



## Effect of maturity at harvest of small-grain grasses on the nutritional composition of forage and ration formulation

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### ABSTRACT

We hypothesized that, relative to harvesting small-grain grasses at the soft dough stage (SFT) of maturity, harvesting small-grain grasses at the boot stage (BT) of maturity would result in less expensive dairy rations when commodity prices are high but not when commodity prices are low. Small plots of small-grain grasses were planted during the fall of 2020 and 2021 in Blacksburg, Blackstone, and Orange, Virginia. In each year and location, 2 varieties of barley, 2 varieties of rye, and 4 varieties of triticale were planted in plots replicated 6 times, yielding 288 plots. Within each year and location, we harvested half of the plots at BT and the other half at SFT. For each of the 6 small-grain grasses, we formulated 8 rations according to 8 different scenarios using the least-cost optimizer. The scenarios included high and low commodity prices, high and low dietary forage (60% and 40% forage, respectively), and the inclusion of small-grain grasses harvested at BT or SFT. Harvesting at SFT yielded 107% to 205% more DM than harvesting at BT. Relative to BT, small-grain grasses harvested at SFT had greater concentrations of OM, NDF, ADF, ADL, and starch but lower concentrations of CP. Relative to BT, small-grain grasses harvested at SFT also had a greater concentration of undegraded NDF (NDF basis). Species had minimal influence on the nutritional quality of small-grain grasses for silage. Under a low-price scenario, the ration formulation system ignored all 6 small-grain grass silages and included corn silage as the only forage source when we did not limit its inclusion. Under a high-price scenario, the ration formulation system included all 6 small-grain grass silages when formulating low-forage diets with unlimited corn silage. However, a preference

between BT and SFT stages did not exist, with the optimizer not consistently selecting a specific maturity stage. After evaluating the yields, the chemical composition, and the effects on ration formulation in this study, future studies should aim to evaluate the influence of maturity at harvest of small-grain grasses on cow performance and environmental impacts.

**Key words:** small grains, small-grain silage, boot stage, soft-dough stage

### INTRODUCTION

Including forages in rations of lactating dairy cows has nutritional, health, and economic benefits. From a nutritional perspective, the microbial fermentation of structural carbohydrates from forages within the rumen provides energy and protein precursors to the host animal, used for milk synthesis. From a health perspective, forages provide structural carbohydrates that support rumen health by avoiding sudden and pronounced reductions of ruminal pH, which are detrimental to dairy cattle. From an economic perspective, forages are typically less expensive than cereal grains and other concentrates, and their inclusion in rations for dairy cattle may decrease feeding costs and maximize income over feed costs.

Barley, oats, rye, triticale, and wheat are cool-season annual grasses with a starchy endosperm within their caryopses or grains (Shewry et al., 2023). Given the starchy structure of their grains, this group of cool-season annual grasses is alternatively called small-grain grasses or cereal grain grasses. Small-grain grasses are commonly grown on dairy farms for 2 reasons. First, dairy farmers grow small-grain grasses as cover crops (SARE, 2007; Brown et al., 2018) to protect the soil from erosion or to manage the nutrients in the soil after harvesting the warm-season crop (i.e., corn or sorghum) in the fall. Second, dairy farmers use the biomass of small-

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The list of standard abbreviations for JDS is available at [adsa.org/jds-abbreviations-25](https://adsa.org/jds-abbreviations-25). Nonstandard abbreviations are available in the Notes.

grain grasses as a feed ingredient for dairy cattle rations, and this forage biomass is typically harvested and stored as silage. Therefore, the term “small-grain silage” non-specifically includes barley, oats, rye, and wheat silages, among others.

When used as silages, small-grain grasses are most commonly harvested at either the boot stage (BT) or the soft dough stage (SFT) of maturity. At BT, the spikes of the plant tillers are within the sheath of the flag leaves. At SFT, the spikes of the plants are exteriorized and visible, and the grain contains a non-milky and soft starchy endosperm. Harvesting at each of these stages has both benefits and drawbacks. For example, Coblenz et al. (2018a,b) evaluated the effects of maturity at harvest on the yield and nutritional quality of triticale for silage and reported that harvesting at SFT resulted in 230% to 270% more forage yield than harvesting at BT. From a land use perspective, it seems logical to harvest at SFT to maximize the amount of forage harvested. From a financial perspective, harvesting at SFT would likely result in less expensive small-grain silages, as a greater biomass yield dilutes the fixed costs. On the contrary, harvesting at SFT delays the planting of the subsequent crop (i.e., corn or sorghum) and likely results in poorer quality forage than when harvesting at BT (Coblenz et al., 2018a,b). Therefore, based on the nutritional quality of the forage, it seems logical to harvest at BT to obtain the best-quality silages, especially when included in the ration for high-producing dairy cows.

Because harvesting at either stage of maturity has benefits and drawbacks, dairy farmers and dairy nutritionists may struggle to decide when to harvest small-grain grasses for silages. Ferreira (2019) suggested that harvesting small grains at BT would result in less expensive diets when commodity prices are high, whereas harvesting small grains at SFT would result in less expensive diets when commodity prices are low. That analysis used a least-cost formulation approach and input data from Coblenz et al. (2018a,b). Given that the study of Coblenz et al. (2018a,b) has data from a single variety of triticale, we considered it necessary to test more small-grain grasses (i.e., species) and varieties within small-grain grasses to perform a more robust analysis.

In this study, we hypothesized that, relative to harvesting small-grain grasses for silage at SFT, harvesting small-grain grasses for silage at BT would result in less expensive dairy rations when (simulated) commodity prices are high but not when prices are low. To test this hypothesis, the first objective of this study was to generate a broad database that would describe the variation among small-grain grasses for forage yields and forage nutritional quality. The second objective was to predict

the least expensive dairy ration as affected by commodity prices and the maturity at harvest of small-grain grasses using the database generated for forage yield and nutritional composition.

## MATERIALS AND METHODS

### *Small-Grain Grasses for Silage*

Small plots of small-grain grasses were planted during the fall of 2020 and 2021 in Blacksburg, Blackstone, and Orange, Virginia (Table 1), as a randomized complete block design with 3 blocks or replicates per location and year. In each location and year, 2 varieties of barley (VA16BFHB-268 and VA11B-141 from Virginia Crop Improvement Association), 2 varieties of rye (GVS Dura Rye from Greener Valley Supply, Verona, VA; and variety not stated, also known as VNS), and 4 varieties of triticale (TriCal Gainer 154, TriCal Thor, TriCal Gunner, and Trical Surge from TriCal Superior Forage, Butte, MT) were planted in sextuplet plots, yielding a total of 288 plots (3.0 m long and 1.2 m wide). Varieties were representative, adapted, and well-performing individuals (yield, forage quality, and maturity) based on their performance in the small-grains forage evaluation at Virginia Tech. Plots were planted with a 7-row no-till seeder with 17 cm between rows, and the seeding rate was 105 kg/ha (Virginia Cooperative Extension, 2023). Fertilization was defined at each location and year according to soil fertility and nutrient management plans. At all locations, plots were fertilized at establishment with 35 to 65 kg N/ha (6% N, 6% P<sub>2</sub>O<sub>5</sub>, and 18% K<sub>2</sub>O) and at the end of the winter (early March) with 20 to 35 kg N/ha as urea and ammonium nitrate.

Within each year and location, half of the plots of the same species and variety (n = 3) were harvested at BT and the other half (n = 3) at SFT. To ensure consistency in harvesting, all sites were visited weekly during early spring. Once the first set of plots reached the desired stage of maturity, visits were increased to twice a week. During each visit, all plots of a particular variety and maturity stage were harvested, provided they were deemed ready for collection. Plots at BT had spikes within the sheath of the leaf flag at the time of harvesting, whereas plots at SFT had a non-milky and firm starchy endosperm when pressing the grains between fingers. These stages were equivalent to scores of 45 and 85 on Zadoks' scale (Zadoks et al., 1974), respectively. The entire biomass from each plot was cut 10 cm above the ground using a hedge trimmer (HS46C, Stihl Inc., Virginia Beach, VA), and a 0.5-kg sample of the biomass was chopped using a commercial lettuce cutter (Vollrath Redco Lettuce

**Table 1.** Planting dates of small-grain grasses and monthly rainfall according to location (Virginia) and harvest year

Item	2021			2022		
	Blacksburg	Blackstone	Orange	Blacksburg	Blackstone	Orange
Planting date	Oct. 6	Oct. 21	Oct. 15	Oct. 13	Oct. 15	Oct. 14
Rainfall, mm						
September	197	95	140	35	64	153
October	76	60	165	23	34	65
November	65	61	130	21	3	17
December	46	80	99	10	13	2
January	35	43	57	50	75	45
February	52	62	82	53	32	40
March	70	49	33	40	76	110
April	17	20	82	31	24	73
May	22	39	16	70	79	137
June	41	49	93	5	8	34
July	18	59	104	36	17	164

King I, Vollrath Co. LLC, Sheboygan, WI). The chopped sample was immediately frozen with dry ice and stored in a freezer until further processing and analysis in the laboratory.

### Forage Yield and Chemical Composition

Forage biomass yield was determined by weighing the entire biomass from each plot. Then, the sample of the chopped forage was dried to constant weight at 55°C in a forced-air oven to determine DM concentration. Wet forage yield for each plot was converted mathematically to a per-hectare basis, and then DM yield was calculated by multiplying the wet forage biomass weight by the respective DM concentration of each plot sample.

Before analysis, all dried samples were ground to pass through a 1-mm screen of a Wiley mill (Thomas Scientific, Swedesboro, NJ). Ash concentration was determined after combusting samples in a furnace (Thermolyne 30400, Barnstead International, Dubuque, IA) for 3 h at 600°C (method 942.05, AOAC, 2019). Crude protein concentration was calculated as percent N  $\times$  6.25 after combustion analysis of N (method 990.03, AOAC, 2019) using a Vario El Cube CN analyzer (Elementar Americas Inc., Mount Laurel, NJ). Ash-free NDF and ADF concentrations were determined using an Ankom200 Fiber Analyzer (Ankom Technology, Macedon, NY). Sodium sulfite and  $\alpha$ -amylase (Ankom Technology) were included for NDF analysis (Ferreira and Mertens, 2007; Ferreira and Thiex, 2023). Acid detergent fiber and ADL concentrations were determined sequentially. After determining ADF weights, residues were incubated for 3 h in 72% sulfuric acid in a 4-L jar that was placed in a DaisyII Incubator (Ankom Technology). Starch concentration was determined using the acetate buffer method of Hall (2009) with  $\alpha$ -amylase from *Bacillus licheniformis*

(FAA, Ankom Technology) and amyloglucosidase from *Aspergillus niger* (E-AMGDF, Megazyme International, Wicklow, Ireland).

### Fiber Degradation Kinetics

All procedures involving animals were approved by the Institutional Animal Care and Use Committee of Virginia Tech. Fiber degradation kinetics were determined as described by Ferreira et al. (2022). Ground samples (0.25 g) were inserted into acetone-rinsed porous bags (F57, Ankom Technology). According to their time point, these porous bags were inserted into 1 of 8 color-coded mesh bags. All color-coded mesh bags were simultaneously incubated (0900 h) in the rumen of 2 rumen-cannulated and lactating Holstein cows fed a TMR containing 42% corn silage, 5% triticale silage, 3% mixed-grass hay, and 50% concentrate mix (DM basis). Bags were sequentially extracted from the rumen 0, 3, 6, 12, 24, 48, 96, and 240 h after insertion in the rumen. One bag was prepared for each time point within each of the 2 cows. Without any previous soaking in water, the 0-h bags were submerged in the ruminal fluid for 30 s before pulling them out of the rumen. All bags were rinsed 3 times (5-min washing cycles) using a washing machine (SKY2767, Best Choice Products, Irvine, CA) and dried in a forced-air oven at 55°C for 48 h. After weighing, all bags were extracted in neutral detergent with  $\alpha$ -amylase and sodium sulfite and reweighed to determine NDF degradation as

$$NDFD_{(\%)} = \frac{iNDF_{(g)} - rNDF_{(g)}}{iNDF_{(g)}} \times 100,$$

where *NDFD* is the degradation of NDF at a certain incubation time (h), *iNDF* is the initial amount of NDF

placed in the filter bag, and *rNDF* is the residue of NDF remaining after incubation in the rumen and extraction with neutral detergent.

Fiber degradation kinetic parameters were estimated using the NLIN procedure of SAS (SAS version 9.4, SAS Institute Inc., Cary, NC). Ruminant in situ NDF degradability (**ISNDFD**) was estimated assuming first-order digestion kinetics with a discrete lag time (Mertens, 1973) and according to the model

$$ISNDFD = (100 - uNDF) \times \left(1 - e^{\left[-k_d \times (T - Lag)\right]}\right),$$

where *ISNDFD* is the degraded NDF (% NDF) at time of fermentation *T* (h), **uNDF** (% NDF) is the undegraded NDF after 240 h of fermentation, *Lag* is the discrete lag time, and **k<sub>d</sub>** is the degradation rate (%/h) of the potentially degradable NDF (**pdNDF**; % NDF). The soluble fraction of NDF (commonly known as “fraction A”) was assumed to be 0, as NDF is not immediately degraded in the rumen (Ohlsson et al., 2007; Coblenz et al., 2018b).

### Digestible Energy Value

The digestible energy (**DE**) concentration of each forage was determined as described by NASEM (2021) but with a few omissions. Briefly, DE (Mcal kg DM) was calculated as

$$\begin{aligned} DE = & 0.056 \times CP_{(\% DM)} \times 0.965 + 0.094 \times Fat_{(\% DM)} \\ & \times 0.73 + 0.042 \times NDF_{(\% DM)} \times ISNDFD_{48} + 0.042 \\ & \times Starch_{(\% DM)} \times 0.91 + 0.04 \times ROM_{(\% DM)} \times 0.96, \end{aligned}$$

where *Fat* was considered constant and equal to 4% (DM basis), *ISNDFD<sub>48</sub>* is the *ISNDFD* after 48 h of fermentation within the rumen, and *ROM* is the residual OM (DM basis), which was estimated as

$$\begin{aligned} ROM_{(\% DM)} = & 100 - [Ash_{(\% DM)} + CP_{(\% DM)} \\ & + Fat_{(\% DM)} + NDF_{(\% DM)} + Starch_{(\% DM)}]. \end{aligned}$$

Default digestibility coefficients (NASEM, 2021) were used for fat, starch, and ROM. For CP, a digestibility coefficient (CPD) was obtained using information for fresh rye (NRC16F124; NASEM, 2021) and calculated as

$$CPD_{(\% CP)} = RDP_{(\% CP)} \times 1.0 + RUP_{(\% CP)} \times 0.65,$$

where *RDP* = 90 and *RUP* = 10 (CP basis).

### Ration Formulation

For this study, we considered the nutritional composition and the fiber digestion kinetics of small-grain grass silages to be the same as those of fresh forages. For each of the 6 small-grain grass silages, we formulated 8 rations according to 8 different scenarios using the least-cost optimizer of CPM Dairy (version 3.0.8.1; CAHP Software Information, Philadelphia, PA). The scenarios included high and low commodity prices, high and low dietary forage (60% and 40% forage, respectively), and the inclusion of small-grain silage when harvesting the crop at BT or SFT.

We obtained monthly commodity prices from 2004 to 2023 from the Feed Grains Database published by the Economic Research Service (2024). After gathering the database, we organized the prices of different commodities in quartiles, and the first (**Q1**) and third (**Q3**) quartiles were used to reflect low-price and high-price scenarios, respectively (Table 2). Then, we loaded the Q1 and Q3 prices in CPM to formulate rations using the least-cost optimizer. We included minerals, vitamins, and other additives in constant amounts and without price for all diets. We considered the market price of corn silage (\$/Mg) to equal the price of 10.1 bushels of corn grain (National Milk Producers Federation, 2010). To price small-grain silages, we calculated the theoretical cost of production (Table 3) and used these prices in both the low-price and the high-price scenarios.

For ration formulation, we used corn silage (NRC16F148), corn grain (NRC16F1070), soybean meal (NRC16F134), corn dried distillers grains (NRC16F61),

**Table 2.** Historical prices<sup>1</sup> (\$/Mg) of commodities (2004 to 2023)

Item	Minimum	Q1 <sup>2</sup>	Median	Q3	Maximum
Corn silage <sup>3</sup>	20	37	41	59	85
Alfalfa hay	85	121	167	194	288
Corn grain	70	132	145	208	300
Soybean meal (48% CP)	154	292	331	412	565
Dried distillers grains	63	115	149	205	302
Wheat middlings	22	72	107	150	293

<sup>1</sup>Prices are free on board (FOB) and as reposted by Economic Research Service (2024).

<sup>2</sup>Q1 = first quartile; Q3 = third quartile.

<sup>3</sup>Price corn silage (\$/Mg) = Price corn grain (\$/Mg) × 0.285 (National Milk Producers Federation, 2010).

**Table 3.** Estimated production cost of barley, rye, or triticale silage according to a simulated input package and reported forage yields when crops are harvested at either the boot stage (BT) or soft dough stage (SFT) of maturity

Item	Barley		Rye		Triticale	
	BT	SFT	BT	SFT	BT	SFT
Silage yield, Mg DM/ha	3.9	9.5	4.4	13.4	6.1	12.6
Spreading manure, <sup>1</sup> \$/ha	70	70	70	70	70	70
Seeds and drilling, <sup>2</sup> \$/ha	174	174	174	174	174	174
Weed control, <sup>3</sup> \$/ha	30	30	30	30	30	30
Mowing, chopping, and hauling, <sup>4</sup> \$/ha	192	388	209	524	269	496
Bag and bagging, <sup>5</sup> \$/ha	147	358	166	505	230	474
Total cost, \$/ha	613	1,020	649	1,303	773	1,244
Silage cost, \$/Mg DM	157	107	148	97	127	99
Silage cost (at 35% DM), \$/Mg	55	38	52	34	44	35

<sup>1</sup>20,000 L/ha at \$3.48/1,000 L.

<sup>2</sup>Seed: 115 kg/ha at \$1.10/kg; drilling: \$47.00/ha.

<sup>3</sup>Herbicides: 0.5 L at \$20.00/L; spraying: \$20.00/ha.

<sup>4</sup>Mowing: \$55.00/ha; chopping: \$25.00/Mg DM; hauling: \$10.00/Mg DM.

<sup>5</sup>Bag: \$9.05/Mg DM; bagging: \$28.60/Mg DM.

and wheat middlings (NRC16F58) as non-research feed ingredients. The nutritional compositions reported in NASEM (2021) were loaded into the feed library of CPM for all these ingredients. For all concentrates, the default ruminal fiber digestion kinetics parameters (i.e., uNDF and  $k_d$ ) from the feed library of CPM were used. For corn silage, we considered a  $k_d$  of pdNDF equal to 2.5%/h (Ferreira et al., 2022).

Animal input for ration formulation included a 670-kg Holstein cow in her second lactation, at 40 mo of age, being 50 d in milk, and producing 45 kg of milk containing 3.80% fat and 3.05% true protein. Ration formulation was constrained to meet 100% to 105% of the requirements for metabolizable energy and metabolizable protein and to contain 28% to 30% NDF, 24% to 30% starch, less than 45% nonfiber carbohydrates, and less than 6% fatty acids.

### Climate Data and Growing-Degree Days

Rainfall and temperature data were obtained from the Piedmont Research Station ([www.weather.gov](http://www.weather.gov)) for the Orange location and from the Kentland Farm and Southern Piedmont weather stations of Virginia Tech for the Blacksburg and Blackstone locations, respectively (Table 1). Growing-degree days (GDD) were calculated as

$$GDD = \left[ \frac{T_{Max} + T_{Min}}{2} \right],$$

where  $T_{Max}$  is the daily maximum air temperature and  $T_{Min}$  is the daily minimum air temperature (McMaster and Wilhelm, 1997). Only days with growing-degree days greater than 0°C counted in the cumulative GDD.

### Statistical Analyses

To evaluate differences in nutritional composition among species and between maturities at harvest, we used the MIXED procedure of SAS (SAS version 9.4, SAS Institute Inc., Cary, NC). The statistical model included the fixed effect of species (2 degrees of freedom [df]), the fixed effect of maturity at harvest (1 df), the species by maturity interaction (2 df), the random effect of environment (5 df), the random effect of variety nested within species (7 df), the random effect of block nested within environment (12 df), and the random residual error. When an interaction existed, Tukey's pairwise comparisons contrasted combinations of species and maturities.

## RESULTS AND DISCUSSION

As a first goal, this study intended to determine the expected forage yield and the nutritional composition of small-grain grasses based on the variability of different varieties grown in diverse environments (Table 4). As expected, harvesting at SFT yielded substantially more biomass than harvesting at BT ( $P < 0.01$ ). However, the magnitude of this difference varied among species, as reflected by the existing interaction ( $P < 0.01$ ). At SFT, triticale yielded 2.1 times more (12.6 vs. 6.1 Mg DM/ha), barley yielded 2.4 times more (9.5 vs. 3.9 Mg DM/ha), and rye yielded 3.0 times more (13.4 vs. 4.4 Mg DM/ha) compared with harvesting at BT (Table 4). The differences in DM yield observed in this study are similar in magnitude to those reported by Jemison et al. (2012) and Coblenz et al. (2018a). These observations should help dairy farmers and nutritionists decide the optimal time for harvesting small-grain grasses for silage. For

**Table 4.** Dry matter yield and nutritional composition<sup>1</sup> of small-grain grasses for silage as affected by maturity at harvest<sup>2</sup>

Item	Barley		Rye		Triticale		SEM	P-value <sup>3</sup>		
	BT	SFT	BT	SFT	BT	SFT		M	S	M × S
DM yield, Mg/ha	3.9 <sup>d</sup>	9.5 <sup>b</sup>	4.4 <sup>d</sup>	13.4 <sup>a</sup>	6.1 <sup>c</sup>	12.6 <sup>a</sup>	0.55	0.01	0.01	0.01
DM, % as-is	18.4 <sup>c</sup>	31.3 <sup>b</sup>	19.2 <sup>c</sup>	39.9 <sup>a</sup>	20.0 <sup>c</sup>	37.7 <sup>a</sup>	0.91	0.01	0.01	0.01
OM	92.2 <sup>d</sup>	95.0 <sup>b</sup>	93.0 <sup>c</sup>	96.5 <sup>a</sup>	93.3 <sup>c</sup>	96.8 <sup>a</sup>	0.27	0.01	0.01	0.01
CP	13.9 <sup>a</sup>	8.5 <sup>c</sup>	13.9 <sup>a</sup>	5.4 <sup>d</sup>	10.8 <sup>b</sup>	6.3 <sup>d</sup>	1.04	0.01	0.01	0.01
NDF	48.9 <sup>c</sup>	55.1 <sup>b</sup>	47.4 <sup>c</sup>	63.6 <sup>a</sup>	52.9 <sup>bc</sup>	62.0 <sup>a</sup>	2.19	0.01	0.16	0.01
ADF	27.5 <sup>c</sup>	32.3 <sup>b</sup>	26.5 <sup>c</sup>	41.0 <sup>a</sup>	30.1 <sup>bc</sup>	38.5 <sup>a</sup>	1.82	0.01	0.15	0.01
ADL	2.7 <sup>c</sup>	4.3 <sup>b</sup>	2.5 <sup>c</sup>	5.4 <sup>ab</sup>	3.0 <sup>c</sup>	5.5 <sup>a</sup>	0.40	0.01	0.16	0.01
ADL, % NDF	5.5 <sup>c</sup>	7.8 <sup>b</sup>	5.2 <sup>c</sup>	8.5 <sup>ab</sup>	5.6 <sup>c</sup>	8.8 <sup>a</sup>	0.53	0.01	0.29	0.01
Starch	4.1 <sup>c</sup>	8.0 <sup>a</sup>	5.4 <sup>bc</sup>	4.9 <sup>c</sup>	6.7 <sup>ab</sup>	6.8 <sup>ab</sup>	0.44	0.01	0.05	0.01
DE, <sup>4</sup> Mcal/kg DM	3.79 <sup>a</sup>	3.33 <sup>b</sup>	3.81 <sup>a</sup>	3.05 <sup>c</sup>	3.69 <sup>a</sup>	3.16 <sup>bc</sup>	0.06	0.01	0.15	0.01

<sup>a-d</sup>Different superscripts in the same row differ ( $P < 0.05$ ).

<sup>1</sup>Nutritional composition on a DM basis unless stated differently.

<sup>2</sup>BT = boot stage; SFT = soft dough stage.

<sup>3</sup>M = main effect of maturity; S = main effect of species; M × S = interaction.

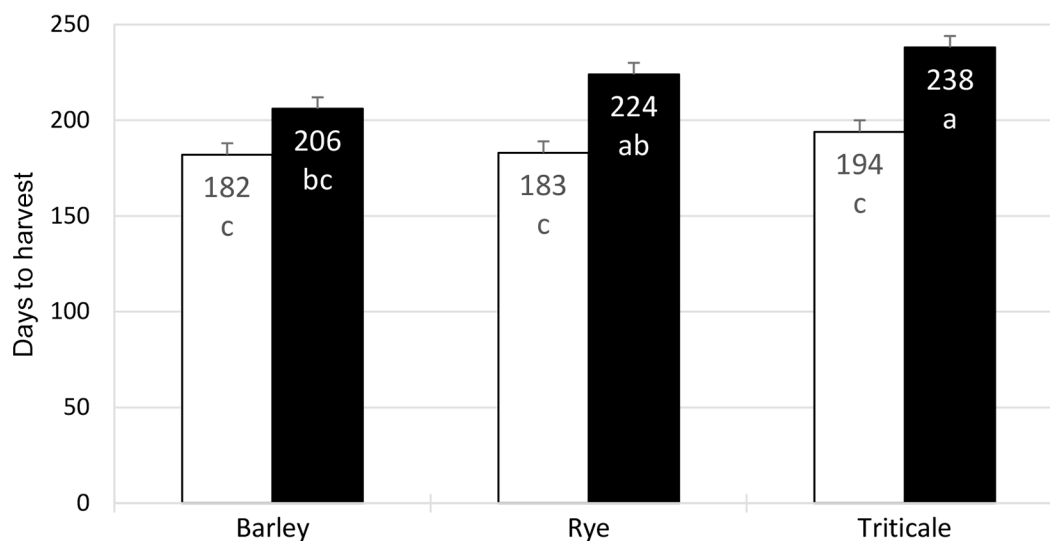
<sup>4</sup>Digestible energy.

example, harvesting at SFT yielded more than twice as much DM for all species, and the difference in yields should result in less expensive silage when harvesting small-grain grasses at SFT than when harvesting at BT, due to the dilution of input costs (Table 3). However, the data of this study also indicate that the difference in silage costs between the 2 stages of maturity is less relevant for triticale (\$9/Mg silage) than for barley (\$17/Mg silage) or rye (\$18/Mg silage).

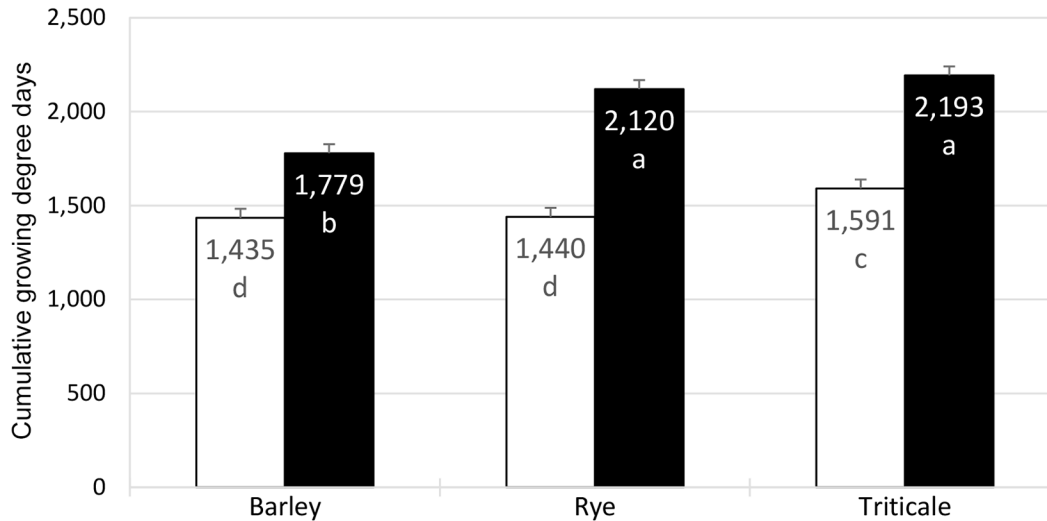
Relative to BT, harvesting at SFT delayed the harvest 33 d on average (Figure 1), and this delay was longest for triticale (44 d) and rye (41 d) and shortest for barley (24 d). Barley and rye also needed fewer GDD than triticale to reach BT (156 and 151, respectively), and barley and

rye reached BT earlier in the spring season than triticale (Figure 2). From these data, we highlight 2 observations. First, these data show that the window for harvesting barley is much narrower than the window for harvesting rye or triticale. This timing is relevant when contracting a custom harvester for ensiling. Second, a 24- to 44-d delay in harvesting, relative to BT, can delay the subsequent establishment of desirable double-cropping options, such as corn or forage sorghum, well into the summer. This can have a detrimental effect on total forage production (Krueger et al., 2012).

Harvesting at different stages of maturity affected the concentration of most constituents in all species. Small-grain grasses harvested at SFT had greater concentra-



**Figure 1.** Number of days from seeding to harvest of small-grain grasses as affected by maturity stage at harvest (boot stage in white columns, and soft dough stage in black columns). Columns with different lowercase letters differ ( $P < 0.05$ ). Error bars represent SEM.



**Figure 2.** Cumulative growing-degree days of small-grain grasses as affected by maturity stage at harvest (boot stage in white columns, and soft dough stage in black columns). Columns with different lowercase letters differ ( $P < 0.05$ ). Error bars represent SEM.

tions of OM than small-grain grasses harvested at BT ( $P < 0.01$ ). As indicated by the existing interaction between species and maturity at harvest ( $P < 0.01$ ), the difference in OM between maturity stages varied among species, being 2.8 percentage units different for barley (95.0% vs. 92.2% OM) and 3.5 percentage units different for rye and triticale (96.7% vs. 93.2% OM). In addition, barley had a slightly lower concentration of OM than rye and triticale ( $P < 0.01$ ). An increase in OM concentration corresponds to a decrease in the concentration of ash, which provides no energy to the animal. This is an indication that a lower energy concentration should be expected in the silage when small-grain grasses are harvested at SFT relative to BT.

As expected, harvesting at SFT resulted in a lower CP concentration for the 3 grass species ( $P < 0.01$ ). However, as reflected by the existing interaction between maturity at harvest and species ( $P < 0.01$ ), the magnitude of the decrease in CP concentration varied among species (10.8% vs. 6.3% CP for triticale, 13.9% vs. 8.5% CP for barley, and 13.9% vs. 5.4% CP for rye). It is worth highlighting the greater CP concentrations of barley and rye, relative to the CP concentration of triticale, when harvested at BT. Therefore, lower CP concentrations for triticale, relative to barley and rye, should be expected when selecting species to grow in dairy farming systems. One reason for the lower CP concentration is that triticale reached BT 11 to 12 d later than barley and rye (Figure 1). This translates into additional GDD accumulation (Figure 2) and, therefore, a plausible dilution of CP due to increased NDF deposition (Table 4). Given that protein concentrates are the most expensive ingredients included in rations for dairy cattle, a lower CP concentration

might also affect the output of ration formulation and the feeding costs.

As we expected, small-grain grasses harvested at SFT had greater NDF ( $P < 0.01$ ), ADF ( $P < 0.01$ ), and ADL ( $P < 0.01$ ) concentrations than small-grain grasses harvested at BT (Table 4). The significant interaction between maturity at harvest and species ( $P < 0.01$ ) indicates that the NDF concentration differed less drastically between maturity stages for barley (55.1% vs. 48.9% NDF) than for rye and triticale (62.8% vs. 50.3% NDF). No differences existed for NDF ( $P = 0.16$ ), ADF ( $P = 0.15$ ), or ADL ( $P = 0.16$ ) concentrations among species. Because NDF is an entity of incomplete and variable digestibility (Van Soest, 1994), lower concentrations of energy should be expected in the silage when small-grain grasses are harvested at SFT relative to BT, and this difference might also affect the output in ration formulation.

As indicated by the interaction ( $P < 0.01$ ; Table 4), harvesting at SFT resulted in a greater starch concentration than harvesting at BT in barley (4.1% vs. 8.0% starch), although the maturity at harvest did not affect starch concentration in rye or triticale (5.2% and 6.8% starch, respectively). Among species ( $P < 0.05$ ), rye contained less starch than triticale (5.2% vs. 6.8% starch), and barley had a low or high concentration of starch depending on the maturity at harvest (4.1% and 8.0% starch for BT and SFT, respectively). Coblenz et al. (2018a) did not report starch concentrations. From this study, we consider the effect of maturity at harvest to be minimal on the starch concentration in small-grain grasses.

In this study, we also evaluated the effect of maturity at harvest on NDF digestion kinetics (Table 5). As expected, harvesting at SFT resulted in a greater uNDF

**Table 5.** Parameters<sup>1</sup> of fiber digestion kinetics of small-grain grasses for silage as affected by maturity at harvest<sup>2</sup>

Item	Barley		Rye		Triticale		SEM	<i>P</i> -value <sup>3</sup>		
	BT	SFT	BT	SFT	BT	SFT		M	S	M × S
Lag, h	1.8 <sup>c</sup>	2.7 <sup>ab</sup>	1.5 <sup>c</sup>	3.5 <sup>a</sup>	2.0 <sup>bc</sup>	3.4 <sup>a</sup>	0.32	0.01	0.31	0.01
pdNDF, % NDF	87.0 <sup>a</sup>	65.9 <sup>b</sup>	86.2 <sup>a</sup>	57.6 <sup>c</sup>	83.0 <sup>a</sup>	61.9 <sup>bc</sup>	1.74	0.01	0.15	0.01
uNDF, % NDF	13.0 <sup>c</sup>	34.1 <sup>b</sup>	13.8 <sup>c</sup>	42.4 <sup>a</sup>	17.0 <sup>c</sup>	38.1 <sup>ab</sup>	1.74	0.01	0.15	0.01
k <sub>d</sub> , %/h	4.50 <sup>a</sup>	2.76 <sup>c</sup>	4.58 <sup>a</sup>	1.95 <sup>d</sup>	3.87 <sup>b</sup>	2.13 <sup>d</sup>	0.22	0.01	0.02	0.01

<sup>a-d</sup>Different superscripts in the same row differ ( $P < 0.05$ ).

<sup>1</sup>pdNDF = potentially degradable NDF; uNDF = undegraded NDF; k<sub>d</sub> = rate of degradation of pdNDF.

<sup>2</sup>BT = boot stage; SFT = soft dough stage.

<sup>3</sup>M = main effect of maturity; S = main effect of species; M × S = interaction.

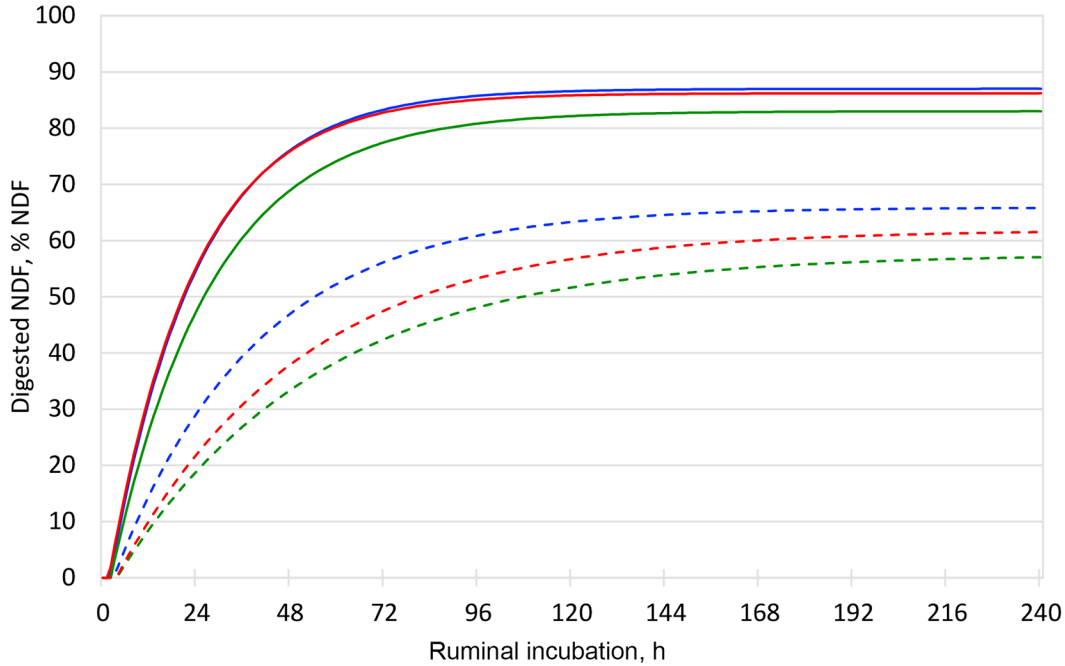
concentration (NDF basis) than harvesting at BT. However, given the significant interaction between species and maturity at harvest ( $P < 0.01$ ), harvesting at SFT affected the uNDF concentration to a much greater extent in rye (42.4% vs. 13.8% uNDF) than for barley and triticale (36.1% vs. 15.0% uNDF). Also, harvesting at SFT resulted in a longer discrete lag than harvesting at BT ( $P < 0.01$ ), and this increase ranged from 0.9 to 2.0 h (Table 5). Similar to our data, Coblenz et al. (2018b) reported an increase in uNDF concentration (NDF basis) from 15.6% to 44.3% for triticale harvested at BT and SFT, respectively. Therefore, a 2- to 3-fold increase in uNDF concentration should be expected when small-grain grasses are harvested at SFT relative to BT.

Differences of k<sub>d</sub> have limited meaning without putting pdNDF and uNDF concentrations in perspective. At BT, all species had similar pdNDF (85.4%) and uNDF (14.6%) concentrations. However, triticale had a k<sub>d</sub> equal to 3.87%/h, whereas barley and rye had k<sub>d</sub> equal to 4.54%/h. These data indicate that, when harvested at BT, pdNDF in triticale had lower degradation potential than barley and rye (Figure 3). Curiously, these differences were not associated with differences in lignification (Table 4). At SFT, barley contained 65.9% pdNDF, rye contained 57.6% pdNDF, and triticale contained an intermediate amount of pdNDF that was not different from barley or rye (61.9% pdNDF) on an NDF basis. Consequently, barley contained 34.1% uNDF, rye contained 42.4% uNDF, and triticale contained an intermediate amount of uNDF that was not different from barley or rye (38.1% uNDF) on an NDF basis. However, barley exhibited a k<sub>d</sub> equivalent to 2.76%/h, whereas rye and triticale exhibited similar k<sub>d</sub> equivalent to 1.95%/h and 2.13%/h, respectively. These data indicate that, when harvested at SFT, pdNDF in barley had the highest degradation potential, triticale had an intermediate degradation potential, and rye had the least degradation potential (Figure 3).

The energy that a dairy cow can obtain from a feed depends on the composition of the feed and on the availability of its constituents (NASEM, 2021). Because harvesting at SFT increased the concentration of

ash, decreased the concentration of CP, increased the concentration of NDF, and reduced the degradability of NDF, we expected a substantial reduction in DE concentration as the maturity of the forage advanced. In agreement with our expectations, small-grain grasses harvested at SFT contained less DE than small-grain grasses harvested at BT ( $P < 0.01$ ). When harvested at BT, no differences existed among species (3.76 Mcal/kg DM;  $P = 0.15$ ). When harvested at SFT, barley and rye had the highest and lowest concentrations of DE (3.33 and 3.05 Mcal/kg DM, respectively), whereas the DE concentration of triticale fell in between those (3.16 Mcal/kg DM). The effect of maturity at harvest on DE concentration is contrary to that reported by NASEM (2021), which reported higher DE for headed barley silage (NRC16F11) than for vegetative barley silage (NRC16F13). This inversion may relate to differences in starch concentrations or the missing information for NDF digestibility at 48 h (NASEM, 2021). Also, it is worth highlighting that our DE calculations did not discount metabolic fecal CP, fecal microbial CP, and endogenous fecal residual OM, as these fractions are a function of DMI (NASEM, 2021).

In this study, we hypothesized that including small-grain grass silage harvested at SFT is more economical than including small-grain grass silage harvested at BT when commodity prices are low but not when prices are high. Under a low-price scenario (Table 6), the ration formulation system ignored all 6 small-grain grass silages and included corn silage as the only forage source when we did not limit its inclusion. Using 100% corn silage as forage, the resulting ration cost \$3.47/cow per day for the low-forage diet and \$4.12/cow per day for the high-forage diet. In the low-price scenario, the Q1 price of corn silage equals \$37/Mg (as-fed basis; Table 2). However, the prices of small-grain grass silages ranged from \$34 to \$55/Mg (Table 3). The relatively low price, coupled with its superior nutritional quality, makes corn silage a more suitable ingredient for creating a feasible ration. This explains why the optimization process excluded the 6 small-grain grasses in this scenario.



**Figure 3.** Fiber digestion kinetics of small-grain grasses (barley = blue, rye = red, triticale = green) as affected by maturity stage at harvest (boot stage = solid lines, and soft dough stage = broken lines).

**Table 6.** Ration formulation convergence, small-grain grass silage (SGGS) inclusion rate, and ration cost according to different scenarios (i.e., low prices, dietary forage, and corn silage [CS] inclusion rate) and as affected by the species and the maturity at harvest of the small-grain grass for silage

Price <sup>1</sup>	Dietary forage <sup>2</sup>	CS inclusion, <sup>3</sup> kg DM/cow per day	SGGS	Maturity <sup>4</sup>	Convergence <sup>5</sup>	SGGS inclusion, kg DM/d	Ration cost, \$/cow per day
Low	Low	Unlimited	Barley	BT	Yes (I)	—	3.47
Low	Low	Unlimited	Barley	SFT	Yes (I)	—	3.47
Low	Low	Unlimited	Rye	BT	Yes (I)	—	3.47
Low	Low	Unlimited	Rye	SFT	Yes (I)	—	3.47
Low	Low	Unlimited	Triticale	BT	Yes (I)	—	3.47
Low	Low	Unlimited	Triticale	SFT	Yes (I)	—	3.47
Low	High	Unlimited	Barley	BT	Yes (I)	—	4.12
Low	High	Unlimited	Barley	SFT	Yes (I)	—	4.12
Low	High	Unlimited	Rye	BT	Yes (I)	—	4.12
Low	High	Unlimited	Rye	SFT	Yes (I)	—	4.12
Low	High	Unlimited	Triticale	BT	Yes (I)	—	4.12
Low	High	Unlimited	Triticale	SFT	Yes (I)	—	4.12
Low	Low	Limited	Barley	BT	Yes (S)	1.70	3.56
Low	Low	Limited	Barley	SFT	Yes (F)	1.70	3.50
Low	Low	Limited	Rye	BT	Yes (S)	1.70	3.52
Low	Low	Limited	Rye	SFT	Yes (F)	1.70	3.51
Low	Low	Limited	Triticale	BT	Yes (S)	1.67	3.50
Low	Low	Limited	Triticale	SFT	Yes (F)	1.70	3.50
Low	High	Limited	Barley	BT	No	—	—
Low	High	Limited	Barley	SFT	No	—	—
Low	High	Limited	Rye	BT	No	—	—
Low	High	Limited	Rye	SFT	No	—	—
Low	High	Limited	Triticale	BT	No	—	—
Low	High	Limited	Triticale	SFT	No	—	—

<sup>1</sup>Low corn silage and commodity prices.

<sup>2</sup>Low = 38% to 42% dietary forage; high = 48% to 62% dietary forage.

<sup>3</sup>Limited: <8 kg DM/cow per day.

<sup>4</sup>BT = boot stage; SFT = soft dough stage.

<sup>5</sup>F = first choice of SGGS within scenario; S = second choice of SGGS within scenario; I = SGGS ignored.

**Table 7.** Ration formulation convergence, small-grain grass silage (SGGS) inclusion rate, and ration cost according to different scenarios (i.e., high prices, dietary forage, and corn silage [CS] inclusion rate) and as affected by the species and the maturity at harvest of the small-grain grass

Price <sup>1</sup>	Dietary Forage <sup>2</sup>	CS inclusion, <sup>3</sup> kg DM/cow per day	SGGS	Maturity <sup>4</sup>	Convergence <sup>5</sup>	SGGS inclusion, kg DM/d	Ration cost, \$/cow per day
High	Low	Unlimited	Barley	BT	Yes (S)	8.23	5.49
High	Low	Unlimited	Barley	SFT	Yes (F)	6.49	5.31
High	Low	Unlimited	Rye	BT	Yes (F)	8.02	5.33
High	Low	Unlimited	Rye	SFT	Yes (S)	3.99	5.44
High	Low	Unlimited	Triticale	BT	Yes (F)	7.35	5.20
High	Low	Unlimited	Triticale	SFT	Yes (S)	4.33	5.38
High	High	Unlimited	Barley	BT	Yes (I)	—	6.03
High	High	Unlimited	Barley	SFT	Yes (I)	—	6.03
High	High	Unlimited	Rye	BT	Yes (I)	—	6.03
High	High	Unlimited	Rye	SFT	Yes (I)	—	6.03
High	High	Unlimited	Triticale	BT	Yes (I)	—	6.03
High	High	Unlimited	Triticale	SFT	Yes (I)	—	6.03
High	Low	Limited	Barley	BT	Yes (S)	8.23	5.49
High	Low	Limited	Barley	SFT	Yes (F)	6.49	5.31
High	Low	Limited	Rye	BT	Yes (F)	8.02	5.32
High	Low	Limited	Rye	SFT	Yes (S)	3.99	5.44
High	Low	Limited	Triticale	BT	Yes (F)	7.35	5.20
High	Low	Limited	Triticale	SFT	Yes (S)	4.33	5.38
High	High	Limited	Barley	BT	No	—	—
High	High	Limited	Barley	SFT	No	—	—
High	High	Limited	Rye	BT	No	—	—
High	High	Limited	Rye	SFT	No	—	—
High	High	Limited	Triticale	BT	No	—	—
High	High	Limited	Triticale	SFT	No	—	—

<sup>1</sup>High corn silage and commodity prices.<sup>2</sup>Low = 38% to 42% dietary forage; high = 48% to 62% dietary forage.<sup>3</sup>Limited: <8 kg DM/cow per day.<sup>4</sup>BT = boot stage; SFT = soft dough stage.<sup>5</sup>F = first choice of SGGS within scenario; S = second choice of SGGS within scenario; I = SGGS ignored.

We performed another simulation constraining the inclusion of corn silage to 8.0 kg DM/cow per day, representing a scenario where corn silage inventories are scarce at the dairy farm (Table 6). Under these conditions, the ration formulation system forced the inclusion of small-grain grass silages when we formulated low-forage diets but did not converge into feasible rations when we formulated high-forage diets (Table 6). Possibly due to high (forced) inclusion rates of silages and their high NDF concentrations, no convergence existed in ration formulation for the high-forage diets (i.e., no ration could be formulated according to the specifications). For the low-forage diets, the ration formulation system included all small-grain grass silages at the same inclusion rates (1.7 kg DM/cow per day), suggesting that the nutritional quality among small-grain grass silages did not affect their inclusion. Interestingly, the formulation system selected small-grain grass silages harvested at SFT as the first choice for barley, rye, and triticale, although the ration costs when including small-grain grass silages harvested at either BT or SFT ranged from \$3.50 to \$3.56/cow per day and differed minimally. Despite the minimal difference in ration cost, these observations partially confirm our hypothesis that, when prices for

protein sources are low, harvesting small-grain grasses at SFT may be more convenient than harvesting at BT.

Under a high-price scenario, the ration formulation system included all 6 small-grain grass silages when formulating low-forage diets with unlimited corn silage (Table 7). However, a preference between BT and SFT did not exist, as the optimizer chose SFT as a first choice for barley and BoS as a first choice for rye and triticale. Given the lower prices relative to the price of corn silage, small-grain grass silages substituted corn silage at rates ranging from 4.0 to 8.2 kg/cow per day, and the cost of the resulting diets ranged from \$5.20 to \$5.49/cow per day. When formulating high-forage diets with unlimited inclusion of corn silage, the ration formulation system ignored all 6 small-grain grass silages and included corn silage as the only forage source.

When formulating low-forage diets and limiting the inclusion of corn silage to 8 kg DM/cow per day, the ration formulation system included all of the 6 small-grain grass silages at the same rates as when corn silage was unrestricted. Hence, no evident preference existed for maturity at harvest, as the optimizer chose SFT as a first choice for barley and BT as a first choice for rye and triticale. Finally, when formulating high-forage diets while

**Table 8.** Ration formulation convergence, corn silage (CS) inclusion rate, and ration cost according to different scenarios (i.e., high and low prices, low dietary forage, and small-grain grass silage [SGGS] inclusion rate) and as affected by the species and the maturity at harvest of the small-grain grass

Price <sup>1</sup>	Dietary forage <sup>2</sup>	CS inclusion, kg DM/cow per day	SGGS	Maturity <sup>3</sup>	Convergence	SGGS inclusion, kg DM/d	Ration cost, \$/cow per day
Low	Low	5.0	Barley	BT	Yes	4.70	3.72
Low	Low	5.0	Barley	SFT	Yes	4.70	3.56
Low	Low	5.0	Rye	BT	Yes	4.60	3.65
Low	Low	5.0	Rye	SFT	Yes	4.67	3.69
Low	Low	5.0	Triticale	BT	Yes	4.57	3.55
Low	Low	5.0	Triticale	SFT	Yes	4.66	3.61
High	Low	5.0	Barley	BT	Yes	4.70	5.53
High	Low	5.0	Barley	SFT	Yes	4.70	5.37
High	Low	5.0	Rye	BT	Yes	4.80	5.43
High	Low	5.0	Rye	SFT	Yes	4.67	5.50
High	Low	5.0	Triticale	BT	Yes	4.54	5.32
High	Low	5.0	Triticale	SFT	Yes	4.67	5.41

<sup>1</sup>High corn silage and commodity prices.

<sup>2</sup>Low = 38% to 42% dietary forage; high = 48% to 62% dietary forage.

<sup>3</sup>BT = boot stage; SFT = soft dough stage.

constraining the inclusion of corn silage to 8 kg DM/cow per day, the ration formulation system did not converge into feasible rations with the ingredients selected. Likely, this is due to the high NDF concentrations of the small-grain grasses.

Another scenario for using small-grain grass silages is when these silages are available (i.e., existing inventories) and included at fixed rates. Considering a fixed inclusion rate of 5.0 kg DM/cow per day of small-grain grass silage (i.e., ~25% of the dietary DM; Table 8), the optimizer yielded rations costing \$3.55 to \$3.72/cow per day at low commodity prices and \$5.32 to \$5.53/cow per day at high commodity prices. Once again, no evident preference existed for maturity at harvest, as the ration formulating system selected BT sometimes and SFT at other times.

## CONCLUSIONS

From a nutritional perspective, species selection had minimal effect on the nutritional quality of small-grain grasses for silage. However, harvesting small-grain grasses at SFT resulted in poorer nutritional quality than harvesting at BT. From a ration formulation perspective, the optimizer tool of the ration formulation system may exclude small-grain grass silages from the diet, and a reason for this is that the nutritional quality of small-grain grasses would likely be inferior to that of other forages, such as corn silage. Also, from a ration formulation perspective, the optimizer did not consistently select a specific maturity stage. After evaluating the yields, the chemical composition, and the effects on ration formulation in this study, future studies should aim to evaluate the effect of maturity at harvest of small-grain grasses on cow performance and environmental impacts.

## NOTES

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**Nonstandard abbreviations used:** BT = boot stage of maturity; DE = digestible energy; GDD = growing-degree days; ISNDFD = in situ NDF degradability;  $k_d$  = degradation rate; pdNDF = potentially degradable NDF; Q1, Q3 = first and third quartiles, respectively; SFT = soft dough stage of maturity; SGGS = small-grain grass silage; uNDF = undegraded NDF.

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