Comparison of diet digestibility, rumen fermentation, rumen rate of passage, and feed efficiency in dairy heifers fed ad-libitum versus precision diets with low and high quality forages

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ABSTRACT
This study compared ad-libitum versus precision-fed diets with 2 forages and different levels of neutral detergent fibre (NDF) to evaluate rumen fermentation, diet digestibility, feed efficiency, and digesta passage rate. Eight Holstein heifers (18.4 ± 0.6 mo) fitted with rumen cannulas were used in a 2-factor, split-plot, Latin square design. The whole-plot factor was feeding system with ad-libitum or precision feeding and 4 heifers in each plot. The subplot included 2 factors: forage quality and NDF content. Diets were formulated to provide the same energy level (0.234 Mcal of ME intake/kg of empty body weight0.75) for precision-fed heifers and 110% of previous intake for ad-libitum-fed heifers. Forage quality and NDF level affected dry matter intake. Mean rumen pH was lower for ad-libitum than for precision-fed diets and volatile fatty acid concentrations were affected principally by forage quality. Ad-libitum diets showed faster rate of passage for solid feeds and fluids, increased rate of digestion, and shorter retention time in the rumen. In addition, both high NDF and low quality forage modified rumen passage rate and shortened retention time. Feed efficiency was improved in precision-fed heifers.

Introduction
Reducing costs associated with raising heifers is one of the important topics in present day dairy farming. Heifers are conventionally fed with high amounts of low quality forages in an attempt to reduce feed costs. However, it is clear that improving feed efficiency in heifers is one of the best ways to improve growth performance and reduce feed costs (Lascano and Heinrichs 2009; Zanton and Heinrichs 2009b; Pino and Heinrichs 2016). Feed efficiency can be improved by reducing DMI and increasing nutrient density (Hoffman et al. 2007; Zanton and Heinrichs 2009b). Diets that reduce DMI, condense energy, and use highly digestible feedstuffs are often referred to as limit-fed or precision-fed diets. Reducing DMI in growing heifers increases nutrient efficiency due to improved nutrient digestion and a reduction in the metabolic expenses of nutrient absorption and oxidative metabolism for maintenance (Reynolds et al. 1991), thus more energy is available to be used in growth (Moody et al. 2007; Zanton and Heinrichs 2009b; Lascano and Heinrichs 2011). Precision-fed diets provide enough nutrients for adequate, economical growth without affecting future performance and milk production (Zanton and Heinrichs 2009b).

In precision-fed diets, high amounts of concentrate used to produce an energy dense diet do not have dramatic impacts on rumen pH due to the limited amounts of DM fed, and rumen fermentation is positively affected by having greater fibre digestion and larger rumen bacterial populations (Moody et al. 2007; Lascano and Heinrichs 2009; Pino and Heinrichs 2016). While it is true that precision-fed diets improve feed efficiency, there is a limited amount of data directly comparing ad-libitum with precision-fed diets for heifers. Using corn silage as the sole forage source, Moody et al. (2007) and Lascano et al. (2009) demonstrated that heifers were more efficient with low forage-to-concentrate ratios (F:C) compared to high F:C. These studies also included some evaluation of the effect of NDF on digestibility and efficiency. Zanton and Heinrichs (2009a) determined that N retention and efficiency decreased as DMI increased and that heifers had improved N retention with precision-fed diets.

Limited studies have evaluated rate of passage in precision-fed dairy heifers; however, it is reported that as forage increases in the diet, retention time in the rumen was greater and rate of passage reduced (Colucci et al. 1990; Lascano and Heinrichs 2009). Slower passage rate increases retention time in the rumen, with microbial growth and feedstuff degradation increasing, leading to greater digestion by the animals (Mertens and Loften 1980; Colucci et al. 1990). Also, in cows the effect of NDF on intake and rate of passage has been demonstrated such that higher intake and lower NDF in the rumen stimulate turnover rate (Dado and Allen 1995). Oba and Allen (2000) and Mertens (2009) also showed that low NDF diets create faster rates of passage; however, this

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information is from lactating cows and has not been validated in precision-fed dairy heifers.

In general, there are many factors that could affect digestibility, including forage quality, NDF level in the diet, and overall diet digestibility. Previous studies from our lab have observed that changes in DMI, and proportions of NDF and concentrates in precision-fed diets can modify rumen fermentation and total tract nutrient digestibility (Moody et al. 2007; Ding et al. 2015; Pino and Heinrichs 2016). However, limited information is available comparing traditional ad libitum feeding to precision-fed diets. We hypothesized that reducing forage quality, either by feeding hay instead of corn silage or by reducing diet NDF, would reduce diet digestibility and increase rate of passage. Furthermore, we hypothesized that lower forage quality would affect feed efficiency when heifers were fed ad libitum diets to a greater extent than when offered precision-fed diets. Therefore, the objective of this study was to evaluate effects and possible interactions of DMI, forage quality, and diet NDF level on feed efficiency, rumen fermentation, and rate of passage.

Materials and methods

Animals, treatments, and experimental design

All procedures involving the use of animals were approved by the Pennsylvania State University Institutional Animal Care and Use Committee (#46266). Eight Holstein heifers (18.4 ± 0.6 mo of age and 457.2 ± 27.29 kg BW) fitted with a 10-cm silicone rumen cannula (Kehl, SP, Brazil) were used in a 2-factor, split-plot, Latin square design with 19-d periods (14 d of adaptation and 5 d of sampling). The whole-plot factor was feeding type with ad libitum or precision feeding and 4 heifers in each plot. The subplot included 2 factors: forage quality and NDF content.

Heifers were kept in tie-stalls 10 d before the experiment began to adapt them to the facility and management and then were randomly assigned to treatments. Heifers were weighed weekly, and BW was determined by the average of 2 measurements taken 1 and 4 h before feeding on the same day. The amount of TMR offered during the experiment was adjusted weekly based on BW to allow an average of 1.0 to 1.1 kg/d of ADG. Targeted ADG was determined based on starting BW and a goal of heifers reaching 85% of the herd’s mature BW at calving. Heifers were housed in individual tie-stalls in a mechanically ventilated barn with free access to water in the stalls. The animals were released to a paved exercise pen for 3.5 h/d on non-sampling days.

Diets

Experimental diets were mixed in a Calan Super Data Ranger (American Calan, Northwood, NH) every 5 d. This ensured that the ration offered on the 5 sampling d had the same composition each d. Grain mixes were prepared before each period as a single mix, and corn silage DM was measured in a microwave (Pino and Heinrichs 2014) before diet mixing. Water was added to the grass hay diets to provide the same moisture as the corn silage diets and to help with the mixing process. The different diets were kept in closed nylon bags to avoid oxygenation and stored in a cooler at 6°C until fed.

Diets were formulated to provide low or high quality forage (rye grass or corn silage respectively) and low or high values of NDF (39.8 or 48.0% NDF on DM basis, accomplished by replacing ground corn with cottonseed hulls). Diets provided a 60:40 F:C. Predicted DMI was calculated based on energy intake for precision-fed diets, and grain mixes were formulated to provide the same energy level (0.234 Mcal of ME intake/kg of empty BW0.75). All diets were balanced to contain 12.5% CP. For ad libitum diets energy intake was determined based on the requirements in NRC (2001) for heifers gaining 1 kg/d. All diets are presented in Table 1. Ad libitum heifers were fed at 110% of expected intake, and diets were fed daily as TMR at noon. The time with feed in the feedbunk (h to consume the whole ration) was recorded daily during sampling d, and orts were weighed, dried, and saved for further analysis.

Sample collection and analysis

Feedstuff samples were collected before every period, and TMR samples were collected on the day of diet mixing. Feedstuff and TMR samples were dried in a forced-air oven at 55°C for 48 h to measure DM, and then ground through a 1-mm screen (Wiley mill, Arthur H. Thomas, Philadelphia, PA) for further analysis. Diet particle size was analyzed (Penn State Particle Separator with 19-, 8-, and 4-mm sieves) on the day diets were mixed, using a composite of the 5 d/treatment.

Urine was collected from d 15 to 19 using the modified cup collector (Lasc ano et al. 2010) to avoid fecal contamination. During the sampling period total urine was weighed and recorded daily after feeding. Only total urine production was measured; its composition was not analyzed. In addition, feces were collected and stored in airtight containers. After feeding, daily feces were mixed, and a 1-kg subsample was saved at 4°C to be composited at the end of each period. Then the subsample was dried in a forced-air oven at 55°C for 72 h and ground through a 1-mm screen (Wiley mill, Arthur H. Thomas, Philadelphia, PA) until analysis.

The composited and dried feeds, fecal, and orts samples were analyzed for DM, ash, and CP (AOAC, 2000 methods 934.01, 942.05, and 968.06 respectively); NDF and ADF were analyzed for each feed and fecal sample using the method described by Van Soest et al. (1991). Analysis of NDF included use of heat-stable α-amylase (Sigma Chemical Co., St. Louis, MO) and sodium sulfite (Van Soest et al. 1991), using an Ankom® fibre analyzer (Ankom Technology Corp., Fairport, NY). Diet CP was calculated from feed CP that were analyzed by Cumberland Valley Analytical Services, Inc. (Maugansville, MD). Starch was determined by methods adapted from Hall (2008) using previously ground samples and Hazyme enzyme (Centerchem, Norwalk, CT). Metabolizable energy intake was estimated for each heifer within each period using the observed OM intake × 0.04409 × 0.82 as described in NRC (2001).

All Rumen contents were totally evacuated manually through the cannula at 1000 h (2 h before feeding) on d 14 and at 1500 h (3 h after feeding) on d 19 for ad libitum diets and 1600 h (4 h after feeding) for precision-fed heifers. The time between feeding and rumen evacuation was different
for ad-libitum and precision diets to ensure we evacuated the rumen near the time of maximum capacity. Ad-libitum-fed heifers stopped eating 2 to 3 h after feeding, and precision-fed heifers consumed the whole meal between 3 and 4 h after feeding. After the evacuation on d 19, rumen digesta was switched between heifers to assist in adaptation for the next period. Mass and volume were determined for ruminal contents (3 kg) were evacuated, mixed and strained through a 0.28-mm breglass mesh screen (New York Wire, Mt. Wolf, PA) to obtain ruminal fluid. Ruminal fluid pH was recorded with a pH metre (model M90, Corning Inc., Corning, NY), and then a 5-mL sub-sample was mixed with 1 mL 0.6% sodium chloride and 1 mL 0.6% Optigena (OptiGen Research, Champaign, IL) and stored at −20°C for later GC analysis of VFA concentrations (Yang and Varga 1989). Another 50-mL sub-sample of ruminal fluid was stored at −20°C and then sent to SDK Laboratories, Inc. (Hutchinson, KS) for Cr quantification using microwave acid digestion and an atomic absorption spectrophotometer.

Chromium concentrations were used to determine Cr dilution rates from the rumen as described by Bartocci et al. (1997). Liquid passage rate (Kf) was calculated as the slope of the semilog plot of Cr concentration against time. The equation used to describe the disappearance curve was:

\[ Y = a e^{-Kf} \]

where: \( Y \) = marker concentration at \( t \) time; \( a \) = marker concentration at zero time; \( Kf \) = dilution constant of marker. Rumen fluid volume (L) was estimated by dividing the amount of \( Cr \) locations in the rumen (dorsal, ventral, anterior, caudal, and central) at 0, 0.5, 1, 2, 4, 6, 8, 12, 16, 20, 22, and 24 h relative to feeding time. Rumen contents were mixed and strained through a 0.28-mm fibreglass mesh screen (New York Wire, Mt. Wolf, PA) to obtain ruminal fluid. Ruminal fluid pH was recorded with a pH metre (model M90, Corning Inc., Corning, NY), and then a 5-mL sub-sample was mixed with 1 mL 0.6% sodium chloride and 1 mL 0.6% Optigena (OptiGen Research, Champaign, IL) and stored at −20°C for later GC analysis of VFA concentrations (Yang and Varga 1989). Another 50-mL sub-sample of ruminal fluid was stored at −20°C and then sent to SDK Laboratories, Inc. (Hutchinson, KS) for Cr quantification using microwave acid digestion and an atomic absorption spectrophotometer.

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### Table 1. Ingredients and chemical composition of diets with high (HFQ) or low forage quality (LFQ) and high (HNDF) or low NDF (LNDF).

| Ingredients, % DM | Ad-libitum diets | Precision feed diets |
|------------------|------------------|----------------------|
| Grass hay        | 60.00            | 60.00                |
| Corn silage      | –                | 60.00                |
| Wheat middling   | 4.00             | 2.00                 |
| Ground corn      | 25.40            | 36.90                |
| Cotton hulls     | 7.55             | –                    |
| Canola meal      | –                | 33.00                |
| Optigena         | 0.35             | 0.40                 |
| Sodium chloride  | 1.00             | 1.00                 |
| Mineral mix      | 1.70             | 1.70                 |
| Chemical composition |
| DM, %            | 71.09            | 71.22                |
| CP, % DM         | 12.71            | 12.76                |
| RDP, % CP        | 21.22            | 18.21                |
| NDF, % DM        | 47.68            | 40.54                |
| ADF, % DM        | 29.45            | 23.67                |
| Hemicellulose, %  | 18.23            | 16.87                |
| Starch, % DM     | 18.32            | 25.30                |
| peNDF, %         | 37.45            | 29.55                |
| Ash, % DM        | 6.42             | 6.66                 |
| ME, Mcal/kg DM   | 2.26             | 2.46                 |
| ME, Mcal/kg BW   | 0.23             | 0.24                 |
| Ca, % DM         | 0.53             | 0.52                 |
| P, % DM          | 0.26             | 0.25                 |
| Na, % DM         | 0.53             | 0.52                 |
| K, % DM          | 1.44             | 1.43                 |
| S, % DM          | 0.19             | 0.21                 |
| Particle size    | >19.0 mm         | 55.95                |
| >19.0–8.0 mm     | 6.67             | 10.36                |
| >8.0–4.0 mm      | 10.12            | 6.58                 |
| <4.0 mm          | 21.46            | 27.10                |

### Notes:
- Slow-release urea (Alltech, Nicholasville, KY, USA) contains 96.8% DM and 269.9% CP.
- Mineral mix, (US Feeds Inc., Eldora, IA) contains 94.28% DM, 11.65% CP, 1.7% soluble CP, 5.46% RUP, 8.29% ADF, 19.2% NDF, 5.5% fat, 12.4% Ca, 0.36% P, 2.63% Mg, 0.44% K, 0.39% |S|, 1,628.87 mg/kg Mn, 542.71 mg/kg ||Cu, 1,639 mg/kg Zn, 232.94 mg/kg Fe, 9.90 mg/kg Se, 9.2 mg/kg Co, 22.2 mg/kg I, 70.748 IU/g vitamin A, 17.637 IU/g vitamin D, and 1.230 IU/g vitamin E.
- Hemicellulose = NDF – ADF.
- peNDF = physically effective NDF.
- ME: Calculated as TDN × 0.04409 × 0.82.
- ME: Mcal/kg metabolic BW.
- Measured with Penn State Particle Separator using 19-, 8-, and 4-mm sieves.
by the antilog of the intercept ($a$) at time zero. The flow rate (L/h) was calculated by multiplying the volume of ruminal fluid by the outflow rate ($k_f$).

The proportions of iNDF in the pooled samples were determined by incubating 5 g of the dried and ground diets for 12 d in the rumen using ANKOM bags (pore size 50 ± 15 µm). Bags were placed in warm distilled water before being inserted in the rumen. Each heifer incubated 3 samples of the same diet that she was eating at that time. Potential extent of NDF digestion (PED = 100 × pdNDF / (pdNDF + iNDF)) was calculated (Grant 1994), where pdNDF is the potentially digestible NDF as proportion of the initial DM (NDF – iNDF).

**Statistical analysis**

All statistical analyses were conducted in SAS (Version 9.4, SAS Institute Inc., Cary, NC) using the MIXED procedure. Dependent variables were analyzed as a 2-factor, split-plot, Latin square design with the diet (ad-libitum or precision feeding) as the whole plot and forage quality and NDF content as the subplot factors. Heifers were considered experimental units because they were individually fed and intake and ADG were known. All denominator degrees of freedom for F-tests were calculated according to Kenward and Roger (1997).

The model used was:

$$Y_{ijkl} = \mu + T_l + F_j + L_m + N_{k(i)} + TF_{ij} + TL_{im} + FL_{jm} + TFL_{ijm} + P_i + e_{ijkl}$$

where $Y_{ijkl}$ is a continuous dependent response variable; $\mu$ is the overall mean; $T_l$ is the fixed effect of diet treatment ($l = 1,2$); $F_j$ is the fixed effect of forage quality ($j = 1,2$); $L_m$ is the fixed effect of NDF level ($m = 1,2$); $N_{k(i)}$ is the random effect of heifer within the diet treatment; $TF_{ij}$ is the interaction of diet and forage quality; $TL_{im}$ is the interaction of diet and NDF level; $FL_{jm}$ is the interaction of forage quality and NDF level; $TFL_{ijm}$ is the three-way interaction between type of diet, forage quality, and NDF level; $P_i$ is the period effect and $e_{ijkl}$ is the residual error. $TFL_{ijm}$ was not significant and was removed from the final model. Repeated measures with heifer by period as the subject were used to analyze rumen pH and VFA using the SP(POW) covariance structure for time intervals not evenly spaced. Time and time by treatment interaction were included in the model for rumen pH and VFA. Interactions with time are stated in the text if significant. Residual variances were assumed normally distributed, and all data is presented as LSM. $P$-values for treatments and interactions will be presented in tables. Residuals over ± 3 SD were considered outliers and were removed prior to analysis. Differences were declared significant at $P \leq 0.05$ and tendencies at $P \leq 0.10$ for main effects.

**Results and discussion**

Ingredients, chemical composition, and particle size of the diets are presented in Table 1. The proportions of ingredients between ad-libitum and precision diets were not equal by design, because the objective was to make precision feeding diets more digestible and reduce DMI. Canola meal was used to balance CP content for all the treatments (12.8% CP). Neutral detergent fibre was formulated with 2 levels for ad-libitum and precision feeding (39.8 or 48.0% NDF). Ad-libitum diets were formulated to provide enough ME to gain 1 kg/d according to NRC (2001). On the other hand, precision-fed diets were formulated to provide 0.23 Mcal ME/kg of empty BW$^{0.75}$, which allowed for an ADG close to 1 kg/d (Zanton and Heinrichs 2009a). Body weight, intakes, and feed efficiency are presented in Table 2. Heifers fed ad-libitum diets consumed 2 kg more DM than precision-fed heifers ($P \leq 0.01$). Furthermore, heifers fed ad-libitum diets consumed 1.86 kg more DM when the diet contained high forage quality (HFQ) than low forage quality (LFQ; $P \leq 0.01$) and only 0.43 kg more DM in the case of high NDF (HNDF; $P \leq 0.01$). Precision-fed diets resulted in greater feed efficiency than ad-libitum diets (feed to gain ratio of 8.59 vs. 10.45; $P \leq 0.01$) due to the increased DMI in ad-libitum diets and similar ADG between the types of diet. Feed efficiency was also greater for heifers that consumed low NDF (LNDF) compared to HNDF ($P \leq 0.01$). Furthermore, an interaction between diet and forage quality affected feed efficiency ($P = 0.03$). Precision-fed diets with HFQ exhibited greater feed efficiency. Greater feed efficiency is one of the principal objectives resulting from precision feeding programmes (Hoffman et al. 2007; Zanton and Heinrichs 2008) that makes it an effective tool to reduce heifer raising costs (Zanton and Heinrichs 2009b).

Heifers fed ad-libitum diets, HFQ, and HNDF had greater intakes of NDF, iNDF, pdNDF, and ADF when compared to heifers fed precision diets, LFQ, and LNDF. In addition, interactions between forage quality and NDF level affected iNDF and ADF intake ($P = 0.04$ and $P = 0.01$, respectively). Heifers that ate LFQ and HNDF had greater iNDF and ADF intake. Starch intake was increased in ad-libitum diets ($P = 0.02$), HFQ ($P \leq 0.01$), and LNDF ($P \leq 0.01$) when compared to heifers fed precision diets, LFQ, and HNDF, respectively. There was also an interaction between type of diet and NDF level ($P = 0.02$). Metabolizable energy intake was only affected by forage quality, with LFQ diets containing more ME than HFQ diets ($P = 0.01$).

While precision-fed diets often lead to improved feed efficiency and reduced DMI (Moody et al. 2007; Zanton and Heinrichs 2008; Lascano and Heinrichs 2011; Pino and Heinrichs 2016), this is the first study directly comparing precision-fed with ad-libitum diets.

Rumen pH, time with feed in the feedbunk, and VFA concentrations are presented in Table 3 and Figures 1 and 2. Mean pH was lower for ad-libitum vs. precision-fed diets (6.37 vs. 6.59; $P \leq 0.01$) as well as LNDF vs. HNDF ($P = 0.04$). In general, rumen pH for ad-libitum-fed heifers was lower and more consistent throughout the day (Figure 1) than for the precision-fed heifers, reflecting both increased intakes and a more even eating pattern throughout the day for the ad-libitum heifers. Maximum pH was only affected by type of diet, where precision-fed diets reached a higher pH than ad-libitum diets (7.28 vs. 6.83; $P \leq 0.01$). On the other hand, minimum pH was lower for precision-fed diets and HFQ ($P = 0.05$ and $P \leq 0.01$ respectively) and showed a tendency to be lower for LNDF ($P = 0.06$). An interaction was observed between type of diet and forage quality, where precision feeding diets with HFQ
Table 2. Body weight, intakes, and feed efficiency in ad-libitum (A-L) vs. precision-fed (P-F) heifer diets with high (HFQ) or low forage quality (LFQ) and high (HNDF) or low NDF (LNDF).

| Item                        | Diet        | LFQ-HNDF | LFQ-LNDF | HFQ-HNDF | HFQ-LNDF | SE | Diet | Forage quality | NDF level | D × F | D × NDF | F × NDF |
|-----------------------------|-------------|----------|----------|----------|----------|-----|------|----------------|-----------|-------|---------|---------|
| BW, kg<sup>a</sup>         | A-L         | 512.9    | 504.4    | 511.0    | 510.2    | 12.70 | 0.30 | 0.85           | 0.15      | 0.59  | 0.83    | 0.27    |
| DMI, kg/d                  | A-L         | 11.0     | 10.3     | 12.6     | 12.4     | 0.49  | ≤0.01| ≤0.01          | ≤0.01     | 0.07  | 0.21    | 0.85    |
| DMI, % BW                  | A-L         | 2.14     | 2.04     | 2.46     | 2.44     | 0.08  | ≤0.01| ≤0.01          | ≤0.01     | 0.02  | 0.07    | 0.17    |
| ADG, kg/d                  | A-L         | 5.22     | 4.17     | 6.08     | 4.82     | 0.24  | 0.01 | ≤0.01          | ≤0.01     | 0.08  | 0.54    | 0.24    |
| ADG, % BW                  | A-L         | 3.63     | 2.54     | 3.50     | 3.54     | 0.16  | 0.01 | ≤0.01          | ≤0.01     | 0.02  | 0.17    | 0.96    |
| NDF, kg/d                  | A-L         | 9.81     | 9.13     | 10.56    | 11.14    | 0.62  | ≤0.01| ≤0.01          | ≤0.01     | 0.03  | 0.91    | 0.25    |
| iNDF, kg/d<sup>b</sup>     | A-L         | 1.50     | 1.14     | 1.82     | 1.21     | 0.08  | ≤0.01| ≤0.01          | ≤0.01     | 0.27  | 0.77    | 0.04    |
| PdNDF, kg/d<sup>c</sup>    | A-L         | 3.26     | 2.56     | 3.54     | 2.63     | 0.17  | 0.02 | ≤0.01          | ≤0.01     | 0.12  | 0.93    | 0.01    |
| ADF, kg/d                  | A-L         | 3.23     | 2.43     | 4.27     | 2.86     | 0.17  | 0.02 | ≤0.01          | ≤0.01     | 0.12  | 0.93    | 0.01    |
| Hemicellulose, kg/d<sup>d</sup> | A-L   | 1.99     | 1.74     | 1.81     | 1.96     | 0.09  | 0.02 | ≤0.01          | ≤0.01     | 0.02  | 0.15    | 0.03    |
| Starch, kg/d<sup>e</sup>   | A-L         | 2.00     | 2.60     | 2.76     | 2.76     | 0.13  | 0.02 | ≤0.01          | ≤0.01     | 0.12  | 0.96    | 0.03    |
| CP, kg/d                   | A-L         | 1.53     | 1.31     | 1.40     | 1.27     | 0.07  | 0.43 | ≤0.01          | ≤0.01     | 0.29  | 0.57    | 0.02    |
| ME, Mcal/d<sup>f</sup>     | A-L         | 24.58    | 24.00    | 23.66    | 22.95    | 1.10  | 0.48 | ≤0.01          | ≤0.01     | 0.26  | 0.14    | 0.75    |

<sup>a</sup>Average BW for the experiment.
<sup>b</sup>Kg of DMI / kg of ADG.
<sup>c</sup>iNDF = indigestible NDF.
<sup>d</sup>PdNDF = potentially digestible NDF.
<sup>e</sup>Hemicellulose = NDF – ADF.
<sup>f</sup>ME: calculated as TDN × 0.04409 × 0.82.

Table 3. Rumen pH, eating time, rate of eating, and VFA in ad-libitum (A-L) vs. precision-fed (P-F) heifer diets with high (HFQ) or low forage quality (LFQ) and high (HNDF) or low NDF (LNDF).

| Item                        | Diet        | LFQ-HNDF | LFQ-LNDF | HFQ-HNDF | HFQ-LNDF | SE | Diet | Forage quality | NDF level | D × F | D × NDF | F × NDF |
|-----------------------------|-------------|----------|----------|----------|----------|-----|------|----------------|-----------|-------|---------|---------|
| Daily pH                    |             |          |          |          |          |     |      |                |           |       |         |         |
| Mean                        | A-L         | 6.41     | 6.33     | 6.41     | 6.33     | 0.06 | ≤0.01| 0.60           | 0.04      | 0.58  | 0.95    | 0.76    |
| Max                         | P-F         | 6.65     | 6.59     | 6.63     | 6.52     | 0.09 | ≤0.01| 0.84           | 0.69      | 0.16  | 0.69    | 0.68    |
| Min                         | A-L         | 5.97     | 5.68     | 5.83     | 5.58     | 0.12 | 0.05 | ≤0.01          | 0.06      | ≤0.01 | 0.19    | 0.77    |
| Min                         | P-F         | 5.98     | 5.9      | 5.25     | 5.23     | 0.12 | 0.05 | ≤0.01          | 0.06      | ≤0.01 | 0.19    | 0.77    |
| Time with feed, h/d<sup>g</sup> | A-L | 24.0     | 24.0     | 24.0     | 24.0     | 0.66 | ≤0.01| 0.17           | 0.93      | 0.17  | 0.93    | 0.90    |
| Rate of eating, kg/h        | A-L         | 3.7      | 3.5      | 4.9      | 4.9      | 0.43 | 0.43 | ≤0.01          | 0.62      | 0.29  | 0.58    | 0.84    |
| Total VFA (mM)              | A-L         | 90.88    | 117.98   | 111.03   | 110.07   | 7.02 | 0.05 | 0.96           | 0.28      | 0.21  | 0.13    | 0.32    |

<sup>g</sup>Time with feed in the feed bunk.
had the lowest minimum pH \( (P \leq 0.01) \). This is likely due to precision-fed heifers consuming their ration rapidly, resulting in greater amounts of fermentation at one time and a drop in pH (Table 3; Figure 1). Heifers fed diets with HFQ had lower rumen pH than LFQ \( (P \leq 0.01) \), likely due to higher starch amounts in corn silage compared to grass hay.

The time heifers spent consuming a meal was less for precision-fed heifers (4.2 vs. 24 h after feeding; \( P \leq 0.01 \)), due to precision-fed heifers consuming less DMI. This also resulted in precision-fed heifers having a greater eating rate than heifers fed ad-libitum (2.66 kg/h vs. 0.481 kg/h; \( P \leq 0.01 \)). The time spent consuming rations by precision-fed heifers was similar to previous studies (Pino and Heinrichs 2016).

Total VFA concentrations were increased for ad-libitum diets \( (P = 0.05; \text{Table 3}) \), as would be expected from higher DMI. Production of VFA peaked for precision-fed diets between 4 and 6 h after feeding (Figure 1), similar to previous observations (Lascano and Heinrichs 2009; Pino and Heinrichs 2016). In general, ad-libitum diets did not show a peak, and the total VFA concentration was homogeneous throughout the day with the exception of LFQ-LNDF that showed a peak 6 h after feeding (Figure 1).

The type of diet did not affect acetate proportion. However, LFQ diets containing grass hay had higher acetate proportions compared with HFQ diets with corn silage \( (P \leq 0.01) \), as did diets with HNDF compared with LNDF \( (P \leq 0.01) \). In addition, we can deduce that the low rumen pH showed by the HFQ diets in the precision-fed heifers 4 to 8 h after feeding reduced rumen acetate proportion for those diets (Figure 2), likely due to changes in fibre digestion during this time (Calsamiglia et al. 2008). Also, there was a tendency for an interaction between forage quality and NDF level that affected rumen acetate levels \( (P = 0.10) \).

Diets with LNDF had greater butyrate concentrations than HNDF diets \( (P \leq 0.01) \). Ad-libitum LFQ diets had increased butyrate compared to ad-libitum HFQ diets, and the opposite was

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**Figure 1.** Rumen pH and total VFA production over 24 h in ad-libitum (left column) vs. precision-fed (right column) heifer diets with high (HFQ) or low forage quality (LFQ) and high (HNDF) or low NDF (LNDF). ♦ with solid line indicates HFQ-HNDF; ■ with dotted line indicates HFQ-LNDF; ▲ with dashed line indicates LFQ-HNDF; ● with dash-dot line indicates LFQ-LNDF.

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true of precision diets, with precision-HFQ resulting in greater butyrate production than precision-LFQ diets. The high proportion of wheat middlings in this diet would result in fast fermentation, which could explain the spike in butyrate. This also likely explains the observed drop in pH. With the exception of precision feeding HFQ-LNDF, the other diets had similar

Figure 2. Fermentation end products over 24 h in ad-libitum (left column) vs. precision-fed (right column) heifer diets with high (HFQ) or low forage quality (LFQ) and high (HNDF) or low NDF (LNDF). ♦ with solid line indicates HFQ-HNDF; ● with dotted line indicates HFQ-LNDF; ▲ with dashed line indicates LFQ-HNDF; ○ with dash-dot line indicates LFQ-LNDF.
values to previous studies with the same F:C and alfalfa as a forage source (Pino and Heinrichs 2016).

Acetate-to-propionate ratio of LFQ diets was greater than HFQ diets due to the higher acetate proportion in the rumen from digestion of grass hay instead of corn silage. There was no interaction between NDF level and time, suggesting that the different amounts of NDF did not affect the rate of NDF digestion.

Overall, rumen fermentation was affected by type of diet, forage quality, and NDF level. The effect of VFA on pH over time is clear and explains most of the changes in pH in the rumen. This information is in agreement with Calsamiglia et al. (2008), who stated that changes in fermentation are explained by changes in microbial populations.

Excretion parameters are presented in Table 4. Wet feces production was not affected by treatments, but dry feces weights were higher with HNDF diets compared to LNDF diets (P = 0.02). Hoffman et al. (2007) reported a decrease in dry feces for heifers consuming reduced DMI. However, the current study showed only a tendency (P = 0.10) for precision-fed heifers to excrete less dry feces. Urine was increased for precision feeding diets. It has been observed in our previous experiments that precision-fed dairy heifers in a confined environment may consume more water, leading to increased urine production.

Apparent total tract nutrient digestibility is presented in Table 5. Starch digestibility was the only parameter evaluated that was affected by the type of diet. Ad-libitum diets had greater starch digestibility than precision-fed diets (P = 0.01). While these values were statistically different, biologically it is of little importance because starch digestion rates were all above 98%.

Dry matter digestibility was affected by forage quality and NDF level. Diets with corn silage were, on average, 5.1% more digestible than diets containing grass hay (P ≤ 0.01). Also, LNDF diets were on average 4.28% more digestible than HNDF diets. Digestibility of NDF was not affected by any treatment. However, ADF digestibility was increased in HFQ diets (P = 0.03), likely due to ADF intake being slightly higher in these diets. Hemicellulose digestibility was decreased in diets formulated with HFQ (P = 0.05) as hemicellulose intake was higher in diets containing LFQ.

In general, apparent total tract digestibility of nutrients was moderately affected by type of diet. We expected greater digestibility for the precision diets due to the lower Kp observed and reports from Zanton and Heinrichs (2009b) and Reynolds et al. (1991) stating digestibility of feedstuffs was dependent on DMI. However, when DMI is reduced, it is necessary to increase energy to maintain rumen bacteria populations and keep the same digestion rates. In this study, diets for precision feeding were formulated with lower ME than ad-libitum diets, which could partially explain why we did not observe higher digestibility.

Pre-feeding rumen digestion kinetics are presented in Table 6 with sample collection at 22 h after feeding. Precision diet-LFQ had greater volume and mass than ad-libitum diet-LFQ while ad-libitum diet-HFQ presented greater volume and mass than precision diet-HFQ. Rumen content density was higher for precision-fed heifers (P = 0.04) and tended to be higher for HFQ diets (P = 0.10). Values were lower than those shown in adult cows (Dado and Allen 1995). Digestible fraction was increased for LNDF diets (P ≤ 0.01). The proportion of NDF digested in the rumen was greater for the grass hay-based diets (P = 0.03) than corn silage diets, and LNDF diets tended to have a greater proportion of NDF digested in the rumen than HNDF diets (P = 0.09).

| Item                  | Diet       | LFQ-HNDF | LFQ-LNDF | HFQ-HNDF | HFQ-LNDF | SE  | P-value* |
|-----------------------|------------|----------|----------|----------|----------|-----|----------|
|                      |            |          |          |          |          | D × NDF | F × NDF  |
| DM                    | A-L        | 60.6     | 63.5     | 65.7     | 71.0     | 2.72 | 0.41     | ≤ 0.01   | 0.02     | 0.48 | 0.91 | 0.28 |
|                      | P-F        | 59.7     | 61.9     | 61.4     | 68.2     | 0.14 | 0.01     | ≤ 0.01   | 0.26     | 0.71 | 0.79 | 0.44 |
| Starch                | A-L        | 98.9     | 98.8     | 99.3     | 99.5     | 0.14 | 0.01     | ≤ 0.01   | 0.26     | 0.71 | 0.79 | 0.44 |
|                      | P-F        | 98.4     | 98.7     | 99.3     | 99.1     | 4.57 | 0.35     | 0.85     | 0.81     | 0.41 | 0.99 | 0.32 |
| NDF                   | A-L        | 47.4     | 45.8     | 46.8     | 49.8     | 4.57 | 0.35     | 0.85     | 0.81     | 0.41 | 0.99 | 0.32 |
|                      | P-F        | 45.4     | 43.0     | 41.5     | 43.3     | 4.03 | 0.29     | 0.03     | 0.35     | 0.69 | 0.97 | 0.38 |
| ADF                   | A-L        | 36.4     | 32.8     | 42.5     | 41.2     | 3.90 | 0.43     | 0.05     | 0.59     | 0.32 | 0.90 | 0.46 |
|                      | P-F        | 34.8     | 28.6     | 36.4     | 37.2     | 3.90 | 0.43     | 0.05     | 0.59     | 0.32 | 0.90 | 0.46 |
| Hemicellulose         | A-L        | 65.3     | 63.7     | 57.3     | 62.6     | 6.90 | 0.43     | 0.05     | 0.59     | 0.32 | 0.90 | 0.46 |
|                      | P-F        | 63.3     | 63.3     | 47.3     | 53.0     | 6.90 | 0.43     | 0.05     | 0.59     | 0.32 | 0.90 | 0.46 |

*DM = Diet; F = Forage quality; NDF = NDF level.

Table 5. Apparent total tract nutrient digestibility in ad-libitum (A-L) vs. precision-fed (P-F) heifer diets with high (HFQ) or low forage quality (LFQ) and high (HNDF) or low NDF (LNDF).
Post-feeding rumen kinetics are presented in Table 7; results were different from those pre-feeding. Rumen volume and mass were greater for precision-fed heifers \((P = 0.05\) and \(P \leq 0.01\) respectively) and LFQ \((P = 0.01\) for both). Furthermore, at this time \((4\ h\ after\ feeding)\ the\ precision-fed\ heifers\ had\ consumed\ their\ entire\ ration\ while\ ad-libitum\ heifers\ consumed\ their\ ration\ more\ slowly\ and\ thus\ had\ consumed\ less\ of\ their\ total\ ration.\ The\ increased\ volume\ and\ mass\ for\ LFQ\ is\ probably\ explained\ by\ higher\ water\ consumption\ because\ the\ DM\ mass\ was\ not\ affected\ by\ forage\ quality.\ Ruminal\ digestion\ of\ NDF\ was\ greater\ for\ grass\ hay\ diets\ \((P \leq 0.01)\ and\ LNDF\ diets\ \((P = 0.05)\).

Ad-libitum diets had faster turnover rates for all of the nutrients evaluated \((P \leq 0.01\ for\ all)\). In this study, DM \(Kp\) was 7.1 vs. 4.9%/h; NDF \(Kp\) was 3.1 vs. 2.1%/h and iNDF \(Kp\) was 2.4 vs. 1.6%/h for ad-libitum vs. precision feeding diets respectively. These results confirm \(Kp\) observations in cows, where rate of passage increases as DMI increases \((Colucci\ et\ al.\ 1982;\ Shaver\ et\ al.\ 1986)\), and suggest that precision feeding diets result in a slower rate of passage than ad-libitum feeding diets. This is also in agreement with a previous study with heifers where higher DMI increased \(Kp\) \((Lascano\ and\ Heinrichs\ 2009)\). A slower \(Kp\) could increase feedstuff digestibility. That was not the case in this trial, but it is necessary to complete more studies comparing ad-libitum vs. precision feeding diets to further explore the impacts of \(Kp\) on digestibility. Dry matter \(Kp\) had a tendency to be faster for LFQ diets \((P = 0.10)\). Turnover rate of NDF was increased in diets with LNDF levels \((P = 0.04)\). Turnover rate of iNDF was faster for diets containing HFQ and LNDF \((P \leq 0.01\ for\ both)\). The rate of digestion \((Kd)\) of NDF showed a tendency to decrease in precision-fed diets \((P = 0.08)\). Furthermore, diets containing HFQ had slower NDF \(Kd\) \((P \leq 0.01)\).

The turnover times explain our results for turnover rates as DM, NDF, and iNDF turnover time was much shorter for ad-libitum diets \((P \leq 0.01\ for\ all)\). These results agree with results presented previously and reinforce that ad-libitum diets reduce retention times for nutrients compared to precision feeding diets, likely due to increased DMI for ad-libitum diets. Diets containing LFQ showed a tendency to increase DM turnover time \((P = 0.09)\). Turnover time for NDF was longer for LNDF.
Table 7. Post-feeding rumen digestion kinetics in ad-libitum (A-F) vs. precision-fed (P-F) heifer diets with high (HFQ) or low forage quality (LFQ) and high (HNDF) or low NDF (LNDF).

| Item                        | Diet       | LFQ-HNDF | LFQ-LNDF | HFQ-HNDF | HFQ-LNDF | SE | Diet | Forage quality | NDF level | D × F | D × NDF | F × NDF |
|-----------------------------|------------|----------|----------|----------|----------|----|------|----------------|-----------|-------|--------|--------|
| Rumen volume, L             | A-L        | 83.34    | 83.66    | 80.44    | 77.22    | 5.76| 0.05 | 0.01           | 0.09      | 0.14  | 0.20   | 0.98   |
|                             | P-F        | 109.08   | 97.82    | 93.31    | 85.91    |    |      |                |           |       |        |        |
| Rumen mass, kg              | A-L        | 66.99    | 65.73    | 64.88    | 62.22    | 6.32| 0.04 | 0.01           | 0.73      | 0.04  | 0.86   | 0.28   |
|                             | P-F        | 88.19    | 95.06    | 76.67    | 68.53    |    |      |                |           |       |        |        |
| Rumen density, kg/L         | A-L        | 0.81     | 0.79     | 0.81     | 0.81     | 0.05| 0.19 | 0.34           | 0.36      | 0.18  | 0.27   | 0.25   |
|                             | P-F        | 0.81     | 0.97     | 0.82     | 0.80     |    |      |                |           |       |        |        |
| Digestible fraction, %      | A-L        | 71.17    | 72.81    | 69.92    | 75.96    | 1.63| 0.63 | 0.79           | 0.01      | 0.13  | 0.93   | 0.19   |
|                             | P-F        | 70.51    | 72.63    | 69.25    | 74.22    |    |      |                |           |       |        |        |
| NDF rumen digestion, %      | A-L        | 29.27    | 31.11    | 11.05    | 21.62    | 3.88| 0.27 | ≤0.01          | 0.05      | 0.23  | 0.97   | 0.26   |
|                             | P-F        | 28.07    | 31.75    | 19.04    | 27.29    |    |      |                |           |       |        |        |

DM = Diet; F = Forage quality; NDF = NDF level.

Fluid intake rate, %/h

Kd⁻¹, NDFd

Kd⁻¹, NDFd

Turnover time, h

DM = Diet; F = Forage quality; NDF = NDF level.

Rumens volume, (P = 0.05), and iNDF turnover time was longer for LFQ and LNDF (P ≤ 0.01 and P = 0.01 respectively).

Rumen fluid volume (Table 8) was not affected by treatment but showed a tendency to be increased for precision-fed diets and HNDF (P = 0.10 and 0.09, respectively). Increased water consumption for precision-fed heifers, shown by increased urine production, explains the tendency for increased rumen fluid volume. Ad-libitum diets had a faster Kl than the precision feeding diets (10.4 vs. 8.6%/h; P = 0.04). Also, LFQ had faster Kl than HFQ diets (P ≤ 0.01). Fluid flow rate only showed a tendency to be faster in LFQ than HFQ diets (P = 0.06). Thus, with the volumes and Kl presented, turnover time was affected by the type of diet and forage quality. Precision-fed diets showed longer retention time for fluids in the rumen than ad-libitum diets (11.5 vs. 9.8 h; P = 0.02). Precision-fed heifers typically had faster turnover times, but an ad-libitum-HFQ diet had faster turnover time than both precision-LFQ diets.

Overall, results of rumen volume, Kl, outflow, and turnover time in the rumen are very similar to results presented in a previous heifer study (Clark and Petersen 1988) as well as previous studies with steers (Okine et al. 1989; Malcolm and Kiesling 1990). In this study, type of diet and forage quality were primarily responsible for differences in rumen fluid and digesta passage rates.

Table 8. Fluid passage rate in ad-libitum (A-F) vs. precision-fed (P-F) heifer diets with high (HFQ) or low forage quality (LFQ) and high (HNDF) or low NDF (LNDF).

| Item                        | Diet       | LFQ-HNDF | LFQ-LNDF | HFQ-HNDF | HFQ-LNDF | SE | Diet | Forage quality | NDF level | D × F | D × NDF | F × NDF |
|-----------------------------|------------|----------|----------|----------|----------|----|------|----------------|-----------|-------|--------|--------|
| Fluid volume, L             | A-L        | 57.0     | 60.0     | 68.3     | 54.4     | 4.55| 0.10 | 0.21           | 0.09      | 0.93  | 0.63   | 0.09   |
|                             | P-F        | 68.8     | 65.8     | 72.2     | 68.9     |    |      |                |           |       |        |        |
| Fluid dilution rate, %/h    | A-L        | 11.1     | 10.7     | 9.4      | 10.5     | 0.006| 0.04 | ≤0.01          | 0.75      | 0.66  | 0.22   | 0.33   |
|                             | P-F        | 9.5      | 9.1      | 8.6      | 7.7      |    |      |                |           |       |        |        |
| Fluid flow rate, L/h        | A-L        | 6.2      | 6.3      | 6.4      | 7.7      | 0.33| 0.65 | 0.06           | 0.13      | 0.30  | 0.73   | 0.17   |
|                             | P-F        | 6.5      | 6.3      | 6.0      | 5.3      |    |      |                |           |       |        |        |
| Fluid turnover time, h      | A-L        | 9.2      | 9.5      | 10.2     | 9.7      | 0.64| 0.02 | ≤0.01          | 0.98      | 0.08  | 0.27   | 0.92   |
|                             | P-F        | 10.6     | 10.3     | 12.7     | 13.0     |    |      |                |           |       |        |        |

Overall, results of rumen volume, Kl, outflow, and turnover time in the rumen are very similar to results presented in a previous heifer study (Clark and Petersen 1988) as well as previous studies with steers (Okine et al. 1989; Malcolm and Kiesling 1990). In this study, type of diet and forage quality were primarily responsible for differences in rumen fluid and digesta passage rates.

Conclusions

In this study we showed that the reduction in DMI for precision feeding diets improved feed efficiency in comparison with ad-libitum diets for dairy heifers. We also found that HFQ diets increased DMI and, in an opposite way, HNDF diets increased DMI, modifying feed efficiency due fibre intake regulating total DMI. Thus, in this study the greatest feed efficiency was obtained by heifers precision-fed LFQ-LNDF diets.
Overall, apparent total tract digestibility was not affected by the type of diet. However, DM digestibility increased with HFQ and decreased with HNDF level. Rate of passage was highly influenced with the rumen at maximum capacity, 3 to 4 h after feeding. Retention time for precision-fed diets was longer than ad-libitum diets, which could improve rumen digestion of nutrients. Also, grass hay diets had longer retention time than corn silage diets. This effect was more significant in precision-fed heifers than in those fed ad-libitum diets.

In summary, the 3 factors analyzed in this study affected in greater or lesser extent ruminal fermentation, rumen pH, nutrient digestion, and rate of passage. The result with the greatest potential for improving dairy profitability was the enhanced feed efficiency observed in precision-fed diets, which could reduce the cost of raising dairy heifers.

Disclosure Statement
No potential conflict of interest was reported by the authors.

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