models; those variables with $P \leq 0.25$ were retained for the multivariable linear regression modeling (Dohoo et al., 2009). The CORR procedure of SAS was used to determine the level of correlation between the retained explanatory variables. In cases where 2 variables were collinear ($r > 0.6$), the one with the most biological plausibility was retained for the multivariable model. For the multivariable models effects were considered significant at $P < 0.05$ and tendencies at $P \leq 0.1$. Manual backward elimination was used to construct the final multivariable models.

2.3 Results and Discussion

2.3.1 Housing, Environment and Management

Average group-level management and cow characteristics are found in Table 2.1. The average lactating herd size of study farms was 162, with an average study group size of 83. Of the 22 farms, 59% milked 2x/d and 41% milked 3x/d. In the summer period, 45% of the farms fed 1x/d and 55% fed 2x/d. In the winter, 50% fed 1x/d and 50% fed 2x/d. For those farms feeding twice a day, the interval between feed deliveries ranged from 1 to 12 h. In the summer, 17% delivered the second feeding within 2 h after the first, 25% between 2-5 h, 25% between 6 to 9 h and 33% greater than 10 h after the first feed delivery. In the winter period, 27% delivered the second feeding within 2 h of the first, 27% between 2 to 5 h, 27% between 6 to 9 h and 18% greater than 10 h after the first feed delivery. For those farms feeding twice a day, 92% and 82% mixed two separate TMR batches for the feed delivery in summer and winter, respectively. Feed push up frequency ranged from 0 to 20x/d, with an average frequency of 4.6 x/d. On average, 36% of herds pushed up feed less than 4x/d and 9% did not push up feed. Those herds with no feed push ups had fixed feed bunk designs (i.e. those with retaining walls for holding feed close to the feed barrier; e.g. J-bunk design) that did not require feed push up.

Average feed bunk space was 0.54 m/cow, ranging from 0.36 to 0.99 m/cow. Of the 22 farms, only 18.2% provided more than the industry recommendation (0.6 m/cow; Grant and Albright, 2001) and 9.1% provided less than 0.4 m/cow. Average bunk space reported in this study is higher than that reported by a cross sectional study in Minnesota (0.46 m/cow; Endres and Espejo, 2010), but much lower than that reported in Spain (0.69 m/cow; Bach et al., 2008).

Post and rail feeder design was most common on farms, with 82% using this feed bunk design and 18% using headlocks. Post and rail feed barriers provide less of a physical barrier during feeding visits; it is hypothesized that this open design increases successful displacements at the feed bunk. Huzzey et al. (2006) reported favorable decreases in aggressive displacements, especially for subordinate cows, when comparing the use of headlocks to post and rail designs.

Average daily barn temperature in summer and winter were 22.2°C and 4.5°C, with a range of 20 to 24.5 and -4.5 to 9.9, respectively. Average barn humidity was 73% in both summer and winter and ranged from 57.3 to 88.9% and 48.8 to 88.6%, respectively, in those seasons. Mean environmental temperatures for this geographical region (centered at Kemptville, Ontario) were -4.8 ± 6.1°C in the winter and 20.5 ± 2.9 and 20.4 ± 3.7°C in the summers of 2011 and 2012, respectively. Average high temperatures were 0.3 ± 5.9°C in the winter and 26.7 ± 3.5 and 27.1 ± 4.4 °C in the summers of 2011 and 2012, respectively. Average low temperatures were -9.9 ± 7.2°C in the winter and 14.2 ± 3.2 and 13.7 ± 3.8°C in the summers of 2011 and 2012, respectively.

2.3.2 Ration Characteristics

Summaries of the ration formulations gathered on farms indicated that farms generally fed TMR with similar base ingredients. Diets typically consisted of a mix of corn silage, alfalfa/grass haylage, high moisture corn, soybean meal, canola meal, hay, straw, and a protein/mineral supplement mix. During the summer period, 27% of farms added water to the ration and no farms added water during winter months. A summary of the nutrient concentrations of the analyzed TMR are presented in Table 2.2. According to NRC recommendations (2001), the average TMR fed met the requirements for all macronutrients and minerals based on average milk production parameters. However, the greatest variability between farms was evident for CP, NDF, and NFC. Specifically, 4 farms fed higher than the recommended maximum level of NFC during the summer months.

Physical characteristics of the fresh and refusal TMR are described in Table 2.3. The refused ration was higher in peNDF, pef, and % long particles and much lower in % short and fine particles than the average offered ration. Rations in this study generally met some of the recommendations of TMR particle size distribution; between 2 to 8% long particles, 30 to 50% medium and short particles, and no more than 20% fine particles (Heinrichs and Kononoff, 2002). On average, all herds fed rations with less than 20% fine particles, 91% and 73% fed rations within the guidelines for short and medium particles, respectively. However, all of the herds fed rations with greater than 8% long particles and 46% of herds fed rations with greater than 20% long particles.

2.3.3 Feed sorting

At the group-level, cows sorted against the long ration particles (97.3%), did not sort for or against medium particles (100%), and sorted for the short and fine ration particles (101%) during both summer and winter seasons. Variability between farms was evident with observed ranges of 88.6 to 100% for long particles and 99.1 to 103.6 for fine particles. These findings are congruent with past research in both tie-stall and free-stall grouped cows (Leonardi and Armentano, 2007), indicating that the observed group-housed cows were sorting against consumption of fiber-rich particles and in favor of highly palatable starch-rich particles. The extent of sorting observed by Leonardi and Armentano (2007) in group-housed cows was more extreme than what we observed. This is likely a function of different methodology and tools used by these researchers to calculate sorting, higher refusal rate (6 to 33% vs. 3.5%), and provision of a much drier diet than found in our study (68% vs 48% DM) (Leonardi and Armentano, 2007). Researchers have found that dry diets (Leonardi et al., 2005; Fish and DeVries, 2012) and feeding for higher refusal rates (Leonardi and Armentano, 2007; Miller-Cushon and Devries, 2010) promote greater feed sorting behavior.

Reduced sorting against long ration particles was associated with feeding for lower refusal rates and tended to be associated with increased feeding frequency (2x vs. 1x/d; Table 2.4). On average, herds feeding 2x/d compared to 1x/d tended to experience a 0.86 percentage point decrease in sorting against long particles at a group-level. The implications of this association are hard to interpret since the results are on a group-level and it is impossible to determine individual cow sorting values for group-housed cows. However, Leonardi and Armentano (2007) reported that the extent of feed sorting is greater in a group setting compared to a tie-stall setting; thus potentially becoming more meaningful at the individual cow level. More importantly, our results showed that every 2 percentage point increase in selective refusal (i.e. sorting against) of long particles on a group-level was associated with a per cow reduction of 0.9 kg/d of 4% FCM (P=0.036). The impact of frequent delivery of fresh feed on reduced feed sorting, on the basis of less change in NDF content in the TMR over the course of the day, has been previously documented (DeVries et al., 2005; Endres and Espejo, 2010). Our study is the first to suggest that increased frequency of feed delivery to group housed cows may beneficially reduce feed sorting at the particle level; thus promoting intake of a ration with the intended particle size distribution to maintain optimal rumen health and productivity.

More sorting in favor of short and fine particles was associated with higher refusal rates (Table 2.4). In contrast, Miller-Cushon and DeVries (2010) found a negative correlation between feeding amount and sorting against short particles. However, sorting patterns exhibited in that study were not typical as cows sorted to a greater extent against shorter particles than long particles (Miller-Cushon and DeVries, 2010). Our results demonstrated that every 2 percentage point increase in refusal rate was associated with a 1.3% increase in group-level selective refusal of long particles and 0.6 and 0.5% increases in group-level selective consumption of short and fine particles, respectively. The average refusal rates in our study are much lower (3.5%, range 0 to 10.3%) than those reported in previous controlled studies (6 to 33%; Leonardi and Armentano, 2007; 11.4 and 18%; Miller-Cushon and DeVries, 2010), but are more representative of commercial feeding. Overall herds were feeding for low feed wastage, with 32% of herds feeding for less than 2% refusal and 73% feeding for less than 5% refusal. The results of this study suggest that feeding for a low refusal amount may not only have economic benefits associated with reduced feed wastage, but may also promote consumption of a diet closer to that intended. To date, no seasonal effects on feed sorting patterns have been studied. Interestingly, cows exhibited more preference for fine particles in the winter compared to summer, with group-level sorting being 0.57 percentage points lower on average in summer months (Table 2.4). Once again, the implications of this finding are impossible to interpret at an individual level. This observation may be partially explained by the higher proportion of herds delivering feed 2x/d in summer compared to winter. This current study as well as past research suggests that increased frequency of feeding reduces the extent of feed sorting (DeVries et al., 2005; Endres and Espejo, 2010).

An increased proportion of fine particles in TMR was associated with more sorting in favor of fine particles and less sorting for medium particles (Table 2.4). Provision of a diet that is proportionally higher in long particles will increase sorting in favor of short particles (Leonardi and Armentano, 2003), while provision of a diet proportionally higher in short particles increases the extent of sorting for those shorter particles (DeVries et al., 2007). The rationale is that formulation of a diet with easily distinguished particle fractions (i.e. increased proportion of long or fine particles) increases the ease with which cows can easily select those highly desired smaller particles.

2.3.4 DMI

Average DMI was similar across seasons and is presented in Table 2.5. Controlling for the effects of DIM, parity and milking frequency, increased frequency of feed delivery (2x vs 1x/d) was associated with a 1.42 kg/d increase per cow in DMI (Table 2.6). Other reports on the effect of frequency of feed delivery on feed intake of group-housed cows are inconsistent. Increasing feeding frequency of heifers improved average daily gain and efficiency of feed utilization, potentially as a result of increased feed intake (Gibson, 1981). Increased frequency of delivery of fresh feed had no effect on feed intake of tie-stall housed cows (Alzahal et al., 2006) and group-housed cows (Phillips and Rind, 2001). However, DeVries et al. (2005) reported favorable increases in daily feeding time and more equal distribution of feeding events throughout the day as a result of delivering feed 2x vs. 1x/d. This has favorable implications for rumen health, as consumption of smaller, more frequent meals is thought to reduce the risk of sub-acute ruminal acidosis (Krause and Oetzel, 2006). Along those same lines, increased frequency of feed delivery reduces the magnitude of postprandial decline in rumen pH, thus contributing to increased ruminal health (French and Kennelly, 1990) Reduced diurnal fluctuations in rumen pH may translate to improved fiber digestibility (Mertens, 1997), which in turn may increase rate of passage and result in greater DMI.

2.3.5 Milk production parameters

Test day milk yield, FCM, and ECM are found in Table 2.5. Factors associated with test day milk yield are presented in Table 2.7. A positive association between increased frequency of feed delivery and milk yield was found, with 2x/d feed delivery being associated with 2.01 kg/d greater yield per cow. While it is unknown if this relationship is causal, this finding is not surprising as increased frequency of feed delivery was also associated with increased DMI (Table 2.6), which is a major determinant of milk yield (Dado and Allen, 1994). Additionally, reduced sorting against long particles at a group level was associated with increased 4% FCM and ECM. It could be hypothesized that less sorting would result in reduced variability in rumen pH (DeVries et al., 2008), increased fiber intake and digestibility (Mertens, 1997); thus contributing to improved diet digestibility to promote increased milk production.

Providing cows with greater water trough space tended to be associated with greater test day milk yield (Table 2.7), as well as greater FCM and ECM. We found that milk yield tended to increase by 0.77 kg/d for every 2cm/cow increase in water trough space; the range of observed water trough space was 3.8 to 11.7 cm/cow. Water is perhaps the most necessary nutrient (NRC, 2001). This result illustrates the importance of water availability for group housed cows and suggests that resource availability greatly impacts potential productivity.

Average group-level efficiency of milk production was 1.41 kg milk/kg DMI (Table 2.5). Greater efficiency of milk yield, FCM, and ECM was associated with milking cows of lower DIM and milking more frequently (3x vs. 2x/d; Table 2.5). This is consistent with past findings that efficiency typically increases as DIM decreases (Britt et al., 2003) and as milking frequency increases (Barnes et al., 1990). Milking 3x/d compared to 2x/d was associated with an 11.6%

increase in efficiency of milk production. Increased efficiency of test day milk yield was associated with less sorting for fine particles (Table 2.7). Efficiency of milk production decreased by 3% for every 1% group-level selective consumption (sorting) of fine particles. Excessive sorting in favor of consuming rapidly-digestible short particle components is a risk factor for depressed rumen pH (DeVries et al., 2008); potentially reducing efficiency of nutrient utilization.

Providing cows with more space at the feed bunk was associated with improved milk fat % (Table 2.8). Every 10cm/cow increase in bunk space was associated with a 0.06 percentage point increase in milk fat percentage. This finding is congruent with our hypothesis that improvements in feed access translate to improvements in herd-level production parameters. Research has shown that providing more feed bunk space results in more consistent feeding patterns throughout the day, i.e. smaller, more frequent meals throughout the day, while decreased feed bunk space increases the rate of consumption and average meal size (Hosseinkhani et al., 2008). Rapid consumption of larger meals increases the risk of ruminal acidosis (Krause and Oetzel, 2006) since the rate of pH decline post-feeding is related to the size of meal consumed (Allen, 1997). Thus, cows with increased bunk space should consume smaller, more frequent meals throughout the day and experience less severe postprandial drops in rumen pH, and so should be able to synthesize more milk fat (Bauman and Griinari, 2003) Additionally, reduced group-level sorting against consumption of long particles was associated with greater milk fat yield (P= 0.052) but not milk fat %. Reduced sorting against long particles results in increased intake of fiber and increased rumen pH (DeVries et al., 2008); thus contributing to optimal rumen conditions for milk fat synthesis.

Group-average milk protein was 3.24% (Table 2.5) and was associated with a 0.15 percentage point decrease during summer months (Table 2.8). Increased milking frequency (3x/d vs. 2x/d) was associated with reduced milk protein % (Table 2.8), but did not affect total protein yield. Every 2cm/cow increase in water space was associated with a 0.05 percentage point decrease in milk protein % (Table 2.8). This result may be a result of our finding that increased water trough space was associated with increased milk yield. Milk protein yield was unaffected by water trough space, thus milk protein % was reduced.

Group average SCC was 225,000 SCC/mL and varied greatly between farms (Table 2.5). Farms with post-and-rail feed barrier, compared to headlocks, had higher SCC (Table 2.6). On average, using a headlock feed barrier was associated with a 43% decrease in group-average SCC. It is unknown whether unmeasured variables had any impact on this finding; however, the impact of using headlocks on competition at the feed bunk may help explain this association. Headlock feed barriers result in an increase in feeding success at the bunk, evidenced by a reduction in aggressive displacement from the feed bunk (Huzzey et al., 2006). Additionally, increased group-average SCC was associated with reduced feed bunk space (Table 2.6). It could be hypothesized in situations with reduced feed bunk space and reduced success at the feed bunk, some cows may choose to lie down sooner following exit from the milking parlour to avoid social interactions; this decreased post-milking standing time may potentially increase the risk of intramammary infection (DeVries et al., 2010). Post-milking standing time is greatly influenced by management factors such as the delivery of fresh feed (DeVries et al., 2010); thus presenting producers with a means of reducing risk of intramammary infection and increasing udder health.

Milk urea nitrogen (MUN) is an indicator of protein metabolism and can be used to monitor crude protein utilization of the ration (Biswajit et al., 2011). Not surprisingly, higher

MUN was associated with increased CP in the ration (Table 2.6), as provision of CP in excess of requirements results in nitrogen excretion (Biswajit et al., 2011). We found that every 1% increase in ration CP was associated with a 12.6% increase in MUN, indicating excess nitrogen excretion. Increased sorting for fine particles and reduced water trough space tended to be associated with increased MUN (Table 2.6). Specifically, every 2cm/cow increase in water trough space was associated with a 3% reduction in MUN and every 1% increase in group-level sorting for fine particles was associated with a 2.8% increase in MUN.

2.4 CONCLUSIONS

The results of this observational study indicate that feeding management practices to promote feed and bunk access are associated with group-average productivity. It was found that herds delivering feed 2x/d vs. 1x/d had greater DMI and milk yield and exhibited less sorting against long ration particles. Additionally, providing cows with more space at the feed bunk was associated with lower group-average SCC and higher milk fat percentage. It must be noted that the results presented in this study are based on group-level averages, thus making it impossible to interpret the conclusions on an individual cow basis. Nevertheless, this field study corroborates many of the findings presented by previous controlled trials investigating the effects of feeding, management, and housing on sorting and productivity measures of group housed dairy cows. Studies of this nature allow a broadened understanding of the associations discovered in controlled studies, while simultaneously generating questions for future research.

2.5 ACKNOWLEDGMENTS

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Table 2.1. Average management and cow characteristics on 22 commercial free-stall farms[1]

Variable	Mean ± SD	Min	Max
Management			
Lactating herd size (n)	161.8 ± 120	66	570
Group size (n)	83 ± 32	36	176
Feed push-up frequency[2] (n/d)	4.6 ± 4	0	20
Bunk space[3] (m/cow)	0.54 ± 0.17	0.36	0.99
Water space[4] (cm/cow)	7.2 ± 2.3	3.8	11.7
Stall stocking density[5](cows/stall)	1.0 ± 0.13	0.71	1.17
Refusal rate[6] (%)	3.5 ± 2.1	0.87	9.3
Cow measurements			
DIM[7]	187 ± 47	94	278
Parity[7]	2.3 ± 0.57	1.01	4.0
BCS[8]	3.36 ± 0.09	3.18	3.51

[1]22 commercial dairy farms were visited for 7 consecutive days in each of summer and winter periods; data were averaged across farm and periods

[2]Frequency and timing of management practices were recorded daily by the farm manager

[3]Bunk space (m/cow) was recorded at the start of the first period and calculated daily as group size fluctuated

[4]Water space (m/cow) was recorded at the start of the first period and calculated daily as group size fluctuated

[5]Number of stalls in the pen were recorded at the start of the first period; stocking density was calculated daily as group size fluctuated

[6]Refusal rate = (DM refused/DM offered) × 100

[7]DIM and parity were obtained for cows in the focal study group and averaged per herd. Measurements were obtained from the monthly DHI milk test which occurred within ± 3 days of the 7d data collection

[8]BCS = body condition score

Table 2.2 Average nutrient composition of the TMR delivered on 22 commercial free-stall farms[1, 2]

Variable (% of DM, unless otherwise noted)	Mean ± SD	Min	Max
CP	16.5 ± 0.85	14.0	18.2
NDF	31.3 ± 1.90	26.0	34.9
ADF	20.5 ± 1.17	17.7	21.9
Ash	7.9 ± 0.41	6.8	8.3
TDN	73.5 ± 1.10	71.8	75.3
NE_L (Mcal/kg)	1.70 ± 0.03	1.66	1.75
NFC	41.2 ± 2.11	37.6	46.8
Ca	0.92 ± 0.12	0.70	1.19
P	0.42 ± 0.03	0.35	0.49
Mg	0.35 ± 0.05	0.26	0.38
K	1.45 ± 0.15	1.18	1.85
Na	0.41 ± 0.09	0.22	0.62
Fe (mg/kg)	324 ± 83	229	553
Mn (mg/kg)	72.2 ± 12.9	50.6	107
Zn (mg/kg)	90.7 ± 14.2	67.6	126.4
Cu (mg/kg)	25.7 ± 4.0	20.2	31.5

[1]22 commercial dairy farms were visited for 7 consecutive days in each of summer and winter periods; data were averaged across each farm and periods

[2]Fresh TMR samples were collected daily for 7 consecutive d in each period; data were averaged across period

Table 2.3 Particle size distribution and characteristics of TMR offered and refused on 22 commercial free-stall farms[1]

Variable (%, unless otherwise noted)	Offered ration Mean ± SD	Refused ration Mean ±SD
DM	47.7 ± 2.8	46.1 ± 3.0
Particle Size[2]		
Long	19.8 ± 6.5	33.1 ± 9.5
Medium	34.3 ± 6.6	35.0 ± 7.2
Short	35.5 ± 4.3	24.8 ± 5.2
Fine	10.5 ± 2.9	6.6 ± 1.4
pef[3]	54.1 ± 5.0	68.2 ± 6.0
peNDF[4] (% of DM)	17.0 ± 2.1	24.5 ± 3.6

[1]22 commercial dairy farms were visited for 7 consecutive days in each of summer and winter periods; data were averaged across farm and periods

[2]Particle size was measured using a Penn State Particle Separator which divided the sample into four fractions: long (>19mm), medium (<19, >8mm), short (<8, >1.18 mm) and fine (<1.18mm)

[3]pef= physical effectiveness factor measured as the sum of the DM proportions retained on the top two Penn State particle sieves

[4]peNDF= physically effective NDF measured by multiplying pef by NDF (%DM) content of the ration

Table 2.4 Final group-level multivariable linear regression models for factors associated with sorting[1] of TMR particle fractions[2]

	Long particle sorting (%)			Medium particle sorting (%)			Short particle sorting (%)			Fine particle sorting (%)		
Variable	β[3]	SE	*P*-value	β[3]	SE	*P*-value	β[3]	SE	*P*-value	β[3]	SE	*P*-value
Intercept	99.2	0.5	<0.001	101.8	3.8	<0.001	102.6	1.25	<0.001	99.3	0.36	<0.001
BCS[5]	-	-	-	-1.7	0.81	0.04	-	-	-	-	-	-
Period												0.004
Winter	-	-	-	-	-	-	-	-	-	Ref[4]		
Summer	-	-	-	-	-	-	-	-	-	-0.57	0.19	
Milking frequency (no/d)						0.003						
2	-	-	-	Ref[4]	-		-	-	-	-	-	-
3	-	-	-	-0.49	0.16		-	-	-	-	-	-
Feeding frequency (no/d)			0.095									
1	Ref[4]	-	-	-	-	-	-	-	-	-	-	-
2	0.86	0.5	-	-	-	-	-	-	-	-	-	-
Refusal rate [6](%)	-0.65	0.1	<0.001	-	-	-	0.29	0.03	<0.001	0.25	0.04	<0.001
% short particles	-	-	-	-0.04	0.017	0.014	-	-	-	-	-	-
% fine particles	-	-	-	-0.1	0.02	<0.001	-	-	-	0.1	0.03	<0.001
NFC (%)	-	-	-	-	-	-	-0.06	0.03	0.04	-	-	-
NE_L (Mcal/kg)	-	-	-	3.93	1.97	0.05	-	-	-	-	-	-

[1]Sorting = 100 × (fraction DMI/ predicted fraction DMI) where fraction = long, medium, short or fine particles. Sorting values equal to 100% indicate no sorting, <100% indicate selective refusal (sorting against) and >100% indicate preferential consumption (sorting for). Data were collected on 22 commercial dairy farms for 7 consecutive days during winter and summer periods.

[2]Particle size determined by Penn State Particle Separator, which has a 19-mm screen (long), 8-mm screen (medium), 1.18-mm screen (short), and a pan (fine).

[3]β = estimated regression coefficient

[4]Ref = reference category

[5]BCS= body condition score

[6]Refusal rate = (DM refused/DM offered) × 100%

Table 2.5 Average productivity measures of dairy cows on 22 commercial free-stall farms[1]

Item	Mean ± SD	Min	Max
DMI[2] (kg/d)	24.3 ± 2.1	20.9	28.7
Milk yield, kg/d			
Milk [3]	34.3 ± 5.9	24.6	46.3
4% FCM[4]	33.2 ± 5.2	24.3	46.8
ECM[5]	35.6 ± 5.4	26.7	48.4
Milk composition[3], %			
Fat	3.75 ± 0.23	3.17	4.14
Protein	3.24 ± 0.15	2.96	3.51
Milk component yield[3] , kg/d			
Fat	1.27 ± 0.18	0.98	1.66
Protein	1.10 ± 0.17	0.82	1.43
Efficiency of milk production[6], kg/kg			
Milk/DMI	1.41 ± 0.16	1.15	1.69
4% FCM/DMI	1.36 ± 0.13	1.12	1.61
ECM/DMI	1.46 ± 0.13	1.22	1.71
MUN[3,7] (mg/dl)	10.49 ± 1.89	6.08	13.68
SCC[3,8] (000's SCC/mL)	225 ± 129	93	600

[1]22 commercial dairy farms were visited for 7 consecutive days in each of summer and winter periods; data were averaged across farm and periods

[2]DMI was calculated daily by subtracting the pen-level DM refused from DM offered and dividing by the number of cows.

[3]Milk production parameters were obtained from a coinciding DHI test (+/- 3 days of data collection period) for cows in the focal group and averaged for group and period (summer and winter)

[4]4% FCM = 4% fat corrected milk

[5]ECM = energy corrected milk

[6]Efficiency of milk production calculated by dividing milk yield by average DMI of focal cows

[7]MUN = milk urea nitrogen

[8]SCC = somatic cell count

Table 2.6 Final multivariable linear regression models for factors associated with DMI, MUN and SCC[1]

	DMI[6] (kg/d)			MUN[4,7] (mg/dL)			LN_SCC[4,8]		
Variable	β[2]	SE	*P*-value	β[2]	SE	*P*-value	β[2]	SE	*P*-value
Intercept	21.5	1.69	<0.001	-40.07	18.1	0.034	4.09	0.53	<0.001
Season						0.042			
2012	-	-	-	Ref[3]			-	-	-
2011	-	-	-	0.94	0.45		-	-	-
DIM[4]	-0.011	0.006	0.056	-	-	-	0.005	0.0015	0.0026
Parity[4]	1.56	0.51	0.001	-	-	-	0.27	0.12	0.033
Milking frequency(no/d)			0.024						
2	Ref[3]	-		-	-	-	-	-	-
3	1.19	0.51		-	-	-	-	-	-
Feeding frequency (no/d)			0.008						
1	Ref[3]	-		-	-	-	-	-	-
2	1.42	0.51		-	-	-	-	-	-
Feeder Design									0.002
Headlock	-	-	-	-	-	-	Ref[3]		
Post-rail	-	-	-	-	-	-	0.56	0.17	
Bunk space (m/cow)	-	-	-	-	-	-	-1.39	0.40	0.0013
Fine sorting (%)	-	-	-	0.31	0.18	0.092	-	-	-

Linear water space (cm/cow)				-0.17	0.083	0.052	-	-	-
CP (%DM)	-	-	-	1.39	0.18	<0.001	-	-	-
Na (%)	-	-	-	-7.16	1.81	<0.001	-	-	-

[1]Data were collected on 22 commercial dairy farms for 7 consecutive days during winter and summer periods.

[2] β = estimated regression coefficient

[3] Ref = reference category

[4]Milk production parameters collected from a coinciding DHI test (+/- 3 days of data collection period)

[5]BCS= body condition score

[6]DMI was calculated daily by subtracting the DM refused from DM offered; averaged over 7 days.

[7]MUN = milk urea nitrogen

[8] LN_SCC = natural log of somatic cell count (SCC$\times$ 1000 cells/mL)

Table 2.7 Final multivariable linear regression models for factors associated with milk yield and efficiency of milk production[1]

	Test day milk yield[4] (kg/d)			Efficiency of test day milk yield (kg milk[4]/kg DMI)		
Variable	β[2]	SE	*P*-value	β[2]	SE	*P*-value
Intercept	32.08	3.7	<0.001	6.40	1.82	<0.001
DIM[6]	-0.06	0.01	<0.001	-0.002	0.0004	<0.001
Parity[6]	3.09	0.84	<0.001	-	-	-
Milking frequency (no/d)			<0.001			<0.001
2	Ref[3]	-		Ref[3]		
3	5.9	0.99		0.16	0.018	
Feeding frequency (no/d)			0.047			
1	Ref[3]	-		-	-	-
2	2.01	0.98		-	-	-
Fine particle sorting[5] (%)	-	-	-	-0.046	0.018	0.014
Linear water space (cm/cow)	0.384	0.22	0.081	-	-	-

[1]Data was collected on 22 commercial dairy farms for 7 consecutive d during winter and summer periods

[2]β = estimated regression coefficient

[3]Ref = reference category

[4]Milk production parameters collected from a coinciding DHI test (+/- 3 days of data collection period)

[5]Fine particle sorting = predicted intake/actual intake of TMR particles <1.18 mm in length

Table 2.8 Final multivariable linear regression models for factors associated with milk fat and protein[1]

	Milk fat[4] %			Milk protein[4] %		
Variable	β[2]	SE	*P*-value	β[2]	SE	*P*-value
Intercept	1.97	0.38	<0.001	3.26	0.11	<0.001
Period			<0.001			<0.001
Winter	Ref[3]			Ref[3]		
Summer	-0.27	0.06		-0.15	0.037	
DIM[4]	0.003	0.0007	<0.001	0.0016	0.0004	<0.001
Parity[4]	-	-	-			
LN_SCC[5]	0.20	0.063	0.003	-	-	-
Milking frequency (no/d)	-	-	-			<0.001
2	-	-	-	Ref[3]		
3	-	-	-	-0.17	0.038	
Bunk space (m/cow)	0.60	0.20	0.006	-	-	-
Linear water space (cm/cow)	-	-	-	-0.023	0.0082	0.007

[1]Data were collected on 22 commercial dairy farms for 7 consecutive days during each winter and summer period.

[2] β = estimated regression coefficient

[3] Ref = reference category

[4]Milk production parameters collected from a coinciding DHI test (+/- 3 days of data collection period)

[5]LN_SCC = natural log of SCC

Chapter 3: Accuracy and precision of total mixed rations fed on commercial dairy farms

3.1 Introduction

Dairy producers are increasingly mindful of factors affecting efficiency of milk production and ultimately their profit margin. Total mixed rations (TMR) were introduced as a means of providing a consistent supply of nutrients to rumen microbes to optimize rumen function and improve efficiency of nutrient utilization (Coppock et al., 1981). Variation in ration composition is unavoidable, but excessive variation can impact both milk production and health of dairy cows (James and Cox, 2008; Stone, 2008). Provision of a consistent ration, with respect to both physical and chemical composition, is an essential part of maximizing cow performance and getting the best value out of the ration.

Inconsistencies in nutrient intake have many causes. Sorting of TMR can result in cows consuming a ration with a different nutrient composition than that delivered (Leonardi and Armentano, 2003), which has been shown to impact production at a herd level (Chapter 2). Even if cows consume TMR with high consistency (i.e. no sorting), the ration delivered may not reflect the ration formulated by the nutritionist, nor be consistent in composition day-to-day. Recent audits of feeding programs on commercial farms suggest that variability in TMR consistency, which can be influenced by nutrient variability, mixing equipment condition, and ingredient mixing order, plays a large role in production efficiency and overall herd profitability (Mikus, 2012). Measures to reduce daily variability in the TMR, including regular feed analyses, accurate batch preparation and education of people preparing the ration, should be taken to ensure maximum herd health and profitability (Stone, 2008).

The objectives of this study were to: 1) determine the degree to which TMR fed differs from ration formulation (accuracy), 2) determine the daily variability in nutrient and physical characteristics of TMR (precision), and 3) examine associations between daily variability in ration characteristics and productivity measures, including milk yield, milk components, DMI, efficiency of milk production and feed sorting on commercial farms.

3.2 Materials and Methods

3.2.1 On-farm Data Collection

A total of 24 commercial dairy farms in Eastern Ontario, Canada were enrolled in this cross-sectional study. This was completed as part of a larger study investigating the relationship between feed sorting, feeding management, and productivity measures of free-stall housed dairy cows; see Chapter 2 for detailed methods. In summary, a list of eligible farms was identified by CanWest DHI (Guelph, Ontario, Canada) based on suitability criteria: primarily Holstein genetics, lactating herd size greater than 50 cows, free-stall housing, and location (within 150 km of Kemptville, Ontario, Canada). Those farms that met the criteria and conveyed interest in participation were enrolled. Two farms were excluded from the study, one during the data collection period due to time commitments and one prior to analysis as sampling and recording protocols were not met. In total, 22 farms were included in the analysis.

Those 22 farms were visited for 7 consecutive days in each of summer (June-September) and winter (December to March). Summer data collection was split over two years; 9 farms were studied in the summer of 2011 and the remaining 13 in the summer of 2012. All 22 farms were visited in the winter of 2011 to 2012. Data collection was limited to one feeding group per farm, where the focal group consisted of the highest producing group of cows with an even distribution of DIM and parity, and a group size greater than 50 cows (or >40% of the total lactating herd population). Groups comprised of primarily fresh and first lactation cows were excluded from selection.

Data collection was scheduled to coincide with a monthly DHI test (± 3 days). Milk production data, including milk yield, fat, protein, MUN and SCC as well as cow characteristics including DIM and parity, were collected and summarized by group. Daily group-level DMI was measured by subtracting feed refusal amount from the amount of feed dispensed from the TMR mixer wagon. Amount delivered was calculated by recording the initial TMR scale weight and subtracting any balance after feed was delivered to the focal group. Daily samples of fresh and refusal TMR were, respectively, taken at the time of delivery and 24 h after delivery. Additional samples were collected and recorded by the herd manager in cases of multiple daily feeding events. Samples were collected to assess particle size, DM and chemical content of the ration. The Penn State Particle Separator (PSPS; Kononoff et al., 2003) separated the particles into 4 fractions: long (>19 mm), medium (<19, >8 mm), short (<8, >1.18 mm) and fine (<1.18 mm) particles. Samples taken for DM and chemical analysis were oven-dried at 55°C for 48 h and then ground to pass through a 1-mm screen (Brinkmann Mill, Brinkmann Instruments Co., Westbury, NY). Both fresh DM samples plus the dried TMR particle fractions, were sent to Cumberland Valley Analytical Services Inc. (Maugansville, MD) for analysis of DM (135°C; AOAC, 2000; method 930.15), ash (535°C; AOAC, 2000; method 942.05), ADF (AOAC, 2000; method 973.18), NDF with heat-stable α-amylase and sodium sulfite (Van Soest et al., 1991), CP (N × 6.25; AOAC, 2000; method 990.03; Leco FP-528 Nitrogen Analyzer, Leco, St. Joseph, MI) and minerals (AOAC, 2000; method 985.01). Refusal samples were analyzed at University of Guelph- Kemptville Campus using an Ankom^{2000} Fiber Analyzer (Ankom Technology, Macedon, NY) for NDF with heat-stable α-amylase and sodium sulfite (Van Soest et al., 1991).

A questionnaire on housing and feeding management practices was administered by personal interview to the herd manager during the week of data collection for each season. A copy of the most recent TMR formulation was obtained as part of this questionnaire for each season; this formulation included a breakdown of the expected TMR nutrient composition (CP, NE_L, NFC, NDF, ADF, Ash, Ca, P, Mg, K, Na, and trace minerals).

3.2.2 Calculations and Statistical Analysis

Coefficients of variation between the formulated ration and ration delivered were calculated for CP, ADF, NDF, Ash, Ca, P, Mg, K, Na, Fe, Mn, Zn, Cu, NE_L, TDN and NFC. This was calculated by dividing the SD between the formulated and analyzed value by the average of those values and expressed as a percent. Differences between the TMR fed and formulated were calculated by subtracting the formulated chemical value from the value obtained from laboratory analysis.

Daily ration variability, as expressed by coefficients of variation (CV), was calculated over each 7-d period for nutrients including CP, ADF, NDF, Ash, Ca, P, Mg, K, Na, Fe, Mn, Zn, Cu, NE_L, TDN and NFC and physical characteristics, including particle size distribution, DM, refusal rate, physically effective fiber (pef) and physically effective NDF (peNDF). Coefficients of variation were calculated by dividing the SD of each nutrient over 7 d by the average of those values over 7 d and was expressed as a percentage. The physical effectiveness factor (pef) was determined as the DM proportion of particles retained by the top 2 sieves of the PSPS (Yang and Beauchemin, 2006). The physically effective NDF (peNDF) was calculated by multiplying the NDF content of the feed by the pef. Refusal rate was calculated by dividing the DM refused by the DM offered and multiplying by 100%.

Sorting for each particle fraction of the PSPS was calculated as the actual intake of each fraction expressed as a percentage of the predicted intake of that fraction (Leonardi and Armentano, 2003). The predicted intake of an individual fraction was calculated as the product of the group level DMI of the total diet multiplied by the DM percentage of that fraction in the fed TMR. Values equal to 100% indicate no sorting, <100% indicate selective refusals (sorting against), and >100% indicate preferential consumption (sorting for).

Prior to analyses, outcomes were screened for normality using the UNIVARIATE procedure of SAS (SAS Institute, 2009). Data were summarized by farm and period (summer and winter) to obtain herd-level averages for the outcomes of interest (milk yield, fat, protein, DMI, efficiency of milk production and feed sorting). Associations between those outcomes and variability (CV) in ration components (CP, ADF, NDF, NE_L, NFC, Ash, Ca, P, Mg, Na, K, DM, pef, peNDF, particle size distribution) were analyzed with multivariable linear mixed models using the MIXED procedure of SAS (SAS institute Inc., 2009), treating period as a repeated measure. Farm within period was included in the model as the subject of the repeated statement. The covariance structure used in the repeated statement was compound symmetry, chosen due to best fit according to Schwarz's Bayesian information criterion. All independent variables were screened in univariable models; those variables with $P \leq 0.25$ were retained for the multivariable linear regression modeling (Dohoo et al., 2009). The CORR procedure of SAS was used to determine the level of correlation between the retained explanatory variables. In cases where 2 variables were correlated ($r > 0.6$), the one with the most biological plausibility was retained for the multivariable model. For the multivariable models, effects were considered significant at $P < 0.05$ and tendencies at $P \leq 0.1$. Manual backward elimination of non-significant and non-trending effects was used to construct the final multivariable models.

3.3 Results and Discussion

3.3.1 Ration variability

The degree of agreement between the fed and formulated rations is found in Table 3.1. On average, the ration fed did not accurately represent the formulated ration. Specifically, greater than 5% CV of the discrepancy between fed and formulated was observed for all nutrient components with the exception of CP, TDN and NE_L (Table 3.1). The greatest variability between fed and formulated was observed for ash, Ca, Na and trace minerals (Table 3.1). The average TMR delivered exceeded formulation for NE_L, NFC, ADF, Ca, P, Mg, and K and underfed CP, NDF, and Na (Table 3.1). On average, these differences were small, but variability between farms, as indicated by large ranges, was evident (Table 3.1).

Average physical and chemical composition of the TMR fed are in Table 3.2 and 3.3, respectively. Table 3.2 demonstrates average daily variability in the physical composition of the ration. Greater than 5% CV in day-to-day variability was observed for refusal rate, % long particles, % medium particles, % short particles, % fine particles and peNDF (Table 3.2). Day-to-day variability in the nutrient composition of the ration is found in Table 3.3. The greatest daily variability was observed for Ca, Mg, Na and trace minerals (Table 3.3). The range in daily variability for both physical and nutrient composition was wide between individual farms (Tables 3.2 and 3.3).

To our knowledge, there are a limited number of studies published that quantify the precision or accuracy of commercial farm feeding and associated implications for production. James and Cox (2008) suggested that rising costs of feed ingredients dictate the need for more rigid monitoring of nutrient balances, also termed precision feeding. They distinguished between the use of precise and accurate feeding, stating that precision refers to consistency between days, while accuracy pertains to how well the fed ration meets the specifications formulated by the nutritionist. The results of our study suggest that commercial rations in the observed herds were delivered more precisely than accurately, because the variability observed between the fed and formulated rations was higher than the observed day-to-day variability. However, for macronutrients, the CV of discrepancies between formulation and delivered TMR and day-to-day variation in the TMR delivered were all less than 10% and mostly less than 5%. James and Cox (2008) also reported that commercial rations lacked precision and accuracy, with variability being attributed to operator errors, equipment failure, and poor layout of the feed loading area. Interestingly, James and Cox (2008) reported that secondary feed workers, those responsible for TMR mixing less than 25% of the time, were more accurate than those primary feeders, likely due to the development of bad mixing practices by those doing it routinely. We did not record the number of feed workers, so it was not possible to further explore this hypothesis, but the majority of farms in our study had one person primarily responsible for batch preparation. Regardless, regular monitoring of between batch variability is likely helpful to evaluate operator accuracy and ensure delivery of a consistent ration.

It is widely accepted that errors in mixing can result in variable ration composition, with respect to both daily variability and discrepancy to the formulated ration, yet there is a lack of work to quantify the degree of agreement between fed and formulated rations on commercial farms. Cox (2007) reported that the phosphorus content of the ration, which was correlated to crude protein content, was significantly different than the value formulated by the nutritionist, but did not comment on whether the average farm under or over fed those nutrient components. An evaluation of rations fed on commercial dairy farms in California indicated considerable variation (CV > 5%) between the fed and formulated ration, particularly for fat, NDF, Ca and CP (Silva-del-Rio and Castillo, 2012). Variation in the nutrient composition and DM content of forages are often the main culprits explaining variability between batches of TMR and can likely impact production (Buckmaster and Muller, 1994). These findings suggest that increased surveillance of the TMR composition, not only of individual feed ingredients, may be helpful as a regular component of feeding management to ensure delivery of TMR with the intended nutrient composition.

3.3.2 Factors associated with DMI

Group-average DMI was 24.3 ± 2.1 kg/d (mean ± SD) (Chapter 2). Reduced variability in NE_L ration content was associated with greater DMI (*P* = 0.005); every 0.5 percentage point increase in NE_L daily variability (CV) was associated with a reduction of 1.0 kg/d DMI. Variability in NE_L content of the ration was correlated (r >0.6) with other nutrient variabilities in the ration, including ash, ADF, NDF, TDN and NFC (data not shown). Accordingly, among these, only NE_L was included in the multivariable model. Given the collinearity in the variability in these nutrients, it is logical to assume that DMI could also be negatively affected by increased variability in those other nutrients. In this study we found that increased DMI was associated with more frequent feed delivery (2x vs. 1x/d) (Chapter 2). Farms feeding 2x/d had NE_L CV of 1.0%, while on farms feeding 1x/d the CV was 1.3%, but the difference was not significant (*P* = 0.13). It could be hypothesized that farms with more intensive feeding programs (i.e 2x/d vs 1x/d) might be more rigid in TMR feeding and mixing protocols and so experience less daily variability in ration composition.

3.3.3 Factors associated with milk production parameters

Group-average milk yield, 4% FCM, and ECM were 34.3 ± 5.9, 33.2 ± 5.2, and 35.6 ± 5.4 kg/d (mean ± SD), respectively (Chapter 2). Greater test day milk yield was associated with greater variability in refusal rate and lower variability in % long particles and NE_L (Table 3.4). Controlling for the effects of crop season (2011 vs. 2012), greater 4% FCM was also associated with greater variability in refusal rate ($P = 0.005$), and lower variability in % long particles in the fed ration ($P = 0.022$) and NE_L ($P < 0.001$). Every 20 percentage point increase in refusal rate variability was associated with 1.3 kg/d greater milk yield and 1.2 kg/d greater 4% FCM. Every 0.5 percentage point increase in variability of NE_L and 5 percentage point increase in % long particles in the fed ration was associated with 3.2 kg/d and 1.2 kg/d lesser milk yield, respectively. Average refusal rate was 3.5 % ± 2.1 (Chapter 2). Those farms with the greatest CV for refusal rate also had much lower refusal rates on average (<2%). However, lower refusal rates were not associated with greater milk yield (Chapter 2), although greater refusal rate variability was. This suggests that the association we found between refusal rate variability and milk yield (Table 3.4) might be attributed to the management style of those farms. James and Cox (2008) reported a similar association with regard to milk yield, with increased deviation in daily loads (kg/d) negatively correlated to milk production. These deviations were attributed to errors in under- and over-feeding, particularly for CP. Additionally, increased variation in milk yield has been linked to periods of poor feeding management, as a result of errors in ingredient DM monitoring (Tylutki et al., 2004).

Group-average milk fat % was 3.75 ± 0.23 (mean ± SD) (Chapter 2). Controlling for the effect of season, greater milk fat % was associated with greater variability in % long particles in the fed ration (Table 3.5) and greater milk fat yield was associated with less variability in NE_L ($P = 0.001$). Every 5 percentage point increase in variability in % long particles in the fed ration was associated with a 0.06 percentage point increase in milk fat %. No association between % long particles in the ration and milk fat % was observed (Chapter 2), which suggests that consistency in particle size inclusion has a greater impact on milk composition than the absolute proportion of long particles. However, there are likely thresholds beyond which the % long particles and NDF content of the ration that would affect milk fat % (Mertens, 1997). One of the intended benefits of TMR is to maintain consistent rumen conditions to maximize efficiency of nutrient conversion (Coppock et al., 1981). The current findings substantiate this claim as increased variability in particle size distribution was associated with milk of lower compositional value.

Group-average milk protein % was 3.24 ± 0.15 (mean ± SD) (Chapter 2). Controlling for the effect of season, greater milk protein % was associated with increased variability in % short particles in the TMR, and reduced variability in % fine particles and CP (Table 3.5). Every 2 percentage point increase in variability of % short particles in the fed ration was associated with 0.03 percentage point increase in milk protein %. Every 2 percentage point reduction in variability of % fine particles and CP was associated with 0.02 and 0.06 percentage point increases in milk protein %, respectively. Variability in % short particles was also modestly correlated to % mid and fine particles ($r = 0.47$ and $r = 0.43$, respectively), which suggests that increased variability in those particles may also negatively impact milk protein %.

Group-level efficiency of test day milk yield, 4% FCM and ECM were 1.41 ± 0.16, 1.36 ± 0.13, and 1.46 ± 0.13 kg milk/kg DMI (mean ± SD), respectively (Chapter 2). Greater efficiency of test day milk yield was associated with increased variability in refusal rate and decreased variability in NE_L (Table 3.4). Refusal rate was not associated with efficiency of milk production (Chapter 2). Interestingly, there was an association between variability in refusal rate and milk yield (Table 3.4), but there was no association with DMI, meaning that greater milk yield was responsible for the increase in efficiency. As speculated earlier, some aspect of management style could explain this finding. Farms targeting lower feed wastage could be expected to have greater variability in refusal rate as they attempted to fine-tune feed amounts each day. Such managers were likely employing tactics to reduce economic costs associated with milk production, and might also have utilized more intensive practices to maximize milk yield. This finding could be due to some unmeasured variable, such as culling rate of low producing cows. Reduced variability in % long particles was associated with increased efficiency of test day milk production (Table 3.4). Less sorting against long particles was associated with greater efficiency of 4% FCM production (Chapter 2). From a biological perspective, less sorting against long particles would be conducive to higher rumen pH (DeVries et al., 2008) and, thus, more efficient utilization of nutrients. Similar associations were found for 4% FCM, with greater 4% FCM associated with increased variability in refusal rate ($P = 0.009$) and lower variability in NE_L content ($P = 0.006$) and a tendency to be associated with lower variability in % long particles in the fed ration ($P = 0.053$). Every 20 percentage point increase in refusal rate variability was associated with 2.7% and 2.3% increases in efficiency of test day milk production and 4% FCM, respectively. Every 5 percentage point increase in % long particle variability was associated with a decrease in efficiency of test day milk yield and 4% FCM by 2.6 and 1.6%, respectively. Every 0.5 percentage point increase in NE_L variability was associated with a decrease in efficiency for both test day milk yield and 4% FCM by 4.3 and 4.4%, respectively.

Variability in nutrient and DM composition of feed ingredients is inherent and efforts to minimize impact on TMR variability should be taken (Weiss and St-Pierre, 2009). There are a variety of tools available at the farm-level for monitoring diet consistency, including the Penn

State Particle Size Separator (Heinrichs and Kononoff, 2002). Regular monitoring of particle distributions, both within and between batches, can help to detect areas of concern to avoid losses in production. Proper education of TMR operators, regular feed sample analysis, use of premixes and reformulating the ration based on changes in DM can help to reduce diet variability (Stone, 2008). Our findings suggest that lower variability in ration composition may translate to improvements in herd productivity, but the specific methods used to reduce variability on our farms were not measured. Further research regarding TMR operator practices and bunk management will enhance understanding of factors influencing TMR variability on commercial dairy farms.

3.3.4 Factors associated with feed sorting

On average, cows sorted against long particles and for short and fine particle fractions (Chapter 2); average group-level sorting values were 97% for long particles and 101% for both short and fine particles. Less group-level sorting against long particles was associated with increased variability in refusal rate and reduced variability in % DM of the fed ration (Table 3.6). Past research has reported increased (Miller-Cushon and DeVries, 2009) or decreased (Leonardi et al., 2005) feed sorting as a result of water addition, depending on initial DM% of the ration. Our study found no association between DM content and feed sorting at a group-level (Chapter 2). Variability in DM content of individual ration ingredients is often cited as sources of variability in the consistency of TMR (Stone, 2008). Lower sorting in favor of fine particles was associated with increased variability in refusal rate and decreased variability in pef (Table 3.6). Lower sorting in favor of short particles was associated with increased variability in refusal rate and tended to be associated with increased variability in % long particles (Table 3.6). As mentioned previously, greater variability in refusal rate was experienced by herds with low feed refusals (<2%). Overall, increased variability in refusal rate and lower feed refusal is associated with less group-level sorting against long particles and for fine particles (Chapter 2). Efforts to minimize sorting for fine particles and against long particles may translate to improvements in milk yield and efficiency of milk production (Chapter 2). Thus, the present findings suggest that more frequent monitoring of particle size distribution and TMR dry matter content may promote more consistent nutrient consumption, which may translate into greater productivity.

3.4 Conclusions

Examination of the rations fed on 22 commercial free-stall farms suggests that the daily variability in TMR composition is considerable and more proactive measures to ensure that the ration delivered is representative of that formulated by the nutritionist may be warranted. Overall, day-to-day variability was lower than the variability observed between fed and formulated rations. However, variability in daily TMR composition had an impact on measures of group-average DMI, milk yield, and efficiency. For example, greater DMI, milk yield, and efficiency of milk production were associated with less variability in energy content of the ration. Lower variability in % long particles in the offered TMR was associated with greater milk yield and efficiency of milk production. Thus, measures to improve TMR composition, in relation to daily variability, may lead to improvements in DMI, milk yield and efficiency of group-housed dairy cows, ultimately increasing herd profitability.

3.5 Acknowledgments

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Table 3.1 Degree of agreement between fed and formulated TMR on 22 commercial dairy farms[1]

Variable (% of DM, unless otherwise noted)	Difference[2] between fed and formulated			Coefficient of Variation[3] (CV) between fed and formulated, %		
	Mean ± SD	Min	Max	Mean ± SD	Min	Max
CP	-0.40 ± 0. 67	-2.1	0.63	3.5 ± 2.0	1.0	10.4
ADF	0.66 ± 2.3	-2.9	4.9	7.2 ± 4.9	2.7	18.5
NDF	-0.55 ± 2.8	-4.7	5.3	6.5 ± 2.9	2.7	12.8
Ash	0.29 ± 1.0	-1.6	1.8	9.4 ± 5.9	1.9	20.3
Ca	0.076 ± 0.01	-0.074	0.24	9.7 ± 5.0	4.0	18.5
P	0.02 ± 0.03	-0.043	0.067	6.5 ± 2.5	3.0	10.7
Mg	0.02 ± 0.02	-0.023	0.067	6.7 ± 3.5	1.1	13.1
K	0.04 ± 0.11	-0.14	0.27	6.1 ± 2.5	2.7	11.9
Na	-0.01 ± 0.07	-0.084	0.16	11.6 ± 5.7	4.2	23.4
Fe (mg/kg)	170.3 ± 130.3	-22.7	355.1	52.4 ± 39.3	6.4	115.8
Mn (mg/kg)	7.6 ± 17.3	-17.0	32.1	18.4 ± 9.8	1.8	32.4
Zn (mg/kg)	14.3 ± 21.3	-19.8	57.2	17.5 ± 10.7	2.2	34.2
Cu (mg/kg)	6.2 ± 6.3	-5.1	16.0	22.4 ± 14.0	4.6	47.0
TDN	2.7 ± 1.8	-0.15	5.0	2.8 ± 1.40	1.0	4.8
NE_L (Mcal/ kg)	0.05 ± 0.05	-0.0047	0.18	2.6 ± 1.8	0.5	7.9
NFC	1.2 ± 3.4	-6.7	6.1	5.7 ± 3.4	1.9	11.7

[1]22 commercial dairy farms were visited for 7 consecutive days in summer and winter months; fresh TMR samples were collected daily for 7 consecutive days in each period, data were averaged for each farm and period.

[2]Difference = nutrient composition of fed ration – formulated nutrient composition; negative values indicate deficiencies compared to the TMR formulated by the nutritionist

[3]Coefficient of variation (CV) = (standard deviation between average value fed and formulated / average of value fed and formulated) × 100; expressed as a percentage

Table 3.2 Day-to-day variability in ration characteristics on 22 commercial dairy farms[1]

		Standard Deviation[2] (SD)			Coefficient of Variation[3] (CV), %		
Variable	Mean[4]	Mean ± SD	Min	Max	Mean ± SD	Min	Max
DM (%)	47.7	1.7 ± 0.8	0.74	3.8	3.6 ± 1.5	1.6	7.5
Refusal rate[5] (%)	3.5	2.2 ± 1.0	0.71	4.1	74.2 ± 26.0	28.8	126.9
% long particles	19.8	2.9 ± 0.8	0.86	4.2	16.1 ± 6.9	8.1	31.0
% medium particles	34.3	2.5 ± 0.9	1.3	5.0	7.7 ± 4.1	3.1	22.1
% short particles	35.5	2.1 ± 0.9	0.74	4.8	6.1 ± 3.2	1.9	17.3
% fine particles	10.5	1.3 ± 0.7	0.59	3.4	12.9 ± 4.5	5.0	21.6
pef[6] (%)	54.1	2.5 ± 0.9	1.1	5.3	4.7 ± 1.9	2.0	11.1
peNDF[7] (%)	17.0	1.3 ± 0.8	0.49	4.5	7.7 ± 3.9	2.7	22.5

[1] 22 commercial dairy farms were visited for 7 consecutive days in summer and winter months; fresh TMR samples were collected daily for 7 consecutive days in each period, data were averaged for each farm and period.

[2]Standard deviation (SD) over 7 d

[3]Coefficient of variation (CV) = (standard deviation over 7 d/ average value over 7 d) × 100

[4]Mean= average value delivered in the ration over 7 d

[5]Refusal rate = (DM refused/DM offered) × 100

[6]pef= physical effectiveness factor measured as the sum of the DM proportions retained on the top two Penn State particle sieves

[7]peNDF= physically effective NDF measured by multiplying pef by NDF (%DM) content of the ration

Table 3.3 Daily variation in TMR nutrient composition on 22 commercial dairy farms[1]

Variable (% of DM, unless otherwise noted)	Mean[4]	Standard Deviation[2] (SD)			Coefficient of Variation[3] (CV), %		
		Mean ± SD	Min	Max	Mean ± SD	Min	Max
CP	16.5	0.56 ± 0.2	0.24	1.1	3.5 ± 1.4	1.4	7.6
ADF	20.5	0.89 ± 0.24	0.59	1.5	4.4 ± 1.2	2.8	7.4
NDF	31.3	1.3 ± 0.8	0.65	2.6	4.1 ± 1.6	2.1	7.7
Ash	7.9	0.35 ± 0.15	0.13	0.87	4.7 ± 2.1	1.8	12.2
TDN	73.5	0.79 ± 0.26	0.27	1.5	1.1 ± 0.3	0.38	2.0
NE_L (mcal/kg)	1.7	0.02 ± 0.007	0.006	0.037	1.2 ± 0.4	0.35	2.1
NFC	41.2	1.5 ± 0.72	0.66	3.7	3.7 ± 1.8	1.6	8.8
Ca	0.92	0.07 ± 0.03	0.03	0.17	7.7 ± 4.2	3.1	22.1
P	0.42	0.018 ± 0.008	0.0064	0.048	4.1 ± 2.0	1.6	11.1
Mg	0.35	0.018 ± 0.008	0.008	0.036	5.2 ± 2.6	2.5	14.9
K	1.45	0.07 ± 0.03	0.029	0.12	4.7 ± 1.7	2.1	8.9
Na	0.41	0.04 ± 0.02	0.018	0.11	10.5 ± 5.9	4.3	30.4
Fe (mg/kg)	324	39.4 ± 12.2	19.6	65.9	12.5 ± 4.3	7.6	22.8
Mn (mg/kg)	72.2	7.8 ± 5.1	2.5	25.8	10.7 ± 6.3	4.2	30.0
Zn (mg/kg)	90.7	8.3 ± 3.8	2.7	18.8	9.2 ± 4.6	4.0	24.9
Cu (mg/kg)	25.7	2.4 ± 1.3	1.1	5.7	9.9 ± 5.6	5.4	26.5

[1]22 commercial dairy farms were visited for 7 consecutive days in summer and winter months; fresh TMR samples were collected daily for 7 consecutive days in each period, data were averaged for each farm and period.

[2]Standard deviation (SD) over 7 d

[3]Coefficient of variation (CV) = (standard deviation over 7 d/ average value over 7 d) × 100

[4]Mean= average value delivered in the ration over 7 d

Table 3.4 Final multivariable linear regression models for ration variability[1] factors associated with milk yield and efficiency of milk production[2]

Variable	Test day milk yield[4] (kg/d)			Efficiency of test day milk yield (kg milk[4]/kg DMI)		
	β[3]	SE	*P*-value	β[3]	SE	*P*-value
Intercept	40.69	2.83	<0.001	1.53	0.087	<0.001
CV[5] refusal rate	0.065	0.025	0.012	0.0019	0.0008	0.017
CV[5] long particles	-0.23	0.093	0.017	-0.0073	0.0029	0.015
CV[5] NE_L	-6.33	1.72	<0.001	-0.12	0.053	0.028

[1]Ration variability= coefficient of variation of day-to-day variability in the nutrient composition of the TMR

[2]Data was collected on 22 commercial dairy farms for 7 consecutive d during winter and summer periods

[3]β = estimated regression coefficient

[4]Milk yield collected from a coinciding DHI test (+/- 3 days of data collection period)

[5]Coefficient of variation (CV) = standard deviation over 7 d / average over 7 d; coefficients (β) are per 1 point increase in CV

Table 3.5 Final multivariable linear regression models for ration variability[1] factors associated with milk fat and protein[2]

Variable	Milk fat[5] %			Milk protein[5] (%)		
	β[3]	SE	*P*-value	β[3]	SE	*P*-value
Intercept	3.66	0.095	<0.001	3.44	0.074	<0.001
Period			0.0084			0.008
Winter	Ref[4]			Ref[4]		
Summer	-0.21	0.076		-0.14	0.049	
CV[6] long particles	0.012	0.0045	0.013	-	-	-
CV[6] short particles	-	-	-	0.015	0.0061	0.017
CV[6] fine particles	-	-	-	-0.0087	0.004	0.036
CV[6] CP	-	-	-	-0.031	0.012	0.014

[1]Ration variability= coefficient of variation of day-to-day variability in the nutrient composition of the TMR

[2]Data was collected on 22 commercial dairy farms for 7 consecutive days during winter and summer periods.

[3] β = estimated regression coefficient

[4] Ref = reference category

[5]Milk production parameters collected from a coinciding DHI test (+/- 3 days of data collection period)

[6]Coefficient of variation (CV) = standard deviation over 7 d / average over 7 d; coefficients (β) are per 1 point increase in CV

Table 3.6 Final multivariable linear regression models for ration variability[1] factors associated with sorting[2] of TMR particle fractions[3]

	Long particle sorting, %			Short particle sorting, %			Fine particle sorting, %		
Variable	β[4]	SE	*P*-value	β[4]	SE	*P*-value	β[4]	SE	*P*-value
Intercept	97.6	1.17	<0.001	102.2	0.35	<0.001	101.7	0.38	<0.001
Period									0.065
Winter	-	-	-	-	-	-	Ref[5]		
summer	-	-	-	-	-	-	-0.47	0.25	
CV[6] refusal rate	0.028	0.0092	0.0045	-0.01	0.0036	0.0073	-0.012	0.004	0.004
CV[6] long particles	-	-	-	-0.027	0.014	0.067	-	-	-
CV[6] DM	-0.28	0.13	0.039	-	-	-	-	-	-
CV[6] pef	-	-	-	-	-	-	0.092	0.042	0.036
CV[6] K	-0.28	0.14	0.042	-	-	-	-	-	-

[1]Ration variability= coefficient of variation of day-to-day variability in the nutrient composition of the TMR

[2]Sorting = 100 × (fraction DMI/ predicted fraction DMI) where fraction = long, medium, short or fine particles. Sorting values equal to 100% indicate no sorting, <100% indicate selective refusal (sorting against) and >100% indicate preferential consumption (sorting for). Data was collected on 22 commercial dairy farms for 7 consecutive days during winter and summer periods.

[3]Particle size determined by Penn State Particle Separator, which has a 19-mm screen (long), 8-mm screen (medium), 1.18-mm screen (short), and a pan (fine).

[4]β = estimated regression coefficient

[5]Ref = reference category

[6]Coefficient of variation (CV) = standard deviation over 7 d / average over 7 d; coefficients (β) are per 1 point increase in CV

CHAPTER 4: GENERAL DISCUSSION

4.1 IMPORTANT FINDINGS

A growing body of knowledge exists to suggest that feeding management factors can greatly impact feeding behaviour of group-housed cows and ultimately feed intake, health, and productivity. In Chapter 2, we sought to determine associations between housing and feeding management factors and measures of productivity of group-housed cows. We hypothesized that factors which improved feed access, including feeder design, feeding frequency, and feed bunk space, would improve DMI and milk yield, and reduce feed sorting. Our findings mostly supported this theory, as more frequent feed delivery (2x/d vs. 1x/d) was associated with greater DMI and milk yield and tended to be associated with less sorting against long particles. Provision of more feed bunk space was associated with greater milk fat percentage and lower group-average SCC. The use of headlocks, compared to post-and-rail feeder designs, was associated with higher milk protein yield (kg/d) and lower group-average SCC. We hypothesized that changes in the distribution of feeding and lying events as a result of increased competition at the feed bunk helped to explain associations with SCC. The delivery of fresh feed and exit from the milking parlour, two events which often coincide in commercial settings, greatly stimulate feed bunk attendance and can result in increased aggressive displacements from the feed bunk (DeVries and von Keyserlingk, 2005). Consequently, some cows may choose to lie down sooner following exit from the milking parlour to avoid social interactions and thus may be at increased risk of bacterial invasion from contact with the stall (DeVries et al., 2010). Our results emphasize the importance of sufficient bunk space to allow uniform opportunity to maximize DMI, greater milk fat percentage, and perhaps to contribute to lower SCC.

In Chapter 3, we investigated associations between day-to-day consistency in physical and chemical composition of TMR and measures of productivity. The average TMR fed did not accurately represent that formulated by the nutritionist. The average farm overfed Ca, P, Mg, K, ADF, NFC, NE_L and underfed CP, NDF and Na. Theoretically, underfeeding might not be problematic as nutritionists generally include a safety margin in their formulation to account for uncertainty in ingredient composition. Greater than 5% CV for the discrepancy between the fed and formulated ration was recorded for all nutrients with the exception of CP, TDN and NE_L. On average, day-to-day variability was greater for physical characteristics of the ration compared to nutritional composition. The greatest variability was observed for refusal rate, particle size distribution, and trace minerals. We found that delivery of a more consistent ration, in relation to % long particles and energy content was associated with greater milk yield and efficiency of milk production. Contrary to expectation, we found that increased variability in refusal rate was associated with less sorting against long particles, less sorting for short and fine particles, greater milk yield and greater efficiency of milk production. Given that we found no association between refusal rate and milk yield, it seems likely that some unmeasured management variable played a role in these curious associations. However, this finding is consistent with Chapter 2, where we found an association between lower refusal rates and less group-level sorting against long particles and for fine particles.

More consistent intake of the ration, as measured by less sorting, had implications for measures of group-average productivity. Specifically, less group-level sorting against the consumption of long particles was associated with greater 4% FCM and ECM, greater efficiency of 4% FCM and ECM and a tendency for increased milk and protein yield (Chapter 2). Not surprisingly, less sorting against the consumption of fine particles was associated with less efficient milk production (Chapter 2), as excess sorting for rapidly-digestible carbohydrates is a risk factor for a health reducing condition called sub-acute ruminal acidosis (DeVries et al., 2008), which can reduce rumen digestion efficiency (Stone, 2004). It could be argued that the level of sorting that we observed was minimal, but we found that every 2 percentage point reduction in sorting against long particles was associated with a loss of nearly 1.0 kg/d 4% FCM and 2% increase in efficiency of 4% FCM production. Additionally, every 2 percentage point increase in group-level sorting for fine particles was associated with a 6% reduction in efficiency of milk production. Overall, improvements in feed availability and access to a consistent ration (i.e similar day-to-day) may improve group-average milk yield, DMI and ultimately herd profitability.

4.2 Future Research

Studies of this nature are useful for establishing a broader understanding of findings previously reported in intensive, controlled studies. As such, our findings corroborated the hypothesis that feeding management factors, in addition to ration characteristics, influence feed sorting behaviour and feed intake of group-housed dairy cows. Several of our findings are interesting and implementation of study designs which account and control for potential sources of confounding variables would further enhance our understanding. For example, we found that the use of headlocks, compared to a post-and-rail feed barrier design, was associated with a 43% reduction in group-average SCC. We also found that increased feed bunk space was associated with a 13% reduction in SCC. It is unknown if these findings can be directly attributable to a decrease in feed bunk competition, or if they are due to unmeasured variables, such as stall and bedding type and management, or milking practices. Further research investigating the direct impact of feed bunk competition on udder health would be practical and of great interest for dairy producers.

One limitation of this study was the single day collection of milk production data. Milk production parameters were averaged across the group and used to determine associations with feeding behaviour measurements and ration characteristics over the week period. Repeated milk sampling, over the week period, might have enhanced our understanding of the relationship between ration variability between days and measures of productivity. Given this limitation of our study, the associations we observed may be underestimated. Nor could we make inferences about the effect of ration variability on the daily variation in milk yield, a measure which may have greater associations with health and productivity of dairy cows.

The dairy industry is greatly concerned with rising costs associated with feed and implementation of nutrient management systems. As such, it seems logical to pursue research regarding more precise feeding practices, to reduce nutrient wastage to the environment while ensuring that the nutritional needs of high-producing dairy cows are met. The findings from this study are useful as they quantified differences in ration composition and implications for productivity of group-housed cows, but questions regarding operator attitudes, individual ingredient variability and equipment maintenance cloud the findings we presented in Chapter 3. Our findings suggest that significant variation exists in TMR composition with respect to both how well it reflects ration formulation and consistency between days. Unfortunately, our data cannot be used to determine specific factors contributing to this variability. It would be useful to pinpoint where the variability is occurring, either due to ingredient variability or as result of mixing procedures, and to recommend practices to reduce this variability.

Our findings are specific to group-housed cows in a free-stall system. Management styles and practices vary between systems but it would be interesting to study these associations in both automatic milking systems (AMS) and tie-stall farms. AMS systems are becoming more prominent in the industry and research in this area is needed, especially given the variability in time budgets of cows in these milking systems.

Overall, this project enhanced our understanding of the relationship between feeding and housing management practices and measures of productivity. A large component influencing the adoption of these suggested management practices, including increased feeding frequency and feed bunk space, is the cost associated with increased materials and labour compared to gains associated with production and health. Thus, research regarding the cost-benefit analysis of these practices is needed to determine feasibility for dairy producers.

4.3 IMPLICATIONS

The strength and stability of the Canadian dairy industry is highly dependent on efficient production of milk with high compositional quality. The findings of this thesis are practical and are easily implemented as a means of improving both potential herd profitability and the health and welfare of group-housed dairy cows.

Our results consistently demonstrated the importance of implementing management practices to promote access to the feed bunk, despite the lack of associations with nutritional factors such as energy and fibre content of the ration. This is perhaps not surprising, given that the average ration delivered met the nutritional demands of a high producing dairy cow. More specifically, these findings emphasize the impact of adequate feed access on measures of group-average productivity, even when a ration of sufficient quality is delivered. Perhaps the most easily implemented practice which we found to improve intake and milk yield and to reduce sorting against long particles is increasing feeding frequency from once to twice daily. Interestingly, less sorting again long particles was also associated with improvements in efficiency of milk production. Increased bunk space was associated with greater milk fat percent and reduced group-average SCC. This finding suggests that efforts to reduce competition at the feed bunk can positively impact milk composition and quality and hence potentially increase herd profitability. Thus, with good feeding management (i.e. measures to minimize feed sorting), increased feed frequency and feed bunk space may improve health, productivity and welfare of group-housed cows.

Measures of productivity were also affected by daily variability in ration composition, especially changes in particle distribution and energy content. It is difficult to interpret the effect of variation and differences in ration composition on meeting the needs of group-housed dairy cows. Our results suggest that day-to-day variability can impact group-level production, however the proportion of cows experiencing nutrient deficiencies is unknown. Over-formulating is a common strategy used by nutritionists to increase certainty that the majority of cows are receiving the required amount of nutrients. However, overfeeding can have different implications for cows within a group. Overfeeding cows later in lactation can result in increased body condition score while overfeeding cows early in lactation may improve nutrient intakes given that consuming sufficient DM is a challenge. Perhaps, reducing variability in ration composition is of more importance for transition cows and subordinate cows that experience challenges maximizing DMI, especially in cases where the TMR formulated may not be designed for their specific nutrient requirements. These findings suggest that in addition to regular feed ingredient analysis, samples of TMR should be taken more frequently, especially during suspected changes in ingredient characteristics, to assess physical and chemical composition and increase certainty of adequate nutrient delivery. Additionally, attention should be directed to the degree of agreement between the formulated ration and that which is delivered.

Overall, the results of this thesis research suggest that herd-level management practices to promote feed access, such as increased feeding frequency and bunk space, may improve intake and promote more balanced nutrient intake and greater milk production. Further, measures to improve TMR composition, in relation to both the precision and accuracy, may lead to improvements in intake, milk yield and efficiency of group-housed dairy cows, ultimately increasing herd profitability.

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