Effects of overstocking at the feedbunk on the growth performance and sorting characteristics of a forage-based diet offered for ad libitum intake to replacement Holstein dairy heifers

W. K. Coblentz,^{*1} M. S. Akins,[†] N. M. Esser,[‡] R. K. Ogden,^{*} and S. L. Gelsinger[†]

^{*}USDA-ARS, US Dairy Forage Research Center, Marshfield, WI 54449

[†]Department of Dairy Science, University of Wisconsin, Madison 53706

[‡]University of Wisconsin Marshfield Agricultural Research Station, Marshfield 54449

ABSTRACT

Various forms of overcrowding are common in heifer-rearing operations. Our objectives for this study were to evaluate the effects of overstocking at the feedbunk (100, 133, 160, or 200% of capacity) on the growth performance, feedbunk sorting behaviors, and hygiene of 128 gravid Holstein heifers (475 ± 55.3 kg) consuming an alfalfa haylage and corn silage diet diluted with processed wheat straw at an inclusion rate of 25.2% (DM basis). In this study, heifers were overstocked only at the feedbunk, and not with respect to available freestalls or pen area. Heifers were blocked by weight, and subsequently assigned to 1 of 16 identical research pens. A total mixed ration was distributed at 1000 h daily for 91 d via a drive-through feed alley, with heifers allowed access to the feedbunk through head-locking feeding gates. Mean weights for the 4 blocks (32 heifers/block) were 406 ± 14.9 , 453 ± 15.3 , 493 ± 17.6 , and 548 ± 21.9 kg. Generally, nutrient intakes were not affected by stocking rate at the feedbunk; mean intakes of dry matter, neutral detergent fiber, and total digestible nutrients across all feedbunk stocking rates were 10.63, 5.19, and 6.29 kg/d, respectively. Overall, the effects of competition at the feedbunk on heifer growth performance were minor, with a collective average daily gain of 1.02 kg/d across all treatments. Only trends for linear increases in total weight gain and BCS were observed with overstocking at the feedbunk. Collectively, overstocked rates also exhibited a trend for better feed-to-gain ratio than pens stocked at 100% of feedbunk capacity (10.3 vs. 11.0 kg:kg). We observed solid evidence that heifers collectively sorted against large (>19 mm) particles, and also exhibited preference for short (>1.18 and <8 mm) and fine (<1.18 mm) feed particles; however, these responses were not affected

by feedbunk stocking rate. Additionally, heifers sorted against neutral detergent fiber as the concentration of neutral detergent fiber remaining in the feedbunk increased during the 24-h period following feeding; conversely, they preferred crude protein, as indicated by a decreasing concentration of this nutrient over time. Heifer hygiene was not affected by competition at the feedbunk. Under the experimental conditions established for this trial, overstocking at the feedbunk did not affect heifer growth performance, but it should not be practiced blindly without attention to other critical components of animal welfare.

Key words: Holstein dairy heifer, sorting behavior, feedbunk stocking rate

INTRODUCTION

Generally, management programs for dairy replacement heifers prioritize low economic and environmental costs while avoiding compromising their later performance as lactating cows (Hoffman et al., 2007). Diets for dairy heifers often are forage-based, especially those formulated for gravid animals that have reduced requirements for energy compared with younger heifers (NRC, 2001). Failure to adjust gravid-heifer diets to these reduced energy standards can result in over-conditioning, which may subsequently affect mammary development or first-lactation milk yield (Sejrsen et al., 1982; Hoffman et al., 1996; Lammers et al., 1999; Radcliff et al., 2000). Two general feeding strategies exist for limiting daily weight gains to acceptable ranges, thereby avoiding over-conditioning. These include (1) dilution of the ad libitum diet with low-energy forages, such as chopped straw, corn fodder, or perennial warm-season grasses (Hoffman et al., 1996; Greter et al., 2008; Coblentz et al., 2015), or (2) offering a diet of greater energy density but deliberately restricting the amount of feed available for consumption (limit feeding; Hoffman et al., 2007; Zanton and Heinrichs, 2007, 2008; Kruse et al., 2010). Positive characteristics

Received February 5, 2018.

Accepted April 25, 2018.

¹Corresponding author: wayne.coblentz@ars.usda.gov

of the limit-feeding strategy include greater residence time within the digestive tract, slower passage rate, greater diet digestibility, reduced fecal output, and improved overall feed efficiency (Loerch, 1990; Hoffman et al., 2007; Kruse et al., 2010). However, disadvantages of the limit-feeding strategy include increased vocalization and standing time by heifers (Hoffman et al., 2007). Perhaps more importantly, the combination of limit-feeding management coupled with inadequate bunk space raises concerns about adverse effects on animal welfare. This situation can increase variability of individual growth rates within the pen or group, but may not affect the overall mean growth rate for that group (Longenbach et al., 1999). Largely, within-pen variability results from increased social tension within the pen group, as well as from inadequate opportunities for some heifers to consume adequate nutrients, which is further compounded by the differences in social hierarchy within any group of heifers or cows (Longenbach et al., 1999; DeVries et al., 2004). Under such circumstances, smaller or less-aggressive heifers can be forced to accept the consequences of a subordinate social position (Longenbach et al., 1999).

Conversely, the potential advantages of dietary dilution with low-energy forages include formulation of diets with energy densities consistent with specific producer goals for growth, reducing feed costs, as well as permitting opportunities for natural foraging behaviors (Greter et al., 2008). Furthermore, if feed is always present in the bunk, the increased vocalization observed for limit-fed heifers noted by Hoffman et al. (2007) may be alleviated. Unfortunately, use of low-energy forages for dietary dilution also may allow heifers to exhibit aggressive sorting behaviors against less-desirable, low-energy dilutants or longer particles (Greter et al., 2008; Coblenz et al., 2015, 2018). Much as described for limit-feeding strategies, aggressive sorting behaviors have the potential to increase within-pen variability with respect to animal performance, particularly when confounded by overstocking coupled with the typical distribution of dominant and subordinate heifer personalities within the pen. If this assemblage of conditions occur, feeding behaviors can be altered and the diet consumed by various heifers within the pen may be unbalanced (DeVries and von Keyserlingk, 2009), with dominant animals discriminating against dilutant forages but submissive heifers forced to accept a greater percentage of these forages within their diet. To date, our efforts to determine under what management conditions these effects might be clearly illustrated have not been conclusive. Dilution of diets with eastern gamagrass [*Tripsacum dactyloides* (L.) L.] haylage, wheat straw, or corn fodder, which varied

widely with respect to sortability, could not be related to heifer growth performance (Coblenz et al., 2015). In a subsequent project (Coblenz et al., 2018) comparing well-processed or poorly processed wheat straw as dietary dilutants, increased within-pen variability for ADG was observed in response to pen overstocking, but this could not be linked to the respective sorting characteristics of the diets. The lack of clear association between diet sortability and within-pen variability with respect to heifer growth performance in these studies could be partially explained by close adherence to recommendations for including straw within heifer or lactating-cow diets (Shaver and Hoffman, 2010), which include proper processing (≤ 7.5 cm particle length), blending within a TMR mixer, and feeding daily to minimalorts. In addition, a relatively large area per heifer within each research pen (7.0 to 10.6 m²/heifer), may have contributed to the undetectable relationship between diet sortability and within-pen variability for ADG. Currently, many heifer-rearing operations overstock heifers with respect to available freestalls or lying area within bedded-pack systems; in addition, heifers also may be overstocked at the feedbunk, such that all heifers may not eat simultaneously. Our objectives for the current study were to evaluate the effects of overstocking at the feedbunk (100, 133, 160, or 200% of capacity) on the voluntary intake, growth performance, feedbunk sorting behaviors, and hygiene of 128 gravid Holstein heifers consuming an alfalfa haylage and corn silage diet diluted with processed wheat straw at an inclusion rate of 25.2% (DM basis). The hypothesis for our study was that overstocking at the feedbunk is likely to have only minimal effects on heifer growth performance if uncoupled from other major sources of stress or poor management, such as inadequate numbers of freestalls, inadequate pen area, or infrequent manure removal.

MATERIALS AND METHODS

Housing, Animals, and Diets

Animals. All animal-handling procedures for this experiment were approved by the Research Animal Resources Committee (RARC) of the University of Wisconsin-Madison (Protocol #A005189). The trial was conducted from mid-April through mid-July 2017 at the University of Wisconsin Marshfield Agricultural Research Station, located near Stratford, Wisconsin. One hundred twenty-eight gravid Holstein heifers (475 ± 55.3 kg) were blocked by weight and subsequently assigned to 1 of 16 identical research pens (4 pens/weight block, 4 pens/treatment). Mean weights ($\pm$ SD)

for the 4 blocks were 406 ± 14.9 , 453 ± 15.3 , 493 ± 17.6 , and 548 ± 21.9 kg, and each research pen was populated with 8 heifers. Approved standards of animal care allowed overstocking at the feedbunk, but not within freestalls; therefore, each heifer had continuous access to an available freestall. Given these approved standards of animal care, the effects of overcrowding at the feedbunk were effectively uncoupled from those of inadequate freestall numbers; these effects are frequently confounded and difficult to separate in many production and research facilities.

Housing. All 16 research pens were designed so that heifers had continuous access to fresh water. Each pen also had an automated mechanical alley-scraping system, 8 freestalls with foam-core mattresses covered with a shallow layer of dried organic solids, and 8 head-locking feeding gates positioned adjacent to the feed alley. The distance from the center of each head-locking feeding gate to the center of the next (adjacent) gate was 0.61 m. Overstocking at the feedbunk was created with plywood partitions attached to the head-locking gates, such that 0, 2, 3, or 4 gates were blocked from use, thereby creating feedbunk stocking rates of 100, 133, 160, and 200%, respectively, based on a consistent pen stocking rate of 8 heifers/pen. Thus, 8, 6, 5, or 4 head gates were available, respectively, or 0.61, 0.46, 0.38, or 0.31 m of linear bunk length per heifer. Head-locking feeding gates were set to allow continuous unrestricted access and regress from the feedbunk unless gates were occupied or blocked by another heifer. Each research pen was configured with a total area (including freestalls) of $84.5 \text{ m}^2/\text{pen}$ ($7.9 \times 10.7 \text{ m}$), which equates to $10.6 \text{ m}^2/\text{heifer}$. Freestalls within each pen were arranged in 2 rows of 4 stalls, with rows positioned in a head-to-head arrangement; research pens also contained a crossover alley to allow easy movement between rows of freestalls and easy access the feedbunk at all times. A thin layer ($\sim 2 \text{ cm}$ depth) of dried organic solids was spread over all stalls approximately every 10 d, and stalls and crossover alleys were raked or scraped daily to remove any feces or wet bedding soiled by urine. Alleys were scraped automatically every 2 h during daylight hours, but alley scraping was discontinued at night to prevent possible injury due to dark conditions in the barn.

Diet. Diet formulation and its related nutrient composition are shown in Table 1; the TMR diet was composed (DM basis) of alfalfa haylage (53.4%), corn silage (21.4%), and chopped wheat straw (25.2%). Wheat straw was processed through a 10-cm screen in a Haybuster model 1100 tub grinder (DuraTech Industries International Inc., Jamestown, ND) before blending with other dietary components for 3 min in a vertical TMR mixer (model 585; Meyer Manufacturing

Corp., Dorchester, WI) with the shear plates extracted to minimize additional processing. In addition, a mineral/vitamin package (see Table 1) was blended into the TMR at a rate of 158 g/heifer per day and delivered to the feedbunk with the TMR. The experimental diet was dispensed to each pen once daily at approximately 1000 h and then pushed back within easy reach of the heifers 5 times daily (1300, 1500, 1830, 1915, and 0600 h). A diet sample ($\sim 400 \text{ g}$) was obtained daily, sealed in a plastic freezer bag, stored at -20°C , and then composited by week for subsequent nutritive analysis. The experimental diet was offered for ad libitum intake throughout the 91-d study using the bunk management system described by Hoffman et al. (2008). Feedbunks were evaluated each morning during collection of orts, and managed to a bunk score of 2, where 0 = no feed particles remaining, 1 = only scattered feed particles remaining, 2 = numerous particles remaining, but the concrete floor still easily visible, or 3 = feed particles covering the entire floor of the bunk. This bunk management system provided an objective basis for adjusting daily feed allocations such that orts were minimized but voluntary intake was not restricted. From a practical perspective, a bunk score of 0 (no orts) triggered a 6% increase in the TMR allocated to that specific pen, calculated on an as fed basis. Similarly, bunk scores of 1 and 3 resulted in a 3% increase and decrease, respectively. Orts were collected from each pen at approximately 0830 h, weighed and mixed in a large plastic tub, and a $\sim 400\text{-g}$ subsample was placed in a sealed freezer bag. Orts subsamples were frozen at -20°C , and then composited by week. Subsamples ($\sim 400 \text{ g}$) of the weekly diet and ort composites were dried to constant weight under forced air ($\sim 96 \text{ h}$) at 55°C to determine mean weekly concentrations of DM within these composites.

Laboratory Analysis of Diets

Dried diet composites were ground through a 1-mm screen in a Thomas Model 4 Wiley mill (Thomas Scientific, Swedesboro, NJ). The University of Wisconsin Soil and Forage Laboratory (Marshfield, WI) then analyzed each diet sample for (1) ash, following combustion for 6 h in a muffle furnace at 500°C ; (2) OM, calculated as $100\% - \text{ash}$; (3) CP (AOAC International, 1998; official method 988.05); (4) Ca, K, and Mg by atomic absorption spectroscopy; (5) P (Schulte et al., 1987); (6) starch (model 2700D, Yellow Springs Instrument Co., Yellow Springs, OH); and (7) fat (AOAC, 1990; official method 920.29). Concentrations of NDF were determined by the methods of Goering and Van Soest (1970); heat-stable α -amylase and sodium sulfite were included within the NDF analysis. An in vitro determi-

nation of NDF digestibility (**NDFD**) was conducted in buffered rumen fluid for 48 h using procedures described previously (Coblentz et al., 2012; Kruse et al., 2010). Additional analyses (ADF and ADL) were performed as described by Goering and Van Soest (1970) during wk 2, 5, 9, and 13 of the trial without a preliminary digestion in neutral detergent. Concurrently, independent NDF and ADF residues were obtained following direct digestion in neutral and acid detergent solutions, respectively, and these fiber residues were then analyzed for residual CP (**NDICP** and **ADICP**, respectively) by the same Kjeldahl methodology as described for CP. For NDICP, the neutral detergent procedures included heat-stable α -amylase but not sodium sulfite, as recommended by Van Soest et al. (1991), to avoid excessive solubilization of CP from the residual forage fiber. The summative model (NRC, 2001) was used to calculate TDN, where truly digestible fiber was estimated from the 48-h in vitro determination of NDFD. Other measures of energy (ME, NE_G, and NE_M) were calculated per NRC (2001) recommendations.

The mean refusal rate during the 91-d trial was 2.70% of the feed offered (DM basis). Although this represents a very small percentage of the total feed offered, the inclusion of 25.2% wheat straw within the diet suggested that some sorting by heifers was likely. Therefore, orts were not assumed to be of the same composition as the diet, and a single composite ort sample was created for each research pen based on equal contributions from the weekly ort samples described previously. Trial-long ort composites were submitted to the University of Wisconsin Soil and Forage Laboratory for the identical analyses described for the diet samples. Subsequently, actual DM refusals and their associated nutrient composition were used within calculations to determine nutrient intakes for each individual research pen.

Feedbunk Assessment of Changes in Particle Size and Nutritive Value

Sampling Procedures. Sorting behaviors for the experimental diet were assessed by sampling feedbunks

Table 1. Ingredient composition of experimental diets and mean nutrient composition based on weekly analysis (14 wk)

Item, % of DM (unless noted)	TMR	Dietary component		
		Alfalfa haylage	Corn silage	Straw
Dietary forage composition ¹				
Alfalfa haylage	53.4	—	—	—
Corn silage	21.4	—	—	—
Straw	25.2	—	—	—
Nutrient composition ¹				
DM	48.0 ± 4.54	42.3 ± 6.91	43.5 ± 2.88	87.4 ± 2.03
CP	12.6 ± 1.55	19.4 ± 1.82	6.6 ± 0.66	3.9 ± 1.36
NDICP ²	2.09 ± 0.353	2.74 ± 0.491	1.56 ± 0.538	2.09 ± 0.578
ADICP ²	1.00 ± 0.233	1.28 ± 0.314	0.64 ± 0.225	1.00 ± 0.160
NDF ³	49.2 ± 3.95	41.7 ± 2.60	35.8 ± 1.51	75.6 ± 4.98
NDFD, % of NDF ⁴	52.1 ± 5.31	50.5 ± 5.22	55.0 ± 3.35	52.1 ± 6.57
ADF ²	34.6 ± 3.30	32.7 ± 2.15	20.8 ± 0.90	49.0 ± 4.01
ADL ²	5.04 ± 0.431	6.09 ± 0.686	2.09 ± 0.157	5.86 ± 0.542
Starch ²	11.1 ± 1.94	4.3 ± 1.29	37.4 ± 1.68	5.5 ± 4.57
Ether extract	2.46 ± 0.384	2.70 ± 0.373	2.74 ± 0.280	1.45 ± 0.154
Ash	9.6 ± 0.353	9.9 ± 0.75	3.5 ± 0.44	9.4 ± 1.41
P	0.30 ± 0.072	0.37 ± 0.089	0.24 ± 0.037	0.11 ± 0.030
Ca	0.69 ± 0.106	0.83 ± 0.187	0.23 ± 0.031	0.25 ± 0.039
K	2.05 ± 0.323	2.94 ± 0.498	0.73 ± 0.079	1.47 ± 0.355
Mg	0.23 ± 0.041	0.30 ± 0.074	0.09 ± 0.018	0.06 ± 0.012
Energy calculations ⁵				
TDN	59.0 ± 3.26	61.6 ± 2.66	72.8 ± 1.24	45.7 ± 4.84
ME, Mcal/kg	2.18 ± 0.145	2.29 ± 0.118	2.79 ± 0.055	1.59 ± 0.215
NE _M , Mcal/kg	1.32 ± 0.133	1.42 ± 0.107	1.86 ± 0.047	0.75 ± 0.216
NE _G , Mcal/kg	0.74 ± 0.121	0.84 ± 0.097	1.22 ± 0.041	0.21 ± 0.205

¹Mineral package contained 72.1% calcium carbonate, 16.5% salt, 3.35% sulfur, 2.95% selenium 1600, 1.50% vitamin A, 0.75% mineral oil, 0.71% copper sulfate, 0.69% vitamin E (50%), 0.64% zinc sulfate, 0.51% vitamin D, 0.09% iodine mix, 0.005% magnesium sulfate, 0.005% cobalt carbonate, 0.005% manganese oxide (60%), and 0.26% thiamine. Mineral package was blended into the total diet at a rate of 158 g/heifer per d and delivered within the TMR.

²Concentrations of ADF, ADL, starch, neutral detergent insoluble CP (NDICP), and acid detergent insoluble CP (ADICP) were determined for wk 2, 5, 9, and 13 of the trial.

³Neutral detergent solution contained both heat-stable α -amylase and sodium sulfite.

⁴Neutral detergent fiber digestibility (NDFD) determined following a 48-h digestion in buffered rumen fluid.

⁵Energy calculations based on NRC (2001).

over 3 evaluation periods, occurring during wk 5, 9, and 13 of the trial. Following discharge of the TMR at 1000 h each morning, bunks were subsequently sampled at 1300, 1600, 1900, 2200, 0100, or 0600 h. Each evaluation period lasted 6 d, thereby permitting each bunk to be sampled only once daily, which theoretically minimized disruption of eating and sorting behaviors. Sampling times for each pen were randomized across each 6-d evaluation period. Specific sampling procedures were similar to those described previously (Coblentz et al., 2015, 2018), where each feedbunk was divided in half, between the 4th and 5th head-locking gate. Within each half of the feedbunk, a scoop shovel was used at 1 random location to gather all the remaining TMR that intersected the shovel width between the feed alley and the concrete curb supporting the head-locking feeding gates. These large bulk samples for each pen were mixed thoroughly in a large plastic tub, and then a ~1,000-g subsample was placed in a 3.8-L freezer bag and subsequently frozen at -20°C . For each evaluation period, a similar sample of the original diet, as well as the orts collected from each pen, were obtained to further supplement particle size distribution analysis.

Particle Size Distribution and Nutritive Value.

The distribution of particle size groups for the experimental diet, bunk samples, and orts was determined with a Penn State particle separator using a 3-screen system (19, 8, and 1.18 mm; Kononoff et al., 2003). Forage particles were separated into 4 fractions based on retention on the 3 screens: (1) large, >19 mm; (2) medium, <19 and >8 mm; (3) short, <8 and >1.18 mm; and (4) fine, <1.18 mm. After separation, water was removed from each particle size group by drying overnight in a forced-air oven at 105°C . The concentration of each particle-size class was calculated as the dry weight within each size class divided by the total DM weight of all classes $\times 100\%$. Physically effective fiber (*pef*) was calculated as the percentage of total DM retained on the top 2 screens (19 and 8 mm) of the Penn State particle separator (Lammers et al., 1996). Sorting factors for each size class then were calculated as the concentration of each particle-size fraction divided by the concentration of the identical fraction in the original TMR. Therefore, a sorting factor equal to 1.00 suggests no change in concentration, as well as no preference by heifers; sorting factors >1.00 or <1.00 suggest discrimination or preference by heifers, respectively.

In addition to assessment of sorting behaviors on the basis of particle size, bunk samples also were evaluated for NDF by procedures outlined for an ANKOM200 Fiber Analyzer (Ankom Technology Corp., Macedon, NY). Similarly, concentrations of CP for each bunk

sample were determined by rapid combustion methodology (AOAC International, 1998, official method 990.03; model TruMac CN; Leco Corp., St. Joseph, MI). Sorting factors for NDF and CP then were calculated as described previously for various particle-size classes, where values <1.00 or >1.00 suggest preference or discrimination by heifers, respectively.

Some other studies (Leonardi and Armentano, 2003; Greter et al., 2008; DeVries and von Keyserlingk, 2009) have described sorting behaviors on the basis of actual DMI of each particle-size fraction expressed as a percentage of the predicted DMI of that fraction. This concept is greatly complicated within our pen-based research facility because such calculations would require continuous, and likely electronic, measurement of the feed remaining in each bunk, which is not feasible for 16 research pens. Furthermore, diets were offered through a feedbunk-management system designed to minimize orts while simultaneously allowing for maximum voluntary intake. As such, the mean 24-h refusal rate across the entire trial was 2.70% of DM offered, and sorting factors that include intake measurements within their calculations have little meaning, as actual and predicted DMI after 24 h are, for all practical purposes, identical.

Body Measurements

The initial BW for each heifer was calculated as the mean of BW measurements obtained on 3 consecutive days at the beginning of the trial using a cattle chute (Real Tuff, Clearbrook, MN) equipped with an electronic scale (Tru-Test Inc., Mineral Wells, TX); weights were obtained each morning, immediately before feed was delivered. Final heifer BW were obtained similarly, after 91 d. On 1 d during the initial and final 3-d weighing periods, each heifer was measured for heart girth, body length, hip height, and hip width (Esser et al., 2009). The body condition scoring system of Wildman et al. (1982) was used to assess heifer body condition at the beginning and end of the trial; heifers were scored (scale: 1 to 5) concurrently by 2 trained evaluators, where 1 = emaciated and 5 = obese, and increments of 0.5 units were applied to better describe the body condition of each heifer.

Hygiene Assessments

During each of the 3 bunk-sampling periods, all heifers were scored for hygiene of flanks and legs using the 4-point system of Cook and Reinemann (2007), where 1 = heifers free from manure and 4 = heifers covered with caked-on manure. Scores were taken by 2 trained technicians during each bunk-sampling period; there-

fore, each heifer was scored 6 times during the trial. The mean differences between evaluator assessments of hygiene were 0.3 ± 0.21 for flanks and 0.3 ± 0.20 for legs based on ($n = 12$) combinations of weight block and evaluation period.

Statistics

The trial was a randomized complete block design with 4 feedbunk stocking rates (100, 133, 160, and 200% of capacity), and 4 replications (blocks) that were assigned based on initial BW. In all cases, PROC MIXED of SAS (version 9.3, SAS Institute Inc., Cary, NC) was used to conduct the statistical analysis, and the research pen served as the experimental unit (St-Pierre, 2007), thereby permitting 15 total degrees of freedom. Experimental blocks or replications were considered to be a fixed, rather than a random variable, because heifers were blocked initially on the basis of BW. The experimental design was expanded to a split-plot for assessment of sorting factors with sampling times [1300, 1600, 1900, 2100, 0100, 0600, and 0830 h (orts)] included in the analysis. Orthogonal contrasts were used to test the effects of feedbunk stocking rate, including (1) 100% of capacity vs. overstocked (133, 160, and 200%); (2) linear effect of feedbunk stocking rate; and (3) quadratic effect of feedbunk stocking rate. To analyze sorting factors from bunk samples following feed distribution, additional orthogonal contrasts designed to test for linear and quadratic effects of time from feeding (1000 h) were used to describe the daily trends in particle-size or nutrient sorting factors. The PROC IML of SAS was used to adjust polynomial coefficients for uneven spacing of bunk-sampling times to maintain orthogonality; however, feedbunk stocking rates (100, 133, 160, and 200%) were considered to be equally spaced for purposes of this analysis. Statistical significance was declared at $P < 0.05$, with trends of interest described at $P < 0.10$.

RESULTS AND DISCUSSION

Diet Composition and Nutrient Intakes

The relatively high percentage of wheat straw (25.2%; Table 1) used in this diet formulation was necessitated by the elevated NDFD for the wheat straw (52.1% of NDF), which contributed to a relatively high energy estimate of 45.7% TDN. Although this estimate is comparable to that cited by NRC (2001; 47.5%), it was substantially more energy-dense than wheat straw used in other studies at this location (34.3 to 36.0%;

Coblentz et al., 2018), thereby reducing its effectiveness at diluting the energy density of the overall TMR.

The effects of overstocking at the feedbunk compared with stocking at 100% of capacity had no effect on the voluntary intake of any nutrient (Table 2; $P \geq 0.809$). We noted a linear trend ($P = 0.086$) for increased intake of ash with greater competition at the feedbunk, but the overall range of response was small (0.99 to 1.03 kg/d) and of questionable practical relevance. Neither linear nor quadratic responses ($P \geq 0.122$) to stocking rate at the feedbunk were detected for the voluntary intake of any other nutrient. Whereas animal density at the feedbunk had little effect on voluntary intake, collective intakes conformed to normal expectations for dairy heifers. Hoffman et al. (2008) has proposed that voluntary intake for heifers offered forage-based diets is limited by gut fill when 1.0% of BW is consumed as NDF. For this trial, this limitation appears to be quite accurate; based on an approximated midtrial mean heifer weight of 522 kg (Table 3), the overall mean NDF intake (5.19 kg/d) expressed on a percent of BW basis was 0.99%. Although other research has indicated that increased competition at the feedbunk has affected specific feeding behaviors, the DMI of rations offered on an ad libitum basis for dairy heifers (DeVries and von Keyserlingk, 2009), lactating cows (Olofsson, 1999), or transition cows (Proudfoot et al., 2009) often have been affected only minimally.

Heifer Growth and Performance

Based on the initial allocation of heifers, we found no differences in initial BW, frame measurements, or BCS in comparisons of all overstocked feedbunks with those stocked at 100% of capacity ($P \geq 0.202$), nor did we observe detectable linear ($P \geq 0.390$) or quadratic ($P \geq 0.129$) effects of feedbunk stocking rate (Table 3). Similarly, no effects describing competition at the feedbunk were detected ($P \geq 0.110$) for final BW, frame measurements, or BCS. After the 91-d feeding trial was completed, total weight gain tended to increase linearly ($P = 0.086$) with feedbunk competition, ranging from 88 to 97 kg; however, the associated ADG exhibited only a numerically linear ($P = 0.104$) trend, with a mean ADG of 1.02 kg/d across all treatments. The within-pen coefficient of variation (CV) for ADG exhibited a quadratic ($P = 0.042$) trend across feedbunk stocking rates, with greater within-pen variability at the 100 and 200% feedbunk stocking rates (22.1 and 21.0%, respectively) than observed with intermediate competition at the feedbunk. The CV for ADG ranged from 10.5 to 39.1% at the 100% stocking rate, 8.9 to 16.3% at 133%, 9.4 to 13.6% at 160%, and 12.3 to

Table 2. Effects of feedbunk stocking rate on nutrient intakes of Holstein dairy heifers

Item	Feedbunk stocking rate, ¹ %				SEM	Contrast ²		
	100	133	160	200		100% vs. overstocked	Linear	Quadratic
Nutrient intake								
DM, kg/d	10.63	10.36	10.74	10.77	0.111	0.944	0.142	0.205
OM, kg/d	9.62	9.37	9.72	9.74	0.101	0.939	0.147	0.211
CP, kg/d	1.34	1.31	1.35	1.36	0.015	0.999	0.159	0.261
NDF, kg/d	5.20	5.06	5.25	5.26	0.053	0.906	0.144	0.200
Digestible NDF, ³ kg/d	2.71	2.64	2.74	2.75	0.028	0.960	0.124	0.182
ADF, kg/d	3.67	3.57	3.71	3.72	0.038	0.956	0.133	0.213
Starch, kg/d	1.19	1.16	1.20	1.20	0.012	0.999	0.167	0.239
Ether extract, kg/d	0.26	0.26	0.27	0.27	0.004	0.999	0.368	0.497
Ash, kg/d	1.02	0.99	1.03	1.03	0.010	0.945	0.086	0.144
P, g/d	32.0	31.2	32.4	32.4	0.34	0.957	0.153	0.235
Ca, g/d	73.5	71.5	74.1	74.3	0.80	0.871	0.175	0.202
K, g/d	217.9	212.2	219.9	220.4	2.25	0.884	0.164	0.199
Mg, g/d	24.5	23.8	24.7	24.8	0.26	0.809	0.180	0.178
Energy intake								
TDN, ⁴ kg/d	6.29	6.14	6.36	6.38	0.065	0.983	0.128	0.222
ME, ⁴ Mcal/d	23.2	22.7	23.5	23.6	0.24	0.984	0.131	0.221
NE _G , ⁴ Mcal/d	8.0	7.8	8.1	8.1	0.08	0.894	0.122	0.243
NE _M , ⁴ Mcal/d	14.1	13.7	14.2	14.3	0.15	0.958	0.129	0.227

¹Feedbunk stocking rate: 100% = 8 heifers and 8 head-locking feeding gates; 133% = 8 heifers and 6 head-locking feeding gates; 160% = 8 heifers and 5 head-locking feeding gates; and 200% = 8 heifers and 4 head-locking feeding gates. All pens contained 8 freestalls.

²Contrasts: overstocked (133, 160, and 200%) vs. 100% (control); linear effect of feedbunk stocking rate; and quadratic effect of feedbunk stocking rate.

³Values based on NDF intakes, and a 48-h in vitro determination of NDF digestibility.

⁴Energy calculations based on NRC (2001).

Table 3. Effects of feedbunk stocking rate on body size and growth performance of Holstein replacement heifers

Item	Feedbunk stocking rate, ¹ %				SEM	Contrast ²		
	100	133	160	200		100% vs. all overstocked	Linear	Quadratic
Initial								
BW, kg	478	473	474	474	2.9	0.266	0.390	0.551
Length, cm	149	147	148	148	0.9	0.465	0.899	0.363
Hip width, cm	49	50	49	49	0.1	0.410	0.731	0.129
Hip height, cm	142	141	142	142	0.5	0.955	0.947	0.961
Heart girth, cm	187	187	188	187	0.8	0.562	0.718	0.547
BCS	3.49	3.34	3.35	3.37	0.087	0.202	0.392	0.341
Final								
BW, kg	566	567	567	571	3.3	0.508	0.309	0.724
Length, cm	156	158	157	157	1.1	0.387	0.783	0.451
Hip width, cm	53	54	53	54	0.3	0.884	0.936	0.498
Hip height, cm	143	144	145	143	0.6	0.478	0.899	0.110
Heart girth, cm	197	196	197	196	0.3	0.438	0.652	0.753
BCS	3.77	3.80	3.68	3.96	0.157	0.803	0.533	0.464
Growth								
Weight gain, kg	88	93	93	97	3.2	0.107	0.086	0.846
ADG, kg/d	0.97	1.02	1.02	1.07	0.036	0.134	0.104	0.892
CV, ³ %	22.1	13.4	11.2	21.0	3.9	0.157	0.750	0.042
Length, cm	8	11	9	9	1.3	0.216	0.741	0.207
Hip width, cm	4	4	4	4	0.3	0.685	0.950	0.224
Hip height, cm	2	3	3	2	0.5	0.405	0.815	0.068
Heart girth, cm	10	9	9	9	0.8	0.347	0.580	0.601
BCS	0.28	0.46	0.34	0.59	0.084	0.099	0.066	0.675
Feed:gain, kg:kg	11.0	10.1	10.5	10.2	0.31	0.078	0.168	0.443

¹Feedbunk stocking rate: 100% = 8 heifers and 8 head-locking feeding gates; 133% = 8 heifers and 6 head-locking feeding gates; 160% = 8 heifers and 5 head-locking feeding gates; and 200% = 8 heifers and 4 head-locking feeding gates. All pens contained 8 freestalls.

²Contrasts: overstocked (133, 160, and 200%) vs. 100% (control); linear effect of feedbunk stocking rate; and quadratic effect of feedbunk stocking rate.

³ANOVA using the coefficient of variation for ADG obtained from each research pen as the response variable.

39.6% at 200%. However, the quadratic effect of stocking rate was largely associated with greater variability in the heaviest weight block at the 100 (39.1%) and 200% (39.6%) stocking rates; the CV for all other pens was $\leq 19.9\%$. The change in BCS tended to be greater ($P = 0.099$) with overstocking compared with the 100% stocking rate (0.46 vs. 0.28 BCS units), and tended ($P = 0.066$) to increase linearly with competition. Based on the similar nutrient intakes across treatments (Table 2) and the linear trend for increased weight gain with greater feedbunk competition, we noted a trend ($P = 0.078$) for greater efficiency of gain from overstocking compared with the positive-control rate (100%; 10.3 vs. 11.0 kg:kg).

Overall, the effects of competition at the feedbunk on heifer growth were minor, with several tendencies suggesting weight gains and feed efficiency were marginally improved with competition for feed. Historically, these relationships have been difficult to establish, both with restricted and ad libitum feeding programs. With restricted or limit-feeding, previous studies generally have documented altered feeding behaviors in response to increased competition at the feedbunk (Keys et al., 1978; Keys and Pearson, 1980; Longenbach et al., 1999), but ADG has been reduced only with an extreme limitation of feedbunk space in 1 study (0.20 m/heifer; Keys et al., 1978). Longenbach et al. (1999) employed a more restricted limit-feeding approach, where feed was available only from 4.1 to 8.4 h daily, and found that within-pen variability was increased with competition, but the mean performance of the pen or group was not affected. With ad libitum feeding, Coblenz et al. (2018) reported reduced ADG in response to overstocking in a freestall/headlocking-feeding gate management system; however, all heifers maintained acceptable growth rates in the trial, and the effects of overstocking also interacted with the thoroughness with which straw was processed within the TMR. In that study, some increased within-pen variability of ADG was associated with overstocking. However, the sortability of the diet, as affected by straw processing, had no effect on within-pen variability in ADG when offered for ad libitum intake, but targeted for near-complete consumption within 24 h of feed delivery. In addition, Huzzey et al. (2006) has suggested that headlocking feeding gates may provide some protection against competitive interactions at the feedbunk compared with a post-and-rail barrier feeding system.

Changes in Particle Size Distribution and Nutritive Value

Particle Size Distribution. The main effect of feedbunk stocking rate ($P \geq 0.205$), as well as the

interaction of stocking rate with sampling time ($P \geq 0.364$), did not affect sorting for any particle size class; therefore, only main effect means for sampling time are presented (Table 4) and discussed. Large particles (>19 mm) initially comprised $14.2 \pm 5.05\%$ of the diet, but by 1300 h the calculated sorting factor had already increased to 1.21, indicating a 21% increase within 3 h of feed distribution. Sorting factors for large particles increased linearly ($P < 0.001$) across sampling times, reaching a maximum of 1.80 when orts were gathered at 0830 h the next morning. In contrast, the concentration of medium-sized particles (>8 , <19 mm) remained static during sampling times, exhibiting sorting factors with only a very limited range (0.95 to 1.01) that were explained by a quadratic trend ($P = 0.097$) over time. From a practical perspective, medium-sized particles comprised nearly half ($48.6 \pm 3.10\%$) the total diet, and these responses during sampling times indicate little evidence of preference or discrimination during the 24-h postdistribution period. Overall, temporal effects on concentrations of *pef* were similar to those discussed for large particles; sorting factors increased linearly ($P < 0.001$) over time without a detectable quadratic effect ($P = 0.789$). Although this response describes discriminatory behavior by heifers against *pef* particles, the maximum sorting factor (1.15), achieved during collection of orts, suggests the aggressive sorting against large particles was muted considerably by the static temporal response to medium-sized particles in the feedbunk. In contrast, concentrations of both short and fine (pan) particles declined linearly ($P \leq 0.012$) across sampling times, although heifer preference for fine particles was much stronger than that of short particles based on the minimum sorting factor (0.60 vs. 0.92). No quadratic effects were observed ($P \geq 0.380$) for sorting factors of either short or fine particles.

Generally, sorting behaviors exhibited by heifers were consistent with previous experiments conducted in our facilities (Coblenz et al., 2015, 2018), in which heifers exhibited discriminatory sorting behaviors against large and *pef* particles. However, overall responses for *pef* particles mask sharply contrasting responses for large and medium particles, where temporal heifer responses to medium particles are typically static or modestly preferential. As observed in other experiments in which diets were diluted with wheat straw, heifers exhibited preferences for short and fine particles, with the greatest reduction of sorting factors associated with fine particles. In these previous experiments (Coblenz et al., 2015, 2018), differences in sorting behaviors by heifers across diets could not be associated directly with heifer growth performance. This may be related to daily dietary allocations that are targeted for minimal refusals after 24 h, which is consistent with Wisconsin feeding

Table 4. Particle-size sorting behaviors for Holstein heifers offered a diet at 1000 h daily containing 25.2% wheat straw

Item	Concentration, ¹ % of DM	Sampling time, h (sorting factor ²)							Contrast, <i>P</i> > <i>F</i>	
		1300	1600	1900	2200	0100	0600	0830	SEM	Linear ³ Quadratic ³
Large (>19 mm)	14.2 ± 5.05	1.21	1.26	1.31	1.42	1.57	1.65	1.80	0.064	<0.001 0.292
Medium (>8 mm, <19 mm)	48.6 ± 3.10	0.98	0.98	0.97	1.01	0.98	0.97	0.95	0.025	0.192 0.097
Physically effective fiber (>8 mm) ⁴	62.9 ± 2.14	1.03	1.04	1.05	1.10	1.11	1.12	1.15	0.013	<0.001 0.789
Short (>1.18 mm, <8 mm)	18.2 ± 3.32	0.99	0.99	1.04	0.94	0.94	0.94	0.92	0.034	0.012 0.750
Fine (<1.18 mm)	18.9 ± 1.41	0.91	0.86	0.82	0.74	0.70	0.64	0.60	0.022	<0.001 0.380
NDF	52.0	1.01	1.04	1.04	1.04	1.06	1.06	1.09	0.011	<0.001 0.635
CP	12.9	1.02	1.00	0.99	1.00	0.99	0.97	0.95	0.011	<0.001 0.474

¹Initial concentration of particle-size classes or nutrients within the original TMR.
²Sorting factor was calculated as percentage of DM of any particle size or nutrient at the designated sampling time divided by the percentage of DM of that particle size or nutrient within the original TMR. Therefore, sorting factors <1 indicate preference, and sorting factors >1 indicate discrimination by heifers.
³Linear and quadratic effects of sampling time.
⁴DM retained on the top 2 (19- and 8-mm) screens of the Penn State particle separator.

recommendations for straw in TMR diets (Shaver and Hoffman, 2010).

Nutritive Value. Calculated sorting factors for NDF and CP were not affected by competition at the feedbunk ($P \geq 0.912$) or by the interaction of main effects ($P \geq 0.113$). As such, only the main effect of sampling time is summarized (Table 4) and discussed. Opposite trends were observed for NDF and CP, where heifers discriminated against NDF, but exhibited a preference for CP; sorting factors increased and decreased, respectively, with linear ($P < 0.001$) effects of time in both cases. No quadratic effect ($P \geq 0.474$) was observed for the temporal response of either nutrient-sorting factor. Logically, these responses are consistent with expectations based on particle size, where aggressive discrimination against large particles that were mostly composed of straw containing high concentrations of NDF could easily be associated with the increased concentrations of NDF retained in the feedbunk over time. Conversely, accumulation of large particles likely would depress concentrations of CP in the feedbunk, as the concentration of CP within the straw was only 3.9% (Table 1). Generally, trends for discrimination against ADL and NDF, as well as preference for CP and TDN, have been observed previously for TMR diets including straw and were exacerbated with poor straw processing (Coblentz et al., 2018).

General Comments on Feedbunk Competition

Visual observation of heifers indicated that competitive activity for feed was initiated with disbursement of the TMR and continued for approximately 1 h following feed distribution, from 1000 to 1100 h daily. After 1100 h, we observed little evidence of continued competition at the feedbunk throughout the remainder of the day. Observed displacements of heifers from the feedbunk were most often initiated by an aggressor butting the rear underside of the body near the undeveloped udder, with the attack coming from the side or between the hind legs of the heifer eating at the feedbunk. Alternatively, heifers also were displaced by crowding, in which an aggressor forced herself between 2 heifers eating until one or both were displaced from the feeder. Generally, the actions of aggressors did not target the head, likely because the headlocking feeding gates provided some protection in this respect (Huzzey et al., 2006), and such attacks had to be initiated by another heifer already eating.

The relationship between competition for feed and displacements from the feedbunk has been well-documented, although a wide variety of feeding systems have been employed. These include headlocking gates adjacent to a feed alley, post-and-rail barriers, stand-

Table 5. Hygiene scores¹ for legs and flanks as affected by feedbunk stocking rate for Holstein dairy heifers

Item	Legs	Legs CV ² %	Flanks	Flanks CV ² %
Feedbunk stocking rate ³				
100%	1.7	13.9	1.3	22.3
133%	1.7	13.2	1.4	28.9
160%	1.7	12.6	1.2	17.5
200%	1.7	10.9	1.3	19.7
SEM	0.04	1.80	0.05	2.13
Contrasts, ⁴ $P > F$				
100% vs. all overstocked	0.526	0.432	0.505	0.924
Linear	0.160	0.258	0.136	0.076
Quadratic	0.712	0.786	0.938	0.327

¹Hygiene scores assessed on a scale of 1 = no manure and 4 = caked on manure (Cook and Reinemann, 2007).

²Coefficient of variation for hygiene scores from each pen used as a response variable and subjected to ANOVA.

³Feedbunk stocking rate: 100% = 8 heifers and 8 head-locking feeding gates; 133% = 8 heifers and 6 head-locking feeding gates; 160% = 8 heifers and 5 head-locking feeding gates; and 200% = 8 heifers and 4 head-locking feeding gates. All pens contained 8 freestalls.

⁴Contrasts: overstocked (133, 160, and 200%) vs. 100% (control); linear effect of feedbunk stocking rate; and quadratic effect of feedbunk stocking rate.

alone group feeders with intakes determined manually, or electronically monitored feed bins capable of discerning the individual voluntary intake of 1 or more cows or heifers, depending on the intensity of competition desired. In all cases (Olofsson, 1999; DeVries et al., 2004; Huzzey et al., 2006; González et al., 2008; Proudfoot et al., 2009; Greter et al., 2011; Lobeck-Luchterhand et al., 2015), increased competition for feed has been positively associated with displacements from the feedbunk. Although this association has been consistent across trials, the wide range of research objectives and facility designs used in these studies somewhat complicate interpretation. Generally, most previous studies have prioritized assessment of multiple behavioral traits using a relatively limited number of heifers or cows; in contrast, Lobeck-Luchterhand et al. (2015) conducted evaluations with a greater production-scale emphasis. Within the present experiment, it should be emphasized that increased competition for feed in a production-styled system did not result in injury to any of the heifers in the trial; however, this remains a potential concern. Regardless, the effects of competition for feed did not have negative effects on heifer growth performance.

Hygiene

Hygiene scores (Table 5) were not affected by feedbunk stocking rate in assessments of legs (mean = 1.7; $P \geq 0.160$) or flanks (mean = 1.3; $P \geq 0.136$); more importantly, these scores indicate relatively good cleanliness that could not be related to competition by heifers at the feedbunk. Furthermore, we consider these

scores to be supportive documentation of high standards of general animal care and that heifers did not lose their footing or fall to the floor during competition at the feedbunk. By comparison, Cook and Reinemann (2007) reported a median of 59% of cows scoring either 3 or 4 for lower legs in a study of 46 Wisconsin dairy herds, and a median of 47% within a subset of the 25% of herds exhibiting the best hygiene. A median of 15% of cows scoring 3 or 4 was reported for flanks. Our within-pen CV for legs and flanks was largely unaffected by competition at the feedbunk. We detected no contrasts for the within-pen CV of legs (mean = 12.7; $P \geq 0.258$), and only a linear trend was observed for CV of flanks (mean = 22.1; $P \geq 0.076$).

In a previous study (Coblentz et al., 2018), overcrowding at the feedbunk confounded with inadequate numbers of available freestalls resulted in increased within-pen variability with respect to hygiene scores. Results of the present study, conducted in the same facilities, suggest variability with respect to hygiene is likely related more closely to overcrowding in freestalls than at the feedbunk. For this trial, other common forms of stress, such as extreme crowding for lying space in bedded-pack barns, insufficient freestall numbers, infrequent cleaning of pens, irregular or inconsistent refreshing of bedding, inconsistent animal size or weight within the pen, as well as poor feeding management, were largely nonfactors in our results. If present, these types of stresses are likely to interact with competition at the feedbunk to affect heifer growth performance and compromise animal well-being. It should not be implied from these results that other aspects of animal care can be ignored or compromised without consequence.

CONCLUSIONS

Competition for feed did not negatively affect heifer growth performance, sorting behaviors, or hygiene. This confirms our hypothesis; however, it must be emphasized that high standards of animal care with respect to pen area, available freestalls, manure removal, and so on were employed throughout the study. Whereas overstocking at the feedbunk did not affect heifer growth performance, it should not be inferred that it can be practiced blindly without close attention to other critical components of animal welfare.

ACKNOWLEDGMENTS

Mention of trade names or commercial products in this article is solely for the purpose of providing specific information, and does not imply either recommendation or endorsement by the USDA. Research supported through appropriated USDA-ARS CRIS funds (Project #5090-12630-005-00D).

REFERENCES

- Association of Official Analytical Chemists (AOAC). 1990. *Official Methods of Analysis*. 15th ed. Assoc. Off. Anal. Chem., Arlington, VA.
- AOAC International. 1998. *Official Methods of Analysis*. 16th ed. AOAC Int., Arlington, VA.
- Coblentz, W. K., M. S. Akins, N. M. Esser, R. K. Ogden, and S. L. Gelsinger. 2018. Effects of straw processing and pen overstocking on the growth performance and sorting characteristics of diets offered to replacement Holstein dairy heifers. *J. Dairy Sci.* 101:1074–1087. <https://doi.org/10.3168/jds.2017-13199>.
- Coblentz, W. K., N. M. Esser, P. C. Hoffman, and M. S. Akins. 2015. Growth performance and sorting characteristics of corn silage-alfalfa haylage diets with or without forage dilution offered to replacement Holstein dairy heifers. *J. Dairy Sci.* 98:8018–8034.
- Coblentz, W. K., P. C. Hoffman, N. M. Esser, and M. G. Bertram. 2012. Using eastern gamagrass to construct diets that limit intake and caloric density for dairy heifers. *J. Dairy Sci.* 95:6057–6071.
- Cook, N. B., and D. J. Reinemann. 2007. A toolbox for assessing cow, udder, and teat hygiene. Pages 31–43 in *Proc. 46th Annual Mtg. Natl. Mastitis Council*, San Antonio, TX. Natl. Mastitis Council, Madison, WI.
- DeVries, T. J., and M. A. G. von Keyserlingk. 2009. Competition for feed affects the feeding behavior of growing dairy heifers. *J. Dairy Sci.* 92:3922–3929.
- DeVries, T. J., M. A. G. von Keyserlingk, and D. M. Weary. 2004. Effect of feeding space on the inter-cow distance, aggression, and feeding behavior of free-stall housed lactating dairy cows. *J. Dairy Sci.* 87:1432–1438.
- Esser, N. M., P. C. Hoffman, W. K. Coblentz, M. W. Orth, and K. A. Weigel. 2009. The effect of dietary phosphorus on bone development in dairy heifers. *J. Dairy Sci.* 92:1741–1749.
- Goering, H. K., and P. J. Van Soest. 1970. *Forage Fiber Analyses (Apparatus, Reagents, Procedures, and Some Applications)*. Agric. Handbook No. 379. USDA-ARS, Washington, DC.
- González, L. A., A. Ferret, X. Manteca, J. L. Ruiz-de-la-Torre, S. Calsamiglia, M. Devant, and A. Bach. 2008. Performance, behavior, and welfare, of Friesian heifers housed in pens with two, four, and eight individuals per concentrate feeding place. *J. Anim. Sci.* 86:1446–1458.
- Greter, A. M., T. J. DeVries, and M. A. G. von Keyserlingk. 2008. Nutrient intake and feeding behavior of growing dairy heifers: Effects of dietary dilution. *J. Dairy Sci.* 91:2786–2795.
- Greter, A. M., B. L. Kitts, and T. J. DeVries. 2011. Limit-feeding dairy heifers: Effect of feed bunk space and provision of a low-nutritive feedstuff. *J. Dairy Sci.* 94:3124–3129.
- Hoffman, P. C., N. M. Brehm, S. G. Price, and A. Prill-Adams. 1996. Effect of accelerated postpubertal growth and early calving on lactation performance of primiparous Holstein heifers. *J. Dairy Sci.* 79:2024–2031.
- Hoffman, P. C., C. R. Simson, and M. Wattiaux. 2007. Limit feeding of gravid Holstein heifers: Effect on growth, manure nutrient excretion, and subsequent early lactation performance. *J. Dairy Sci.* 90:946–954.
- Hoffman, P. C., K. A. Weigel, and R. M. Wernberg. 2008. Evaluation of equations to predict dry matter intake of dairy heifers. *J. Dairy Sci.* 91:3699–3709.
- Huzzey, J. M., T. J. DeVries, P. Valois, and M. A. G. von Keyserlingk. 2006. Stocking density and feed barrier design affect the feeding and social behavior of dairy cattle. *J. Dairy Sci.* 89:126–133.
- Keys, J. E., and R. E. Pearson. 1980. Stocking density effect on weight gain of yearling Holstein heifers in freestall and loose housing. *J. Dairy Sci.* 63:483–486.
- Keys, J. E., R. E. Pearson, and P. D. Thompson. 1978. Effect of feedbunk stocking density on weight gains and feeding behavior of yearling Holstein steers. *J. Dairy Sci.* 61:448–454.
- Kononoff, P. J., A. J. Heinrichs, and D. R. Buckmaster. 2003. Modifications of Penn State forage and total mixed ration particle separator and the effects of moisture content on measurements. *J. Dairy Sci.* 86:1858–1863.
- Kruse, K. A., D. K. Combs, N. M. Esser, W. K. Coblentz, and P. C. Hoffman. 2010. Evaluation of potential carryover effects associated with limit feeding gravid Holstein heifers. *J. Dairy Sci.* 93:5374–5384.
- Lammers, B. P., D. R. Buckmaster, and A. J. Heinrichs. 1996. A simple method for the analysis of particle sizes of forages and total mixed rations. *J. Dairy Sci.* 79:922–928.
- Lammers, B. P., A. J. Heinrichs, and R. S. Kensing. 1999. The effects of accelerated growth rates and estrogen implants in prepubertal Holstein heifers on estimates of mammary development. *J. Dairy Sci.* 82:1753–1764.
- Leonardi, C., and L. E. Armentano. 2003. Effect of quantity, quality, and length of alfalfa hay on selective consumption by dairy cows. *J. Dairy Sci.* 86:557–564.
- Lobeck-Luchterhand, K. M., P. R. B. Silva, R. C. Chebel, and M. I. Endres. 2015. Effect of stocking density on social, feeding, and lying behavior of prepartum dairy animals. *J. Dairy Sci.* 98:240–249.
- Loerch, S. C. 1990. Effects of feeding growing cattle high-concentrate diets at a restricted intake on feedlot performance. *J. Anim. Sci.* 68:3086–3095.
- Longenbach, J. I., A. J. Heinrichs, and R. E. Graves. 1999. Feed bunk length requirements for Holstein dairy heifers. *J. Dairy Sci.* 82:99–109.
- NRC. 2001. *Nutrient Requirements of Dairy Cattle*. 7th rev. ed. Natl. Acad. Press, Washington, DC.
- Olofsson, J. 1999. Competition for total mixed diets fed for ad libitum intake using one or four cows per feeding station. *J. Dairy Sci.* 82:69–79.
- Proudfoot, K. L., D. M. Veira, D. M. Weary, and M. A. G. von Keyserlingk. 2009. Competition at the feed bunk changes the feeding, standing, and social behavior of transition dairy cows. *J. Dairy Sci.* 92:3116–3123.
- Radcliff, R. P., M. J. Vandehaar, L. T. Chapin, T. E. Pilbeam, D. K. Beede, E. P. Stainisiewski, and H. A. Tucker. 2000. Effects of diet and injection of bovine somatotropin on prepubertal growth and first-lactation milk yields of Holstein cows. *J. Dairy Sci.* 83:23–29.

- Schulte, E. E., J. B. Peters, and P. R. Hodgson. 1987. Wisconsin procedures for soil testing, plant analysis and feed and forage analysis. Dept. Soil Sci. Bull. No. 6. University of Wisconsin, Madison, WI.
- Sejrsen, K., J. T. Huber, H. A. Tucker, and R. M. Akers. 1982. Influence of nutrition on mammary development in pre- and postpubertal heifers. *J. Dairy Sci.* 65:793–800.
- Shaver, R. D., and P. C. Hoffman. 2010. Use of straw in dairy cattle diets. *Focus on Forage* Vol.12:No. 2. University of Wisconsin Extension, Madison.
- St-Pierre, N. R. 2007. Design and analysis of pen studies in the animal sciences. *J. Dairy Sci.* 90(Suppl. 1):E87–E89.
- Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *J. Dairy Sci.* 74:3583–3597.
- Wildman, E. E., G. M. Jones, P. E. Wagner, R. L. Boman, H. F. Troutt Jr., and T. N. Lesch. 1982. A dairy cow body condition scoring system and its relationship to selected production characteristics. *J. Dairy Sci.* 65:495–501.
- Zanton, G. I., and A. J. Heinrichs. 2007. The effects of controlled feeding of a high-forage or high-concentrate ration on heifer growth and first lactation milk production. *J. Dairy Sci.* 90:3388–3396.
- Zanton, G. I., and A. J. Heinrichs. 2008. Rumen digestion and nutritional efficiency of dairy heifers limit-fed a high forage ration to four levels of dry matter intake. *J. Dairy Sci.* 91:3579–3588.