Effect of silage source, physically effective neutral detergent fiber, and undigested neutral detergent fiber concentrations on performance and carcass characteristics of finishing steers

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ABSTRACT: This study was designed to evaluate the effect of silage source (barley vs. wheat silage) when harvested at two chop lengths (low vs. high physically effective neutral detergent fiber [**peNDF**]) and when barley silage was partially replaced with straw to increase the undigested neutral detergent fiber (**uNDF**) concentration on performance and carcass characteristics of finishing steers. Four hundred and fifty yearling commercial crossbred steers with an initial body weight (**BW**) of 432 ± 30.5 kg were allocated to 30 pens and fed diets containing 90% concentrate:10% forage for 123 d in a completely randomized block design with a 2 × 2 + 1 factorial arrangement. Treatments included 1) barley silage (**BarS**) with low peNDF (**LpeNDF**); 2) BarS with high peNDF **(HpeNDF**); 3) BarS with straw to yield a diet with **LpeNDF + uNDF**; 4) wheat silage (**WhS**) LpeNDF; and 5) **WhS HpeNDF**. There were no silage × peNDF interactions for dry matter intake (**DMI**), average daily gain (**ADG**), or gain to feed ratio (**G:F**), but cattle fed WhS LpeNDF had a lower ($P < 0.01$) proportion of yield grade 3 and a greater proportion in yield grade 2 carcasses than cattle fed BarS LpeNDF or HpeNDF and WhS HpeNDF. Cattle fed WhS LpeNDF had greater ($P = 0.02$) incidence of severe liver abscesses when compared with cattle fed BarS LpeNDF or HpeNDF and WhS HpeNDF. Cattle fed BarS consumed less ($P < 0.01$) uNDF as a percentage of BW, had increased ($P = 0.02$) ADG, heavier ($P = 0.02$) hot carcass weight, with greater ($P = 0.01$) back fat thickness, and ($P < 0.01$) incidence of minor liver abscesses when compared with cattle fed WhS. Feeding HpeNDF did not affect DMI, ADG, or G:F, but increased ($P = 0.02$) marbling score and reduced ($P < 0.01$) the proportion AA quality grade and increased ($P < 0.01$) those classified as AAA when compared with cattle fed LpeNDF. Cattle fed low uNDF had lesser ($P < 0.01$) uNDF intake as a percentage of BW, greater dressing percentage ($P = 0.01$), had a lower ($P < 0.01$) proportion of carcasses in yield grade 2, and a greater ($P < 0.01$) proportion of carcasses in yield grade 3 when compared with cattle fed high uNDF. Thus, silage source, peNDF, and uNDF content do not impact DMI or G:F when diets contain 10% forage, but BarS relative to WhS as well strategies increasing the peNDF concentration may increase ADG, HCW, back fat thickness, dressing percentage, marbling score, and carcasses classified as quality grade AAA. Future research is needed to evaluate the usefulness of peNDF and uNDF in rations for finishing cattle.

Key words: forage, peNDF, roughage, uNDF

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INTRODUCTION

Providing forage to feedlot cattle promotes chewing activity that is thought to increase salivary secretion and help regulate ruminal pH. Provision of forage also stimulates reticulo-ruminal contractions and increases the passage rate of fluid and digesta from the rumen (NASEM, 2016). However, for cattle fed high-concentrate diets, increasing the inclusion of forage dilutes the dietary energy density, and as such, cattle increase dry matter intake (**DMI**) in an attempt to maintain energy intake (Galyean and Defoor, 2003). The NASEM (2016) focused on forage inclusion rate as a predictor of ruminal pH; however, focusing on forage inclusion for finishing diets does not consider differences in the physical effectiveness or digestibility of the forage source. That said, the recommendation by NASEM (2016) is supported by previous and recent studies suggesting that dietary forages be included at a rate of 5% to 10% of dry matter (**DM**) regardless of whether the forage is supplied by corn stalks (Jennings et al., 2020), corn silage (Crawford et al., 2008), or barley silage (Chibisa et al., 2020). Commercial nutritionists seem to further support these forage inclusion rates as finishing diets in the United States typically contain between 8% and 10% of the dietary DM as forage (Samuelson et al., 2016).

As noted above, in beef cattle, previous studies have largely focused on the forage inclusion rate (Quinn et al., 2011; Swanson et al., 2017) and dietary neutral detergent fiber (**NDF**) concentration (Salinas-Chavira et al., 2013; Flores-Mar et al., 2017) rather than considering functional aspects (NASEM, 2016). Generally, for high-concentrate diets, as the forage or NDF inclusion rate increases, DMI increases, and the gain to feed ratio (**G:F**) decreases (Hales et al., 2013). In contrast, several studies have tested the concept of physically effective NDF (**peNDF**) in dairy cattle (Beauchemin and Yang, 2005; Yang and Beauchemin, 2005; Zebeli et al., 2012). Mertens (2002) recommended a minimum requirement of 15% peNDF (DM basis) for feedlot cattle and Llonch et al. (2020) reported that increasing the peNDF concentration without changes in forage inclusion increased rumination time and ruminal pH, while it decreased DMI and NDF intake in beef heifers fed a high-concentrate diet. Increasing peNDF by providing forages with a longer particle size may increase sorting of the diet (Llonch et al., 2020), a behavior already linked to ruminal acidosis in cattle (DeVries et al., 2008). That said, finishing diets that provide adequate peNDF may stimulate rumination activity without negatively impacting performance, rumination, digestibility, or ruminal fermentation (Gentry et al., 2016; Weiss et al., 2017). Consequently, peNDF may represent another strategy of using forage to optimize ruminal function without increasing its inclusion in the diet.

More recently, the application of undigested NDF (**uNDF**) has been applied in ration formulation for dairy cattle (Fustini et al., 2017; Kahyani et al., 2019). The use of uNDF has improved the prediction of NDF-based DMI limitations for forage-based diets (Grant et al., 2020). Both peNDF and uNDF may stimulate rumen motility and rumination, thereby promoting a more regulated ruminal fermentation system without altering the level of forage inclusion (Grant et al., 2018). In dairy-based studies, Fustini et al. (2017; dietary NDF ranging from 31.7% to 35.2%) and Hosseini et al. (2019; dietary NDF ranging from 31.2% to 31.9%) reported that DMI and rumination time were not affected by dietary uNDF. However, cows fed diets with greater uNDF concentration spent less time with ruminal pH < 5.8. Given the relatively low forage inclusion rates in diets for finishing beef cattle, it is not clear whether uNDF may better predict forage requirements than peNDF or forage inclusion alone.

In the Northern Great Plains, barley silage has been a common forage source for feedlot cattle. However, concerns over lodging (Nair et al., 2016) have led to the adoption of wheat silage. Few studies have directly compared barley and wheat silage for feedlot cattle. Relative to barley silage, wheat silage contains less NDF and greater crude protein (**CP**; Burgess et al., 1973; Ohjen and Bolsen, 1980) concentrations. Although these chemical composition

differences are subtle, the use of wheat silage has several advantages including reduced lodging risk and hence may increase the efficiency of harvest (Ashbell and Weinberg, 2003). However, data are needed to compare the performance of cattle as affected by silage source.

We aimed to test the hypothesis that increasing chop length (to increase its peNDF concentration) and adding straw to increase the dietary uNDF concentration increases DMI, growth, and yield grade, and reduces the severity of liver abscesses, regardless of silage source. This study was designed to evaluate the effect of silage source (barley vs. wheat silage), when harvested at two chop lengths (to provide low vs. high peNDF), and when barley silage was fed with straw to increase the uNDF concentration of the diet on performance and carcass characteristics of finishing beef steers.

MATERIAL AND METHODS

All the procedures involving the use of cattle in this study were preapproved by the University of Saskatchewan Animal Research and Ethics Board (protocol number 20100021) and were conducted in accordance to the guidelines of the Canadian Council on Animal Care (Ottawa, ON, Canada). Cattle had 0.91 m of linear bunk space and 21 m^2 of pen space per animal (n = 15 animals per pen). Porosity fencing (15%) on the North and part of the West side of the pens were used for protection from wind. Pens were bedded with straw as required to keep cattle clean and dry.

Forage Preparation and Cereal Grain Processing

Whole-crop barley (*Hordeum vulgare* L., cv. AC Ranger; FP Genetics, Regina, SK, Canada) and whole-crop wheat (*Triticum aestivum* L. cv. CDC Landmark VB; FP Genetics) from a single field were harvested at the mid-dough to hard dough stage of maturity (40.2% and 43.0% DM, respectively) and chopped to a theoretical chop length of either 1.3 (low peNDF) or 1.8 cm (high peNDF) on a single day using a John Deere 8600 (Deere & Company World Headquarters, Moline, IL). All forages were ensiled in horizontal concrete silos, mechanically compacted, and sealed beneath two layers of polythene film. Barley grain was obtained as multiple lots from commercial sources and was dry rolled to processing index (**PI**) of 66%. The PI was measured as the volume weight of the barley after processing (DM basis) expressed as a percentage of its volume weight before processing (DM basis; Beauchemin et al., 2001).

Animals and Experimental Design

The study was conducted at the University of Saskatchewan Livestock and Forage Centre of Excellence (Clavet, SK, Canada). Four hundred and fifty yearling commercial crossbred steers were purchased from a local auction market with an initial body weight (**BW**) of 432 ± 30.5 kg and were allocated to 30 pens (15 steers per pen). The study was designed as a completely randomized block design with a 2 × 2 + 1 factorial arrangement of treatments. Cattle were blocked by BW (6 blocks) and within block, groups of cattle were randomly assigned to a pen, and pens were randomly assigned to one of five treatments. Treatments (Table 1) included either barley (**BarS**) or wheat silage (**WhS**) with each silage source harvested at two chop lengths to yield low (**LpeNDF**) vs. high peNDF (**HpeNDF**) silage. In addition, chopped wheat straw was included (5% of dietary DM) at the expense of LpeNDF barley silage to result in a LpeNDF treatment with greater uNDF content. The remainder of the diets consisted of barley grain, mineral, urea, and limestone. At the time of chopping and throughout the study (see below), samples were collected to confirm the particle size distribution of the silages, straw, and barley grain (Table 2).

Forty days before the start of the study, all steers were identified using an ear tag (Allflex, Dallas, TX), dewormed (Solmectin Pour-on, Solvet, Calgary, AB, Canada), vaccinated (Bovi-shield Gold/One Shot, Zoetis, Canada, Kirkland, QC; Ultrabac 7/Somubac Zoetis, Canada, Kirkland, QC), implanted with 36 mg of zeranol (Ralgro, Merck Animal Health, Roseland, NJ). Steers were re-implanted 63 d after the first implant (on day 23 of the experimental period) with 120 mg of trenbolone acetate and 24 mg of estradiol (Revalor-S, Merck Animal Health, Roseland, NJ). The study lasted 123 d including a 23-d diet transition period where the final diet was fed on day 24 onward. The diet transition (Supplementary Table 1) consisted of six intermediary diets for each treatment. Throughout the study, steers were fed ad libitum once daily between 0830 and 1100 h and had free-choice access to a water trough. All the animals were fed with 33 mg/kg of sodium monensin (Elanco Animal Health, Greenfield, IN) on a DM basis.

Table 1. Diet ingredients and chemical composition of complete diets containing silage (barley vs. wheat silage), harvested at two chop lengths (low vs. high physically effective neutral detergent fiber [peNDF]) and barley silage with added wheat straw to increase undigested neutral detergent fiber (uNDF)

	Barley silage			Wheat silage	
Item	Low peNDF	High peNDF	Low peNDF + uNDF	Low peNDF	High peNDF
Ingredients, % of DM[1]					
Barley grain	87.89	87.89	87.73	87.91	87.91
Barley silage short	10.00	—	5.00	—	—
Barley silage long	—	10.00	—	—	—
Wheat silage short	—	—	—	10.00	—
Wheat silage long	—	—	—	—	10.00
Wheat straw	—	—	5.00	—	—
Mineral[2]	0.18	0.18	0.18	0.18	0.18
Urea	0.50	0.50	0.66	0.48	0.48
Limestone	1.43	1.43	1.43	1.43	1.43
Nutrient content[3], % of DM					
DM, %	81.10 ± 0.44	81.04 ± 0.49	83.02 ± 0.47	81.68 ± 0.56	81.44 ± 0.67
Crude protein	12.45 ± 0.69	12.36 ± 0.72	12.08 ± 0.70	12.51 ± 0.69	12.46 ± 0.69
NDF[4]	19.14 ± 2.80	19.13 ± 2.77	20.73 ± 2.79	19.44 ± 2.80	19.52 ± 2.74
$peNDF_{19.0}$	0.51 ± 0.14	0.66 ± 0.14	0.49 ± 0.19	0.40 ± 0.09	0.73 ± 0.18
$peNDF_{8.0}$	3.06 ± 0.18	2.91 ± 0.16	3.01 ± 0.26	2.99 ± 0.18	3.40 ± 0.21
$peNDF_{4.0}$	13.38 ± 3.34	13.37 ± 3.30	13.82 ± 3.38	13.65 ± 3.32	13.79 ± 3.30
$uNDF_{240\text{-}h}$	6.73 ± 0.15	6.74 ± 0.15	7.79 ± 0.15	7.19 ± 0.15	7.13 ± 0.15
$peuNDF^{5}_{19.0}$	0.15 ± 0.04	0.20 ± 0.04	0.19 ± 0.08	0.15 ± 0.03	0.27 ± 0.07
$peuNDF_{8.0}$	0.92 ± 0.05	0.89 ± 0.06	1.14 ± 0.11	1.14 ± 0.08	1.23 ± 0.10
$peuNDF_{4.0}$	4.40 ± 0.94	4.41 ± 0.96	4.91 ± 0.99	4.82 ± 0.98	4.79 ± 0.99
Acid detergent fiber	9.06 ± 1.41	9.16 ± 1.43	10.69 ± 1.38	9.49 ± 1.45	9.50 ± 1.46
Starch	53.45 ± 2.79	53.60 ± 2.94	52.12 ± 2.70	52.94 ± 2.65	52.94 ± 2.77
Ether extract	1.32 ± 0.28	1.32 ± 0.27	1.23 ± 0.28	1.33 ± 0.28	1.33 ± 0.30
Ca	0.65 ± 0.01	0.64 ± 0.01	0.64 ± 0.01	0.63 ± 0.01	0.65 ± 0.01
P	0.31 ± 0.01	0.31 ± 0.01	0.31 ± 0.01	0.31 ± 0.01	0.31 ± 0.01
NEm[6], Mcal/kg	1.80 ± 0.02	1.80 ± 0.02	1.76 ± 0.03	1.80 ± 0.02	1.79 ± 0.03
NEg[7], Mcal/kg	1.20 ± 0.01	1.20 ± 0.01	1.16 ± 0.02	1.19 ± 0.02	1.19 ± 0.02
Particle size distribution[8], %					
>19.0 mm	1.19 ± 0.33	1.58 ± 0.32	0.93 ± 0.33	0.89 ± 0.20	1.59 ± 0.39
<19.0 > 8.0 mm	6.07 ± 0.42	5.37 ± 0.28	4.72 ± 0.36	5.71 ± 0.30	5.80 ± 0.46
<8.0 > 4.0 mm	53.23 ± 12.43	53.57 ± 12.44	53.39 ± 12.43	53.86 ± 12.46	53.24 ± 12.49
<4.0 mm	38.23 ± 11.64	38.20 ± 11.64	39.69 ± 11.75	38.25 ± 11.62	38.09 ± 11.62

[1]Dry matter.

[2]Mineral contained: Ca: 4.00 %; ether extract: 1.00 %; Co: 750 mg/kg; Cu: 60,000 mg/kg; I: 5,000 mg/kg; Mg: 120,000 mg/kg; Se: 750 mg/kg; Zn: 180,000 mg/kg; Vitamin A: 25, 200 IU; Vitamin D: 2,520 IU; Vitamin E: 158 IU; 33 mg/kg of sodium monensin (Elanco Animal Health, Greenfield, IN) on a DM basis.

[3]Nutrient content is expressed as means ± SD (n = 4).

[4]Neutral detergent fiber.

[5]Physically effective undigested neutral detergent fiber was calculated by multiplying the physical effectiveness factor multiplied by the uNDF content of the diet (Grant et al., 2018).

[6]Net energy for maintenance was calculated from feed samples using the NASEM (2016) equations.

[7]Net energy for gain was calculated from feed samples using the NASEM (2016) equations.

[8]Particle size distribution is expressed as means ± SD (n = 33).

During the course of the study, one steer died due to pneumonia (BarS HpeNDF) and one additional steer was removed due to aggression (WhS HpeNDF). A total of 23.3% of the steers received treatment with the primary reasons for treatment being pink-eye or cloudy eye (66.7% of the treatment cases), swollen joints (16.2% of treatment cases), footrot (10.5%), and respiratory illness (6.7% of the treatment cases).

Samples of the feed ingredients were collected weekly and analyzed for DM and particle size distribution (as is basis) using the Penn State Particle

Table 2. Chemical composition and particle size distribution of low and high physically effective neutral detergent fiber (peNDF) barley and wheat silage, straw, and barley grain

	Barley silage		Wheat silage			
Item	Low peNDF	High peNDF	Low peNDF	High peNDF	Wheat straw	Barley grain
Nutrient content[1], % of DM[2]						
DM, %	40.42 ± 1.71	39.83 ± 2.22	46.11 ± 2.89	43.62 ± 3.98	81.64 ± 2.30	87.78 ± 0.81
Crude protein	12.25 ± 0.15	11.38 ± 0.43	13.03 ± 0.16	12.53 ± 0.19	5.38 ± 0.38	13.43 ± 0.81
NDF[3]	42.25 ± 1.96	42.13 ± 1.64	45.33 ± 1.96	46.13 ± 1.38	74.50 ± 1.76	17.85 ± 3.12
$peNDF_{19.0}$	5.06 ± 1.44	6.60 ± 1.42	4.04 ± 0.85	7.30 ± 1.77	4.79 ± 2.31	0.00 ± 0.00
$peNDF_{8.0}$	30.49 ± 1.72	29.01 ± 1.52	29.82 ± 1.76	33.90 ± 2.01	29.52 ± 3.43	0.01 ± 0.01
$peNDF_{4.0}$	39.01 ± 1.93	38.98 ± 1.52	41.77 ± 1.72	43.17 ± 1.54	48.28 ± 2.75	10.78 ± 3.58
$uNDF^{4}_{240\text{-}h}$	12.75 ± 0.01	12.80 ± 0.02	17.33 ± 0.02	16.69 ± 0.02	34.03 ± 0.02	6.21 ± 0.17
$peuNDF^{5}_{19.0}$	1.52 ± 0.42	2.01 ± 0.44	1.54 ± 0.33	2.65 ± 0.67	2.19 ± 1.09	0.00 ± 0.00
$peuNDF_{8.0}$	9.19 ± 0.44	8.83 ± 0.56	11.40 ± 0.78	12.31 ± 1.00	13.46 ± 1.75	0.00 ± 0.00
$peuNDF_{4.0}$	11.75 ± 0.43	11.86 ± 0.65	15.97 ± 0.82	15.67 ± 0.92	22.00 ± 1.51	3.67 ± 1.02
Acid detergent fiber	25.40 ± 0.70	26.38 ± 0.93	29.75 ± 1.08	29.90 ± 1.24	58.25 ± 0.25	7.80 ± 1.60
Starch	26.53 ± 2.18	28.05 ± 3.65	21.95 ± 0.78	21.93 ± 1.91	1.93 ± 0.41	60.78 ± 3.08
Ether extract	2.37 ± 0.40	2.39 ± 0.26	2.47 ± 0.42	2.55 ± 0.54	0.59 ± 0.29	1.29 ± 0.29
NEm[6], Mcal/kg	1.53 ± 0.02	1.52 ± 0.02	1.48 ± 0.03	1.43 ± 0.06	0.74 ± 0.09	1.97 ± 0.02
NEg[7], Mcal/kg	0.94 ± 0.02	0.92 ± 0.02	0.88 ± 0.03	0.85 ± 0.06	0.21 ± 0.09	1.32 ± 0.02
Particle size distribution[8], %						
>19.0 mm	11.87 ± 3.25	15.75 ± 3.18	8.92 ± 1.99	15.87 ± 3.86	6.63 ± 3.27	0.00 ± 0.00
<19.0 > 8.0 mm	60.28 ± 3.88	53.32 ± 2.53	56.73 ± 2.66	57.54 ± 4.30	33.23 ± 2.72	0.05 ± 0.03
<8.0 > 4.0 mm	20.19 ± 1.85	23.59 ± 1.91	26.31 ± 2.13	20.14 ± 2.43	25.22 ± 2.37	58.27 ± 13.93
<4.0 mm	7.67 ± 1.14	7.34 ± 1.10	8.04 ± 0.89	6.44 ± 0.87	34.92 ± 3.74	40.22 ± 13.12

[1]Nutrient content is expressed as means ± SD (n = 4) with each composite consisting of 8 or 9 individual samples (a total of 33 samples were collected).

[2]Dry matter.

[3]Neutral detergent fiber.

[4]Undigested neutral detergent fiber was obtained after 240-h in vitro digestion.

[5]Physically effective undigested neutral detergent fiber was calculated by multiplying the physical effectiveness factor multiplied by the uNDF content of the diet (Grant et al., 2018).

[6]Net energy for maintenance was calculated from feed samples using the NRC (2001) equations.

[7]Net energy for gain was calculated from feed samples using the NRC (2001) equations.

[8]Particle size distribution is expressed as means ± SD (n = 33).

Separator with aperture sizes of 19, 8, and 4 mm, and a pan according to Heinrichs (2013). Dietary DM coefficients were adjusted on a weekly basis when the new sample differed from the 3-wk running average by more than 2 percentage units. The particle size distribution of each treatment was determined in duplicate using representative 1-L samples. The physical effectiveness factor (**pef**) was determined as the proportion of particles (as fed basis) retained on 19-, 8-, and 4-mm sieves (Heinrichs, 2013). Calculation of the peNDF was adapted from Mertens (1997), with each specific pef multiplied by the NDF concentration of the feed ingredient. Also, physically effective uNDF (**peuNDF**) was determined according to Grant et al. (2018) and was calculated by multiplying the pef by the uNDF content of each feed ingredient and summed to yield a total dietary peuNDF. Therefore, peNDF 19 mm (**$peNDF_{19.0}$**), peNDF 8 mm (**$peNDF_{8.0}$**), peNDF 4 mm (**$peNDF_{4.0}$**), peuNDF 19 mm (**$peuNDF_{19.0}$**), peuNDF 8 mm (**$peuNDF_{8.0}$**), and peuNDF 4 mm (**$peuNDF_{4.0}$**) were determined.

At the start and at the end of the study, individual steers were weighed on two consecutive days prior to feeding but without withholding feed and the average BW was calculated to determine initial and final shrunk BW using full BW multiplied by 0.96 (National Research Council [NRC], 1984). Throughout the study, steers were weighed every 28 d with BW data used to calculate average daily gain (**ADG**) by regressing the observed BW against the day of study. Feed bunks were cleaned corresponding to days of BW measurement and the residual feed was weighed and sampled to determine DM concentration. The difference in weight between the amount of DM offered and the quantity of DM refused was used to determine DMI

every 28 d for each pen and was expressed both in kg and as a percentage of the average pen BW. The G:F was calculated for each pen as ADG divided by DMI. The dietary net energy of maintenance (**NEm**) and net energy of gain (**NEg**) based on animal performance were estimated as described by Zinn et al. (2002). For the calculations, the retained energy for large framed yearling calves was used (retained energy = $[0.0437BW^{0.75}] \times ADG^{1.097}$; NRC, 1984) where BW was the shrunk (4% shrink) mid-test weight. NEg was determined from NEm according to Zinn and Shen (1998) using the equation: NEg = NEm × 0.877 − 0.41.

Feed ingredient and refusal samples were dried in a forced air oven at 55°C for 72 h for DM determination (method 930.15; AOAC, 1990). Subsequently, samples were ground using a hammer mill (Retsch ZM 200 grinder, Haan, Germany) to pass through a 1-mm screen. All dried and ground feed samples were submitted for chemical analysis to Cumberland Valley Analytical Services (Waynesboro, PA) where CP, NDF, acid detergent fiber (**ADF**), uNDF, starch, ether extract, calcium, phosphorus, NEm, and NEg were determined. The CP concentration was determined using AOAC (2000) method 990.03 using a LECO FP-528 Nitrogen Combustion Analyzer (LECO, St. Joseph, MI). The NDF concentration was determined using the method of Van Soest et al. (1991) including α-amylase and sodium sulfite, and ADF was determined using AOAC (2000) method 973.18; both with the modification that Whatman 934-AH (GE Healthcare Life Sciences, Chicago, IL) glass 1.5-µm microfiber filters were used in place of a fritted glass crucible. The uNDF concentration was obtained after 240-h in vitro digestion (Raffrenato and Van Amburgh, 2010). Starch concentration was determined with correction for free glucose as described by Hall (2009) and ether extract was determined according to AOAC (2000) method 2003.05 using the Tectator Soxtec System HT 1043 Extraction unit (Tectator, Foss, Eden Prairie, MN). Calcium and phosphorus concentrations were determined according to AOAC (2000) method 985.01 with the modification that a 0.35-g sample was ashed for 1 h at 535°C, digested in open crucibles for 25 min in 15% nitric acid on a hotplate, diluted to 50 mL, and analyzed on axial view using a Perkin Elmer 5300 DV ICP (Perkin Elmer, Shelton, CT). The NEm and NEg of feed were calculated using NASEM (2016) equations.

At the end of the study (on day 124 of the experimental period), all steers were transported 660 km on the same day to a federally inspected abattoir (Cargill Meat Solutions, High River, AB). Cattle were held overnight without feed but with access to water. Hot carcass weight (**HCW**) was measured (kidney, pelvic, and heart fat was not included) and used to calculate the dressing percentage by dividing the carcass weight by the average BW measured at the end of the study after correction (4%) for shrink. Carcasses were chilled for 28 h, and subsequently, the Canadian Beef Grading Agency yield and quality grades were determined by a licensed grader (Calgary, AB, Canada) based on maturity, sex, and muscle score and fat depth measured on the ribeye between the 12th and 13th ribs. The Canadian Beef Grading Agency yield grades indicate retail yields > 52.34% for yield grade 1; 52.34% to 50.0% for yield grade 2; 47.7% to 50.0% for yield grade 3; 45.4% to 47.7% for yield grade 4; and <45.5% for yield grade 5. Canadian quality grades AAA, AA, and A are equivalent to USDA Choice, Select, and Standard, respectively. In addition, a computer vision grading system (VBG 2000 e+v Technology GmbH, Oranienburg, Germany) was used to determine back-fat thickness, rib eye area, yield score, and marbling score with measurements conducted between the 12th and 13th ribs. Liver scores were classified as clear (no abscesses), minor (one or two small abscesses, or up to two to four well-organized, under 2.54 cm in diameter), or severe (one or more greater than 2.54 cm in diameter abscesses, along with inflammation of liver tissue surrounding the abscess) as per the Elanco Liver Check System (Elanco Animal Health, Greenfield, IN). Carcass-adjusted final BW was calculated as the HCW divided by the dressing percentage. Carcass-adjusted ADG was determined on a carcass-adjusted final BW basis, and carcass-adjusted G:F was obtained using carcass-adjusted ADG divided by DMI.

Statistical Analysis

Pen was considered as the experimental unit ($n = 6$ per treatment). For all variables, two data sets were generated for statistical analysis. The first data set included only the treatments accounting for the 2 × 2 factorial arrangement. The model included fixed effects of silage type (BarS vs. WhS), peNDF (LpeNDF vs. HpeNDF), and the silage × peNDF interaction. Block was considered as a random effect in the model. The second data set was used to create a single polynomial contrast to compare the BarS LpeNDF and the BarS LpeNDF with added uNDF. The model included the fixed effect

of treatment and block as a random effect. Tests for normality (Shapiro–Wilk and Kolmogorov–Smirnov) and heterogeneity of treatment variances (GROUP option of SAS) were confirmed before analyzing data. Continuous data (DMI, ADG, G:F, HCW, dressing percentage, rib eye area, back fat thickness, and marbling) were analyzed using the PROC MIXED procedure of SAS (SAS Inst., Inc., Cary, NC) with the Tukey's test to compare means that differed ($P < 0.05$). Categorical data (yield grades, quality grades, and liver scores) were analyzed using the PROC GLIMMIX procedure of SAS (SAS Inst., Inc.) with a binominal error structure and logit data transformation. Following analysis, the means and SEM were reverse transformed for presentation in the tables. Results were considered significant when $P \leq 0.05$ and trends were considered when $0.05 < P \leq 0.10$.

RESULTS

Although no statistical comparisons were made, altering the peNDF content of either BarS or WhS did not affect the overall NDF concentration of the diets (Table 1). Only a small numerical difference in the NDF concentration was observed when increasing the uNDF concentration by replacing 50% (DM basis) of the barley silage with straw. The peNDF calculated using only the 19-mm sieve was numerically increased for HpeNDF of both BarS and WhS but was similar between the BarS with low and high uNDF. The uNDF concentration was more than 1 percentage unit greater for the high uNDF than the low uNDF diets. However, increasing uNDF numerically reduced the NEg predicted from chemical composition by 0.04 Mcal/kg relative to BarS LpeNDF.

Initial BW and final BW were not affected by silage, peNDF, or the interaction between silage and peNDF, nor were they affected by uNDF ($P \geq 0.18$; Table 3). DMI, when expressed in kg/d or as a percentage of BW, and carcass-adjusted final BW were not affected by silage, peNDF, the interaction between silage and peNDF, or uNDF ($P \geq 0.13$). Cattle fed WhS had greater ($P < 0.01$) uNDF intake as a percentage of BW when compared with cattle fed BarS (0.16% vs. 0.15% of BW; SEM = 0.002). Also, cattle fed high uNDF had greater ($P < 0.01$)

Table 3. Effect of silage source (barley vs. wheat silage), chop length (low vs. high physically effective neutral detergent fiber [peNDF]), and replacement of barley silage with wheat straw to increase the undigested neutral detergent fiber (uNDF) content on feedlot performance of yearling beef steers (15 steers per pen with 6 pens per treatment)

	Barley silage			Wheat silage			*P*-value			
Item	Low peNDF	High peNDF	Low peNDF + uNDF	Low peNDF	High peNDF	SEM	SIL[1]	peNDF	SIL×peNDF	uNDF
Initial BW[2], kg	431.4	431.8	431.6	431.2	431.7	12.44	0.65	0.22	0.92	0.61
Final BW, kg	634.2	628.7	631.3	627.8	627.4	14.00	0.18	0.30	0.37	0.51
DMI[3], kg/d	12.0	11.7	11.9	11.7	11.9	0.26	0.69	0.46	0.13	0.60
DMI, % of BW	1.90	1.86	1.88	1.86	1.90	0.02	0.98	0.89	0.16	0.72
uNDF, % of BW	0.15	0.15	0.17	0.16	0.16	0.002	<0.01	0.98	0.16	<0.01
Carcass-adjusted final BW, kg	634.3	628.5	631.2	627.6	627.3	14.01	0.15	0.27	0.32	0.51
Live ADG[4], kg/d	1.61	1.58	1.56	1.54	1.54	0.02	0.02	0.40	0.51	0.25
Carcass-adjusted ADG, kg/d	1.63	1.59	1.61	1.58	1.58	0.02	0.17	0.21	0.33	0.49
Live G:F[5], kg/kg	0.134	0.135	0.132	0.132	0.123	0.002	0.07	0.57	0.39	0.56
Carcass-adjusted G:F, kg/kg	0.136	0.136	0.136	0.136	0.133	0.002	0.25	0.26	0.48	0.81
NEm[6], Mcal/kg	1.88	1.89	1.86	1.87	1.84	0.02	0.15	0.67	0.27	0.75
NEg[7], Mcal/kg	1.24	1.25	1.22	1.23	1.20	0.02	0.15	0.68	0.27	0.75

[1]Silage effect.

[2]Body weight.

[3]Dry matter intake.

[4]Average daily gain was determined by regressing BW with the day of study.

[5]Gain to feed ratio was calculated for each pen as ADG divided by DMI.

[6]Net energy for maintenance was calculated based on DMI and ADG as described by Zinn et al. (2002) and Zinn and Shen (1998).

[7]Net energy for gain was calculated based on animal performance for the finishing period as described by Zinn et al. (2002) and Zinn and Shen (1998).

uNDF intake as a percentage of BW when compared with cattle fed low uNDF. There was no main effect of peNDF or interaction between silage and peNDF ($P \geq 0.16$) for uNDF intake as a percentage of BW. Cattle fed BarS had greater ($P = 0.02$) ADG when compared with cattle fed WhS (1.59 vs. 1.54 kg; SEM = 0.02); however, no difference was observed for carcass-adjusted ADG. Moreover, carcass-adjusted ADG was not affected by peNDF, the interaction between silage and peNDF, or uNDF ($P \geq 0.17$). Cattle fed BarS tended to have greater ($P = 0.07$) G:F on a live weight basis but not on a carcass-adjusted basis when compared with cattle fed WhS (0.135 vs. 0.131 kg/kg; SEM = 0.002). There were no effects of peNDF, silage × peNDF interaction, or uNDF ($P \geq 0.39$) on G:F. Carcass-adjusted G:F, NEm, and NEg were also not affected ($P \geq 0.15$).

Cattle fed BarS had heavier ($P = 0.02$; Table 4) HCW when compared with cattle fed WhS (374.8 vs. 370.8 kg; SEM = 8.59). A tendency for a silage × peNDF interaction was observed ($P = 0.09$), where cattle fed BarS LpeNDF had heavier HCW when compared with cattle fed WhS LpeNDF, but other means did not differ. There was no effect of uNDF ($P = 0.18$) on HCW. Cattle fed BarS tended to have greater ($P = 0.07$) dressing percentage when compared with cattle fed WhS (59.4% vs. 59.1%; SEM = 0.15) and cattle fed HpeNDF had greater ($P = 0.03$) dressing percentage when compared with cattle fed LpeNDF (59.4% vs. 59.1%; SEM = 0.15). Also, cattle fed BarS with low uNDF had greater ($P = 0.01$) dressing percentage than cattle fed high uNDF. There was no interaction between silage × peNDF for dressing percentage ($P = 0.22$).

Cattle fed HpeNDF tended to have greater ($P = 0.09$) rib eye area when compared with cattle fed LpeNDF (88.6 vs. 86.4 cm^2; SEM = 1.75), but there were no silage, silage × peNDF interactions, or uNDF effects ($P \geq 0.26$). Cattle fed BarS had

Table 4. Effect of silage source (barley vs. wheat silage), chop length (low vs. high physically effective neutral detergent fiber [peNDF]), and when barley silage was partially replaced with straw to increase the undigested neutral detergent fiber (uNDF) content on carcass characteristics of yearling beef steers (15 steers per pen with 6 pens per treatment)

	Barley silage			Wheat silage			*P*-value			
Item	Low peNDF	High peNDF	Low peNDF + uNDF	Low peNDF	High peNDF	SEM	SIL[1]	peNDF	SIL×peNDF	uNDF
Hot carcass weight, kg	376.0	373.7	372.0	369.3	372.3	8.73	0.02	0.83	0.09	0.18
Dressing percentage[2], %	59.3	59.4	58.9	58.8	59.4	0.17	0.07	0.03	0.22	0.01
Rib eye area, cm^2	87.8	88.5	87.8	85.0	88.7	1.87	0.32	0.09	0.26	0.97
Back fat thickness, cm	1.29	1.33	1.26	1.17	1.25	0.05	0.01	0.11	0.54	0.19
Marbling, %	3.05	3.16	3.11	2.95	3.07	0.10	0.22	0.15	0.99	0.41
Marbling score[3]	427.4	452.4	432.6	414.3	433.6	11.00	0.08	0.02	0.74	0.62
Yield grade[4], %										
CBGA 1	11.1	10.0	14.4	12.2	11.1	1.31	0.40	0.40	0.97	0.12
CBGA 2	53.3[b]	56.7[b]	63.3	63.3[a]	54.4[b]	2.01	0.07	0.17	<0.01	<0.01
CBGA 3	35.6[a]	31.1[a]	18.9	22.2[b]	32.2[a]	1.81	<0.01	0.10	<0.01	<0.01
CBGA 4	0.00	2.2	3.3	2.2	2.2	0.51	0.97	0.97	0.97	0.97
Quality grade[4], %										
CBGA AA	32.2	18.9	31.1	32.2	24.4	1.81	0.09	<0.01	0.09	0.69
CBGA AAA	66.7	80.0	67.8	67.7	75.6	1.83	0.18	<0.01	0.18	0.69
Prime	1.1	1.1	1.1	1.1	0.0	0.34	0.97	0.97	0.97	1.00
Liver score[5], %										
Clear	63.3	62.2	62.2	61.1	65.6	1.94	0.77	0.40	0.17	0.70
Minor	16.7	16.7	17.8	10.0	13.3	1.44	<0.01	0.19	0.19	0.62
Severe	20.0[b]	21.1[b]	20.0	28.9[a]	21.1[b]	1.69	0.02	0.09	0.02	1.00

[1]Silage effect.

[2]Dressing percentage was determined by dividing the carcass weight by the body weight measured at the end of the study after correction (4%) for shrink.

[3]According to U.S. Department of Agriculture (USDA) where 200 to 299 = trace; 300 to 399 = slight; 400 to 499 = small; 500 to 599 = modest; and 600 to 699 = moderate.

[4]Percent of total according to Canadian Beef Grading Agency (CBGA; Calgary, AB, Canada).

[5]Liver scores were classified as clear, minor, or severe adapted by the Elanco Liver Check System (Elanco Animal Health, Greenfield, IN).

[a,b]Means without a common superscript letter differ ($P < 0.05$) between silage × peNDF interaction.

greater ($P = 0.01$) back fat thickness when compared with cattle fed WhS (1.31 vs. 1.21 cm; SEM = 0.04). Marbling, when expressed as percentage was not affected by silage, peNDF, the silage × peNDF interaction, or uNDF ($P \geq 0.15$). However, cattle fed BarS tended to have greater ($P = 0.08$) marbling score when compared with cattle fed WhS (439.9 vs. 424.0; SEM = 9.05). Cattle fed HpeNDF had greater ($P = 0.02$) marbling score when compared with cattle fed LpeNDF (439.9 vs. 424.0; SEM = 9.05).

The proportions of carcasses classified as yield grade 1 were not affected by any treatment parameters ($P \geq 0.12$). However, feeding WhS LpeNDF resulted in a greater ($P < 0.01$) proportion of carcasses classified as yield grade 2 than cattle fed BarS with LpeNDF or HpeNDF and WhS HpeNDF. Correspondingly, cattle fed WhS LpeNDF had a lower ($P = 0.10$) proportion of carcasses classified in yield grade 3 than cattle fed barley silage LpeNDF or HpeNDF and wheat silage HpeNDF. Also, cattle fed high uNDF had greater ($P < 0.01$) proportions of carcasses grading yield grade 2 and fewer in yield grade 3 when compared with cattle fed low uNDF. Carcasses classified in yield grade 4 were not affected by silage, peNDF, interactions between silage and peNDF, or uNDF ($P = 0.97$).

Cattle fed WhS tended to have greater ($P = 0.09$) proportions of carcasses grading quality grade AA when compared with cattle fed BarS (28.17% vs. 24.97%; SEM: 1.27), but proportions grading AAA or prime did not differ. Cattle fed HpeNDF had a lower ($P < 0.01$) proportion of carcasses classified as AA when compared with cattle fed LpeNDF (21.5% vs. 32.2%; SEM: 1.27), but had a greater proportion of carcasses grading AAA ($P < 0.01$). The dietary uNDF did not affect ($P \geq 0.69$) quality grades of carcasses.

The proportion of livers without abscesses were not affected by silage, peNDF, the silage × peNDF interaction, or uNDF ($P \geq 0.17$) where 62.89% of the livers had no evidence of abscesses. Cattle fed BarS presented a higher ($P = 0.002$) incidence of minor liver abscesses (16.7% vs. 11.6%; SEM = 1.00) when compared with cattle fed WhS. A main effect of peNDF, interaction between silage and peNDF, and uNDF was not observed ($P \geq 0.19$) for minor liver abscesses. A silage × peNDF was observed for severe liver abscesses ($P = 0.02$) where steers fed WhS with LpeNDF presented a higher incidence of severe liver abscesses when compared with cattle fed BarS with LpeNDF or HpeNDF and WhS with HpeNDF. There were no effects of uNDF on liver abscess rates.

DISCUSSION

The peNDF concept was introduced by Mertens (1997) and is related to physical characteristics of fiber that influence chewing activity and the biphasic nature of ruminal contents. The Penn State Particle Separator with aperture sizes of 19.0, 8.0, 1.18 mm, or more recently 4.0 mm, and a pan are used (Kononoff and Heinrichs, 2003; Heinrichs, 2013) as a field approach to estimate peNDF. In most previous studies, a critical sieve aperture opening of 1.18 mm was used to determine particles that would be retained in the rumen and considered physically effective at stimulating rumination (NASEM, 2016). More recently, a critical particle size of 4 mm has been suggested for dairy cattle as particles larger than 1.18-mm can pass through the omasal orifice (Heinrichs, 2013). Regardless of the critical threshold used for the pef, peNDF is calculated by multiplying the pef by the NDF concentration of the diet (Mertens, 1997). As such, the peNDF concentration can be augmented by increasing forage inclusion or particle length of forages in the diet (Yang and Beauchemin, 2005, 2009). However, it has been recognized that forages with the same pef may elicit different responses in chewing activity (Mertens, 2002). Despite differential pef effects among forages, Mertens (2002) reviewed data from eight publications and recommended a minimum of 15% of peNDF (DM basis, using $pef_{1.18}$) for feedlot cattle, with a range of 12% to 18%. The recommendation of Mertens (2002) further suggested that dietary peNDF concentrations of 15.3% were required to maximize ADG, 22% to minimize liver abscesses, and 25% to maximize DMI. Additionally, Fox and Tedeschi (2002) recommended peNDF to be between 7% and 10% (DM basis) for high-concentrate diets to maintain ruminal pH above 5.7 (using tabular, rather than measured, pef values). Clearly, there is wide disparity in the recommended peNDF values. The dietary $peNDF_{4.0}$ values observed in this study were less than recommendations made by Mertens (2002) to maximize ADG (15.3% of DM), but this may be due to the use of a 4-mm sieve as a critical threshold rather than a 1.18-mm sieve, as used by Mertens (2002). However, the peNDF values in the present study were within the range evaluated by Llonch et al. (2020) where a $peNDF_{4.0}$ of 10.4% was deemed as optimal with increasing peNDF reducing DMI and increasing dietary sorting.

Although we attempted to manipulate peNDF by altering the theoretical chop length of the silage sources, the peNDF based on the material retained

on the 4-mm sieve and greater were not markedly different. The lack of response for $peNDF_{4.0}$ was due to an increase in the proportion of particles retained on the 19-mm sieve, but there was a corresponding decrease in the proportion retained on the 8-mm sieve when silages were chopped to a greater theoretical chop length. Despite the subtle differences in $peNDF_{19.0}$ and no differences among diets for $peNDF_{4.0}$, we observed several differences related to quality grades and marbling. That said, DMI, ADG, and G:F were not affected by peNDF in the present study. Corroborating with data found in this study, Addah et al. (2015) and Gentry et al. (2016) evaluated $peNDF_{1.18}$ inclusions ranging from 8% to 13% and did not observe effects of peNDF on ADG or G:F. These results are interpreted to suggest that the use of peNDF, based on the material retained on 4-mm sieve, may not adequately capture biological effects of forage particle size for finishing cattle.

We hypothesized that increasing peNDF concentration of diets would increase DMI, ADG, and G:F, while reducing the severity of liver abscesses. The hypothesis was based on the premise that increasing peNDF concentration would help cattle regulate ruminal pH as exposure to ruminal acidosis transiently decreases DMI (Castillo-Lopez et al., 2014; Pederzolli et al., 2018), causes more erratic DMI (Owens et al., 1998), reduces G:F (Castillo-Lopez et al., 2014), and has been theorized to be a predisposing factor for liver abscess formation (Owens et al., 1998). The lack of effect of peNDF on DMI, ADG, and G:F may have been because changes in dietary peNDF concentration were only subtle or may indicate that both peNDF concentrations in the study (low and high) were below the critical threshold recommended by Mertens (2002) to maximize ADG and DMI. That said, a greater proportion of cattle fed WhS with LpeNDF had severe liver abscesses than when fed WhS with HpeNDF or BarS with LpeNDF or HpeNDF. Generally, liver abscesses are thought to be a consequence of ruminal acidosis and rumenitis in cattle fed high-concentrate diets (Amachawadi and Nagaraja, 2016), suggesting that increasing the peNDF of WhS may have mitigated some of the risk for liver abscesses. Supporting the previous statement, Brown and Lawrence (2010) and Rezac et al. (2014) reported decreases in ADG, HCW, dressing percentage, back fat-thickness, and yield grade in carcasses with liver abnormalities. The underlying reasons for a greater proportion of severe liver abscesses with WhS in the present study are unclear given its lower starch concentration and greater NDF concentration than BarS. Additionally, the tendency for a silage × peNDF interaction for HCW observed where feeding BarS with LpeNDF tended to result in greater HCW than steers fed WhS with LpeNDF, with no differences among the other treatments. Also, cattle fed LpeNDF had lower dressing percentage, marbling score, and proportion of carcasses classified in yield grade 3, which may be attributed to a higher incidence of severe liver abscesses in cattle fed BarS LpeNDF and LpeNDF, which is known to negatively impact carcass characteristics of cattle (Brown and Lawrence, 2010; Rezac et al., 2014).

In the present study, we tested the effect of increasing dietary uNDF by partially replacing barley silage with straw. Cotanch et al. (2014) defined uNDF as the functional fiber fraction that influences physical effectiveness, gut fill, digestion, and passage dynamics of forages. Measurement of uNDF entails determining the NDF residue remaining after 240 h of in vitro fermentation (Raffrenato and Van Amburgh, 2010). The use of uNDF has improved the prediction of DMI over that based on lignin (Raffrenato et al., 2019) for dairy cattle and provides insight into digestibility of the forage and hence the indigestible ruminal pool size. Although NDF intake does not limit DMI in feedlot cattle (Galyean and Defoor, 2003), uNDF may be useful as an indicator for the ruminal NDF pool size and hence it may be another factor to assess the potential to stimulate rumen motility and rumination. However, in the present study, we did not observe any effects of uNDF on DMI, ADG, or G:F. The lack of response is speculated to be due to the relatively small changes in dietary uNDF concentration and that uNDF intake does not regulate DMI for finishing cattle. That said, there were clear effects of uNDF on dressing percentage suggesting that even small increases in uNDF may affect rumen fill and may decrease dressing percentage. The effects on yield grade are more difficult to explain as there were no other effects of uNDF on carcass measurements such as back fat thickness or ribeye area. We are also unaware of any other studies evaluating uNDF on performance responses and carcass characteristics of finishing cattle.

Few studies have compared performance of cattle fed BarS and WhS. For dairy cattle, Burgess et al. (1973) did not observe differences between barley and wheat silage on DMI, milk yield, milk fat and protein, ruminal acetate, propionate, and ammonia concentrations. Ohjen and Bolsen (1980) compared wheat, barley, oat, and corn silages in three studies with growing steers. In one study, ADG, DMI, and G:F of cattle fed wheat silage

were reduced relative to those fed barley silage. Walsh et al. (2008) did not report differences between whole-crop barley and wheat silage on DMI, ruminal fermentation characteristics (except ammonia), and DM digestibility between whole-crop barley and wheat silage when fed to growing beef cattle. In the current study, cattle fed BarS had greater ADG and improved carcass characteristics. The silages used in the present study were harvested at similar DM content, yet BarS had numerically greater starch, NEg, and lower NDF, uNDF, and ADF concentrations than WhS. The greater HCW, marbling score, and greater proportion of carcasses in the AAA quality grade for cattle fed BarS were potentially reflective of its greater energy content despite only a modest dietary inclusion rate. Other studies have also reported that silage source, despite a low inclusion rate, can affect carcass characteristics (Johnson et al., 2020), further suggesting that improved characterization of the fiber source could improve modeling systems used to formulate rations for beef cattle.

CONCLUSION

In conclusion, silage source, peNDF, and uNDF concentration of finishing diets did not impact DMI and G:F of feedlot beef steers. The use of BarS increased ADG, HCW, and back fat thickness compared with WhS, whereas increasing peNDF concentration of diets via increasing chop length improved dressing percentage, marbling score, and carcasses classified as quality grade AAA. The use of WhS with low peNDF concentration should be avoided due to the reduced proportion of carcasses classified as yield grade 3 and increased incidence of severe liver abscesses. Increasing uNDF independent to peNDF may decrease dressing percentage and the proportion of carcasses classified as yield grade 3. These data suggest that further characterization of NDF as peNDF or uNDF may be warranted under finishing diet scenarios, but further research is needed to determine optimal dietary concentrations.

SUPPLEMENTARY DATA

Supplementary data are available at *Translational Animal Science* online.

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