Effects of growth stage and growing degree day accumulations on triticale forages: 1. Dry matter yield, nutritive value, and in vitro dry matter disappearance

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ABSTRACT

The use of triticale (*X Triticosecale* Wittmack) in dairy-cropping systems has expanded greatly in recent years, partly to improve land stewardship by providing winter ground cover. Our objective was to establish relationships relating indices of nutritive value with growth stage or accumulated growing degree days $>5^{\circ}\text{C}$ for triticale forages grown in central Wisconsin. Replicated 3.7-m $\times$ 9.1-m plots were established following removal of corn for silage (fall 2015) and soybeans (fall 2016) and then harvested at various growth stages the following spring. Plants were assigned a numerical growth stage based on a linear staging system suitable for use as an independent regression variable. Response variables [e.g., dry matter (DM) yield, indices of nutritive value, and parameters from in vitro DM disappearance kinetics] were regressed on growth stage and growing degree days using linear, quadratic, cubic, or quartic models. For spring 2016, the mean DM yield at the boot stage (3,804 kg of DM/ha) was only 30% of that observed at the soft dough stage of growth (12,642 kg of DM/ha). Although yields were reduced during spring 2017, primarily due to spring flooding, the relationship between respective yields at these growth stages was similar (1,453 vs. 5,399 kg of DM/ha). Regressions of DM yield (kg/ha) on growth stage for 2016 were explained by a cubic model ($Y = 0.0663x^3 - 9.44x^2 + 595x - 9,810$) compared with a simple linear response for 2017 ($Y = 103x - 3,024$); in both cases, coefficients of determination were very high ($R^2 \geq 0.934$). Many nutritional and in vitro DM disappearance characteristics were affected by the juxtaposition and balance of 2 generally competing factors: (1) increased concentrations of structural plant fiber

coupled with concurrent lignification as plants matured and (2) the accumulation of highly digestible carbohydrate during seed head development. A comparison of respective energy yields between the boot and soft dough stages of growth for 2016 (2,488 vs. 8,141 kg of total digestible nutrients/ha) and 2017 (1,033 vs. 3,520 kg of total digestible nutrients/ha) suggests that yields of energy are greater at soft dough stage and are mostly driven by DM yield. An informed harvest management decision for lactating cows may still favor a boot-stage harvest because of superior nutritional characteristics, a need to plant double-cropped corn expeditiously, or both. Harvest timing of triticale forages for other livestock classes would appear to be more flexible, but prioritizing a subsequent double crop may reduce the effects on DM yield to a secondary consideration.

Key words: double cropping, harvest timing, nutritive value, triticale

INTRODUCTION

The use of triticale (*X Triticosecale* Wittmack) in dairy-cropping systems has expanded greatly in recent years, partly in response to environmental pressures, such as a desire to capture N from land-applied manure or to improve stewardship of the land by providing winter ground cover. However, triticale also is recognized as a valuable forage crop (McCormick et al., 2006; Gibson et al., 2007; Baron et al., 2012) with the potential for use across a range of livestock classes, but appropriate use of triticale requires proper synchronization of forage nutrient composition with the nutrient demands of each livestock class. Generally, triticale functions as a winter-annual forage; most production scenarios in the north-central United States focus on fall establishment after removal of corn for silage or soybeans (Schwarte et al., 2005; Gibson et al., 2007), followed by harvest as silage the following spring or early summer. However, when this production strategy is used, accumulation of

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DM during spring is affected negatively by delayed fall planting dates, which has been attributed to inadequate leaf area, and reduced light interception that subsequently reduces the rate of spring growth (Schwarte et al., 2005).

Several previous studies have attempted to provide some guidance concerning proper agronomic or harvest management for triticale. These studies have used a wide scope of perspectives that include (1) assessment of fall growth alone (Coblentz and Walgenbach, 2010), (2) assessment of fall and spring growth combined (Maloney et al., 1999; McCormick et al., 2006), (3) multiple species comparisons established in monocultures or mixtures (Cherney and Marten, 1982a; Khorasani et al., 1997; McCormick et al., 2006), (4) focused emphasis on the effects of plant maturity on forage quality (Khorasani et al., 1997; Cherney and Marten, 1982a,b), (5) assessment of simulated grazing or haying scenarios on DM yield (Drake and Orloff, 2005), (6) N and P fertilization strategies and their subsequent effects on forage quality (Harmoniey and Thompson, 2005), (7) timing of seeding dates and their effects on fall and spring DM yield and associated forage quality (Griggs, 2006), and (8) substitution of triticale for corn silage in diets of midlactation cows (Harper et al., 2017). Generally, recommendations for harvest of high-energy forage suitable for dairy cows are to cut when the flag leaf is fully emerged but no seed heads are visible (Kilcer et al., 2010). When this harvest schedule has been used, triticale silage has been successfully substituted for corn silage at a rate of 10% of dietary DM (Harper et al., 2017). Historically, harvests at the late milk to early dough stages of growth also have been common (McDonald et al., 1991; McCartney and Vaage, 1994; Kennelly and Weinberg, 2003). Using that management scheme, triticale silage was found to be less acceptable than barley or oat silage for beef heifers and sheep, based primarily on poor palatability and reduced DMI (McCartney and Vaage, 1994). Additional perspective is needed to relate indices of nutritive value to growth stage or growing degree days (**GDD**) for spring harvests of triticale forages established the previous fall after removal of corn for silage or soybeans. From a practical perspective, this production scenario has proved to be somewhat challenging throughout central Wisconsin. Growing seasons are relatively short, and soils are heavy and poorly drained; both of these conditions complicate the processes of removing a corn silage or soybean crop, applying dairy manure, and establishing a subsequent triticale double crop for harvest the following spring. Our objectives were to establish relationships relating indices of nutritive value with growth stage or accumulated GDD for triticale forages grown

under a challenging double-cropping environment in central Wisconsin.

MATERIALS AND METHODS

Forage Establishment and Management

2015–2016. Thirty 3.7-m × 9.1-m plots were established in 5 field blocks (6 plots/block) on a Loyal silt loam soil at the University of Wisconsin Marshfield Agricultural Research Station, located near Stratford, Wisconsin (44°39' N, 90°08' W). Blocks were established based on soil topography (slope). 'Forerunner' triticale (Legacy Seeds, Scandinavia, WI) was no-till drilled (model 1206NT; Great Plains Manufacturing, Salina, KS) into each plot of residual corn silage stubble (without tillage) at a seeding rate of 108 kg/ha on September 30, 2015. Immediately before planting, the plot area received 56,100 L/ha of dairy slurry via a broadcast-type tank spreader. Soil samples were taken by block to a 0.15-m depth the following spring (April 19); tests indicated pH = 7.1 ± 0.19 , OM = $3.8 \pm 0.29\%$, P = 99 ± 5.1 mg/kg, and K = 229 ± 28.7 mg/kg (University of Wisconsin Soil and Forage Laboratory, Marshfield, WI). Plots were broadcast fertilized with urea (46-0-0) at a rate of 52 kg of N/ha on May 2.

2016–2017. Thirty 3.7-m × 9.1-m plots were established in 5 field blocks on a Withee silt loam soil, again at the University of Wisconsin Marshfield Agricultural Research Station. The actual number of field blocks in the study was reduced to 4 because 1 block was lost due to flooding damage created by wet conditions during April 2017 (Table 1). 'Forerunner' triticale was not available before establishment in 2016; therefore, 'Tri-Cal' triticale (Byron Seeds LLC, Rockville, IN) was substituted and no-till drilled into soybean stubble as described previously at a seeding rate of 108 kg/ha on October 22, 2016. No dairy slurry was applied during the fall of 2016, in part because the previous crop was soybeans. Soil samples were taken by block to a 0.15-m depth the following spring (May 7); tests indicated pH = 7.1 ± 0.05 , OM = $3.4 \pm 0.13\%$, P = 26 ± 3.9 mg/kg, and K = 129 ± 4.6 mg/kg. Plots were then broadcast fertilized with urea (46-0-0) at a rate of 52 kg of N/ha on May 8.

Weather. All weather data (Table 1) reported for this project were obtained from the University of Wisconsin Marshfield Agricultural Research Station, and 30-yr monthly means for temperature and precipitation were obtained from NOAA (2002). Growing degree days were calculated using the averaging method with a 5°C base temperature: $GDD = [(maximum\ daily\ temperature - minimum\ daily\ temperature)/2] - 5^\circ C$,

where GDD were then summed over the desired growing interval. For this analysis, GDD accumulations began on January 1, thereby omitting any GDD from the previous fall. A value of 0 was assumed for any individual day when the calculated GDD was <0.

Harvest Management

2015–2016. Within each block, the 6 plots were assigned randomly to 1 of 6 harvest dates. For 2016, these dates corresponded to a clear progression of advancing growth stages: (1) vegetative (May 12), (2) stem elongation (May 19), (3) boot (May 25), (4) heading (May 31), (5) anthesis (June 9), and (6) soft dough (July 1). On designated sampling dates, two 9.1-m-long swaths were removed from each plot with a 1.07-m-wide flail-type forage plot harvester equipped with load cells, thereby allowing electronic collection of wet plot weights. Plots were harvested to a 7.5-cm stubble height. Within each plot, a grab subsample (~1,200 g) was removed from the collection box for each swath, placed in a 42-cm × 30-cm cloth bag (Legend Inc., Sparks, NV), and dried under forced air at 55°C to constant weight (~96 h). Dry weights from each sample bag were then used to calculate 2 estimates of forage DM concentration for each plot; these were then averaged before subsequent calculations of DM yield. Dried samples from each plot were composited and then retained for subsequent analysis of nutritive value. On each harvest date, canopy height was determined from 3 random locations/plot. Canopy height was measured to the tip of inflorescence or the apex of the highest leaf, whichever was taller. In addition, 3 plants/plot were assessed for growth stage using the linear model of Stauss (1994), where tillering = 20 to 29, stem elongation = 30 to 39, booting = 40 to 49, heading = 50 to 59, anthesis = 60 to 69, seed development = 70 to 79, and seed ripening = 80 to 89.

2016–2017. Harvests during the second year of the trial were conducted with procedures identical to those described for 2015 to 2016. Although it was our intention to match growth stages at harvest across years, this was not possible due to the wet conditions observed from April through June of 2017, when cumulative rainfall totaled 470 mm and was 56% greater than normal (Table 1). As such, some harvests had to be delayed because of muddy field conditions. Actual growth stages and harvest dates for 2017 were (1) elongation (May 24), (2) boot (May 29), (3) late boot (June 2), (4) early anthesis (June 8), (5) watery seed (June 23), and (6) soft dough (June 30).

Laboratory Analysis

Dried whole-plant triticale forages were ground through a 1-mm screen in a model 4 Wiley mill (Thomas Scientific, Swedesboro, NJ) and then sealed in plastic sample bags pending subsequent analysis for nutritive value. Concentrations of laboratory DM were determined by drying 1.0-g samples of each forage overnight in a convection oven at 105°C; subsequently, whole-plant ash was determined from these same subsamples by combustion in a muffle furnace at 500°C for 6 h. Forages were analyzed sequentially for NDF, ADF, hemicellulose, cellulose, and ADL using the batch procedures described by Ankom Technology Corp. (Macedon, NY) for an Ankom200 Fiber Analyzer. Heat-stable α -amylase was included in the NDF analysis procedures, but sodium sulfite was omitted because it attacks lignin and therefore should be omitted from sequential analyses including ADL (Van Soest et al., 1991). Water-soluble carbohydrates (WSC) were quantified using the phenol-sulfuric acid reaction as described by Dubois et al. (1956), with final concentrations determined colorimetrically. Concentrations of

Table 1. Summary of weather data for Marshfield, Wisconsin, from August 2015 through July 2017

Month	Mean monthly temperature, °C ¹				Precipitation, mm ¹			
	2015	2016	2017	30-yr normal	2015	2016	2017	30-yr normal
January	—	−10.0	−8.0	−11.3	—	17	59	25
February	—	−6.1	−3.3	−8.0	—	18	37	22
March	—	2.3	−2.0	−1.5	—	121	68	50
April	—	5.7	8.1	6.6	—	46	151	75
May	—	13.6	11.9	13.2	—	72	145	94
June	—	18.9	18.3	18.5	—	168	174	105
July	—	21.0	20.9	21.0	—	110	105	103
August	19.2	20.8	—	19.6	78	99	—	110
September	18.3	16.6	—	14.3	169	151	—	102
October	8.9	10.2	—	8.1	58	55	—	63
November	4.1	5.4	—	−0.4	68	48	—	58
December	−0.6	−7.4	—	−8.2	126	53	—	33

¹NOAA (2002).

N in each sample were assessed by a rapid combustion procedure (model TruMac CN, Leco Corp., St. Joseph, MI), and a conversion factor of 6.25 was used to calculate CP. The total forage CP pool was further partitioned by nonsequential digestions in neutral or acid detergent (**NDICP** and **ADICP**, respectively), where CP within each residue was quantified with the rapid combustion procedure described previously. For determinations of NDICP, the NDF solution contained heat-stable α -amylase but no sodium sulfite, which is known to cleave disulfide bonds and dissolve cross-linked proteins, thereby reducing recovery of CP from NDF residues (Van Soest et al., 1991). The summative approach was used to calculate energy density (TDN), where the ADL option was used to estimate truly digestible fiber (Weiss et al., 1992; NRC, 2001) and NE_L was calculated as described by NRC (2001).

Apparent In Vitro Disappearance of DM and Rate Kinetics

An in-depth assessment of apparent in vitro DM disappearance (**IVDMD**) was conducted on forages harvested during 2016 using the Ankom Daisy II Incubator System (Ankom Technology Corp.). To limit sample numbers to a manageable scope, triticale forages harvested at the vegetative stage of growth were eliminated from the sample set. This stage of growth was selected for elimination because it is unlikely that any livestock producer would harvest triticale for silage at that immature growth stage, and in-depth analysis of nutritive value indicated only minor differences between the vegetative and stem elongation stages of growth. Subsamples (0.30 g) of each forage harvested in 2016 ($n = 25$) were heat sealed in F57 fiber filter bags and incubated in quadruplicate for 3, 6, 9, 12, 18, 24, 36, 48, 72, 96, 144, or 240 h as recommended by Ankom Technology Corp. Prior to loading the F57 filter bags with sample, each empty fiber bag was pre-rinsed in acetone and air dried per instructions of the aforementioned manufacturer. The 0.30-g sample size was retained across all incubation times and was selected as a compromise between the smaller sample size (0.25 g) recommended by the manufacturer for short incubation times and ensuring that adequate residue remained after the 240-h incubations, some of which included highly digestible forages. Quadruplicate incubations were conducted in 3 identical incubator boxes such that (1) each forage-incubation time combination was represented (in singlet) within each of 4 runs, (2) each fermentation jar containing a specific incubation time was placed in a different box position (top right, top left, bottom right, and bottom left) during each

of the 4 runs, and (3) each jar containing a specific incubation time was evaluated at least once in each of the 3 incubator boxes. These procedures were used as an extra precaution against bias created by run-to-run variability. In addition, the temperature within each incubator box was standardized (39°C) to an independent thermometer before conducting the incubations. Rumen fluid used in the inoculum was obtained from 2 nonlactating Holstein cows offered a forage-based diet comprising (DM basis) alfalfa haylage (53.4%), corn silage (21.4%), and chopped wheat straw (25.2%). Nutrient composition of the diet was 12.6% CP, 49.2% NDF, 11.1% starch, 2.46% ether extract, and 59.0% TDN; University of Wisconsin Soil and Forage Laboratory). Rumen fluid was siphoned from each cow with a hand-operated pump through a ruminal cannula directly into prewarmed (39°C) insulated bottles and then transported to the laboratory. Insulated bottles were placed in a chest-type insulated cooler during transport. After filtering the rumen fluid through 4 layers of cheesecloth, a total of 400 mL of rumen fluid with equal contributions from each donor cow was added to each incubation jar containing buffers and samples. The head space within each incubation jar was purged twice with CO_2 ; these purges were conducted immediately after buffers and sample bags were added to the incubation jars for prewarming to 39°C and immediately after rumen fluid was added to each incubation jar before final lid placement and subsequent incubation.

The 4 values obtained for each combination of forage and incubation time were averaged before any assessment of rate kinetics. Disappearance kinetics of DM were calculated based on 3 pools of DM, where fraction A represented the percentage of forage DM disappearing at a rate too fast to measure, fraction B was the percentage of DM disappearing at a measurable rate, and fraction U was considered to be the percentage of DM indigestible in buffered rumen fluid. Data were fitted by nonlinear regression (PROC NLIN; SAS Institute, 2010) using options BEST = 10 and METHOD = Marquardt for the following model:

$$\text{DM remaining (\%)} = \left\{ B \times e^{[-K_d \times (T-L)]} \right\} + U,$$

where K_d = DM disappearance rate per hour, T = incubation time (h), and L = discrete lag time (h). Therefore, L can be described as the time interval required before disappearance of fraction B begins. An additional condition was placed on the regression model whenever $L > T$; under those conditions, DM remaining (%) = $B + U$. Fraction A was calculated as $A = 100\% - (B + U)$. Within this analysis, U was

determined by nonlinear regression and, although very similar, it was not equated arbitrarily to the DM remaining after the 240-h incubation.

Statistics

For all response variables, PROC MEANS of SAS (SAS Institute, 2010) was used to calculate the mean and standard deviation for either 5 (2016) or 4 (2017) field replications on each harvest date. Response variables obtained for each individual plot (experimental unit) were then regressed against growth stage or GDD accumulated from January 1 using PROC REG of SAS (SAS Institute, 2010). For each response variable evaluated, linear, quadratic, cubic, and quartic models were considered. Selection of the most appropriate model required a significant ($P < 0.05$) coefficient for each polynomial term coupled with the greatest possible coefficient of determination (R^2); however, to avoid overfitting, higher-ordered models were eliminated from consideration when there were not clear physiological explanations for the complex character of the curve. The intercept was retained in the model irrespective of whether it differed ($P < 0.05$) from 0.

RESULTS AND DISCUSSION

Weather

Mean monthly temperature and precipitation data (Table 1) describe 2 production years that differed from

each other primarily on the basis of spring precipitation. For 2017, rainfall exceeded the expected norms by 101% in April, 54% in May, and 66% in June, totaling 470 mm over that 3-mo period. As mentioned previously, this resulted in periods of standing water and some subsequent stand loss during 2017. For both production seasons, rainfall during September exceeded normal expectations (102 mm; NOAA, 2002), totaling 169 and 151 mm for 2015 and 2016, respectively. In addition, mean monthly temperatures for November 2015 (4.1°C) and November 2016 (5.4°C) were both warmer than the 30-yr normal (−0.4°C).

Agronomic Characteristics

Agronomic characteristics of triticale forages are summarized in Table 2. Sharp contrasts existed between the 2 often-observed growth stages (boot or soft dough) for harvest (Kennelly and Weinberg, 2003; Kilcer et al., 2010). Based on these results, producers could expect to harvest triticale for silage at boot stage during the last week of May and at soft dough around July 1 throughout central Wisconsin. At boot stage (stage = 43), canopy heights were 68 cm in 2016 and 60 cm in 2017; however, canopy heights had more than doubled (≥ 142 cm) by the soft dough stage of growth during both production years. Although plants harvested at the boot stage exhibited percentages of DM ($\leq 17.3\%$) that clearly would require field wilting before ensiling, the DM concentrations at the soft dough stage of growth ($\geq 35.4\%$) exceed a common threshold

Table 2. Agronomic characteristics of triticale forages harvested at Marshfield, Wisconsin, during 2016 and 2017

Harvest date	Descriptive growth stage	GDD ¹	Stage (linear) ²		Canopy height, ³ cm		Harvest DM, %		DM yield, kg of DM/ha	
			Mean ⁴	SD ⁴	Mean	SD	Mean	SD	Mean	SD
2016										
May 12	Vegetative	195	30	0.4	37	3.7	14.2	1.44	1,203	182.5
May 19	Elongation	220	32	0.4	47	3.8	16.9	0.51	1,825	331.3
May 25	Boot	300	43	1.2	68	4.9	15.5	0.99	3,804	653.2
May 31	Heading	388	52	0.7	88	4.3	16.9	1.46	4,705	421.8
June 9	Anthesis	489	66	0.6	138	2.4	21.4	0.71	7,537	510.2
July 1	Soft dough	817	84	0.5	144	2.3	35.4	1.22	12,642	762.4
2017										
May 24	Elongation	269	35	4.5	43	7.8	18.0	0.93	715	335.0
May 29	Boot	321	43	0.3	60	2.4	17.3	0.19	1,453	333.3
June 2	Late boot	355	49	4.1	66	9.9	20.0	0.38	1,800	294.8
June 8	Early anthesis	447	60	1.4	112	15.0	20.6	0.91	3,018	878.7
June 23	Watery seed	676	71	0.4	135	4.5	32.8	0.42	4,483	560.8
June 30	Soft dough	750	82	1.4	142	4.6	36.0	0.17	5,399	510.8

¹Growing degree days accumulated from January 1 using 5°C as a base temperature.

²Stage of growth identified as tillering (20–29), stem elongation (30–39), booting (40–49), heading (50–59), anthesis (60–69), seed development (70–79), and seed ripening (80–89; Stauss, 1994).

³Canopy height measured to the apex of the highest leaf or the tip of inflorescence, whichever was taller.

⁴Mean and SD based on 5 field replications on each harvest date for 2016 and 4 field replications for 2017.

(30%; Muck and Kung, 2007) for avoiding problematic clostridial fermentations and production of effluent in many silo types. As such, direct cutting at soft dough appears to be a viable option.

Perhaps most important, there were stark differences in DM yield between these 2 growth stages. During 2016, plots produced 12,642 kg of DM/ha at the soft dough stage of growth, but only 30.1% of that amount was harvested at boot stage (3,804 kg of DM/ha). Although overall forage production was greatly affected by flooding and standing water during 2017, thereby reducing DM yields at all growth stages compared with 2016, the relative percentage associated with a boot-stage harvest compared with soft dough was similar (26.9%). This yield drag associated with a boot-stage harvest of triticale was severe but has been documented in reports for other cereal grain forages. Edmisten et al. (1998) harvested barley, oat, rye, and wheat forages at multiple growth stages over 3 yr in North Carolina; yield comparisons between boot- and soft dough-stage harvests always resulted in a yield drag with an earlier harvest, but yields at boot stage ranged between 47.4 and 63.9% of those at soft dough in 8 of 10 species-production year combinations. A yield comparison (42.2%) between these growth stages for barley in Virginia was comparable in scope (Acosta et al., 1991); generally, yield differentials between the boot and soft dough stages of growth have been more favorable for other cereal grain forages than observed in the present study for triticale. Strictly from an agronomic standpoint, an approximate 70% reduction in yield realized by adopting a boot-stage harvest management strategy may seem excessive; however, in central Wisconsin, delaying harvests until July 1 to obtain peak DM yield would preclude the possibility of double-cropping corn or soybeans after removing the triticale forage.

The most appropriate regression model relating DM yield with growth stage or GDD varied across years (Figure 1), but coefficients of determination remained very high in all cases ($R^2 \geq 0.915$). Higher-ordered models were required to describe DM yield for 2016, which contrasted with the simple linear relationships that were identified for 2017. These differences in the complexity of regression models between years may have been related to the lack of alignment with respect to growth stages at harvest as well as the flooding and unfavorable weather observed during 2017 that negatively affected DM yields. Previously, curvilinear relationships between DM yield and GDD for triticale forages have been reported (Schwarte et al., 2005; Gibson et al., 2007), and exceptionally high coefficients of determination ($R^2 \geq 0.85$) have been noted in studies across several locations with a common N fertilization rate (Schwarte et al., 2005).

Nutritive Value

NDF and ADF. Despite the precipitation differences across production years, concentrations of NDF and ADF (Figure 2) changed in similar patterns as a function of growth stage. Generally, NDF and ADF increased beginning at stem elongation and continued through anthesis in 2016, but the maximum shifted slightly to an early seed development stage in 2017. For 2016, mean concentrations of NDF ranged from 41.3 to 66.3% across specific harvest dates (Table 3), with a similar range observed in 2017 (41.1–65.2%). For ADF, concentrations across harvest dates ranged from 21.2 to 40.0% in 2016 and 21.8 to 40.5% in 2017. After reaching an apex at the anthesis or the watery seed stages of growth, concentrations of both fiber components declined thereafter, as NDF and ADF were diluted by the partitioning of NSC into developing seed heads. Various forms of dilution response resulting in static or reduced concentrations of NDF at mature growth stages have been observed consistently for a variety of cereal grain forages (Cherney and Marten, 1982b; West et al., 1991; Coblenz et al., 2000). This dilution response for triticale was substantial in magnitude, reducing mean NDF by 9.8 percentage units between the anthesis and soft dough stages of growth in 2016 and by 5.7 percentage units between watery seed and soft dough in 2017 (Table 3). Regression models relating NDF or ADF with growth stage (Figure 2) were inconsistent across years, although the general response was similar and coefficients of determination were quite high ($R^2 \geq 0.950$). West et al. (1991) has described regression relationships between NDF and growth stage or GDD for wheat forages grown in Arkansas; in that study, clear effects of dilution via grain fill were illustrated, but regression models also differed between cultivars based largely on maturation rate. As mentioned previously, higher-ordered (quartic) models for our triticale forages may have been selected for 2016 because growth stages at harvest were not exactly aligned with 2017 and concentrations of NDF or ADF at the vegetative and stem elongation stages of growth were similar, whereas no vegetative harvest was obtained in 2017. Generally, dilution associated directly with grain fill contributed to the higher-ordered nature of all NDF and ADF regression models by reducing concentrations of these fiber components at advanced growth stages. Regressions of NDF and ADF on GDD (Table 4) were explained by quadratic ($P < 0.001$) models in all cases; however, coefficients of determination ($R^2 \geq 0.926$) suggest that GDD also was an excellent predictor variable for these fiber components.

ADL. For both 2016 and 2017, concentrations of ADL (Table 3) exhibited a typical response to plant

Figure 1. Regression relationships for DM yield on growth stage (top) and growing degree days (bottom; 5°C base temperature) for triticale forages harvested during 2016 and 2017 at Marshfield, Wisconsin. Regression equations on growth stage at harvest were as follows: 2016, $Y = 0.0663x^3 - 9.44x^2 + 595x - 9,810$, $R^2 = 0.985$, root mean squared error (RMSE) = 508.1 kg of DM/ha; 2017, $Y = 103x - 3,024$, $R^2 = 0.934$, RMSE = 466.6 kg of DM/ha. Regression equations with growing degree days as the independent variable were as follows: 2016, $Y = -0.00590x^2 + 24.3x - 3,267$, $R^2 = 0.980$, RMSE = 578.1 kg of DM/ha; 2017, $Y = 9.15x - 1,486$, $R^2 = 0.915$, RMSE = 527.6 kg of DM/ha. The overall model for each regression was significant at $P < 0.001$.

maturity, increasing with growth stage or GDD and reaching concentrations $\geq 4.07\%$ at the soft dough stage of growth. Ambient temperature is positively associated with lignification (Ford et al., 1979; Van Soest, 1982) and likely contributed to these responses; however, our concentrations of ADL are somewhat less than those reported elsewhere for headed triticale silages (NRC,

2001; 5.8%). In contrast, cereal grain forages (oat) that joint and elongate during cooler fall temperatures typically exhibit very low concentrations of ADL (often $< 2\%$) and as a result are prone to extensive lodging in response to late-fall snowstorms (Coblentz and Walgenbach, 2010; Coblentz et al., 2013a,b). Unlike NDF and ADF, dilution resulting from grain fill had only

Figure 2. Regressions of NDF (top) on growth stage were as follows: 2016, $Y = 0.0000369x^4 - 0.00886x^3 + 0.745x^2 - 25.4x + 342.5$, $R^2 = 0.975$, root mean squared error (RMSE) = 1.67%; 2017, $Y = -0.000570x^3 + 0.0828x^2 - 3.14x + 74.9$, $R^2 = 0.950$, RMSE = 2.06%. For ADF (bottom), regression equations were as follows: 2016, $Y = 0.0000276x^4 - 0.00661x^3 + 0.557x^2 - 19.1x + 250.7$, $R^2 = 0.971$, RMSE = 1.30%; 2017, $Y = -0.000492x^3 + 0.0760x^2 - 3.26x + 64.1$, $R^2 = 0.956$, RMSE = 1.53%. The overall model for each regression was significant at $P < 0.001$.

mild effects on ADL, and mean concentrations of ADL (Table 3) increased across all harvest dates during 2016, ranging from 1.14 to 4.54%. This response was explained by close quadratic ($P < 0.001$) relationships with both growth stage (Figure 3; $R^2 = 0.917$) and GDD (Table 4; $R^2 = 0.920$). Respective cubic ($P < 0.001$) and quadratic ($P < 0.001$) models with high coefficients of determination ($R^2 \geq 0.967$) were selected for 2017. Although responses for both years described

curvilinear character, characterized by plateauing or mildly declining concentrations at advanced growth stages, the sharp depressions caused by grain fill that were described for NDF and ADF were not observed for ADL. Cherney and Marten (1982b) reported a sharp decline in ADL concentrations within the inflorescence of oat, triticale, wheat, and barley, but this did not offset collective increases in concentrations of ADL within the stem, leaf sheath, and leaf blade compo-

Table 3. Fiber composition (% of DM), whole-plant ash (% of DM), and water-soluble carbohydrates (WSC; % of DM) for triticale forages harvested at Marshfield, Wisconsin, during 2016 and 2017

Harvest date	Descriptive growth stage	NDF		ADF		Hemicellulose		Cellulose		ADL		Ash		WSC	
		Mean ¹	SD ¹	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
2016															
May 12	Vegetative	41.9	0.89	23.0	0.82	18.9	0.57	21.0	0.60	1.14	0.077	11.5	0.54	12.0	1.48
May 19	Elongation	41.3	1.09	21.2	0.42	20.1	0.84	19.4	0.52	1.16	0.186	10.6	0.32	16.0	1.46
May 25	Boot	49.7	1.94	27.9	1.47	21.8	0.77	25.0	0.91	2.67	0.869	10.2	0.82	13.4	2.50
May 31	Heading	61.9	1.12	36.0	0.60	25.9	0.72	32.3	0.51	3.22	0.190	9.3	0.84	7.3	1.29
June 9	Anthesis	66.3	0.79	40.0	0.80	26.3	0.61	35.4	0.67	4.16	0.204	7.6	0.66	7.1	0.98
July 1	Soft dough	56.5	2.18	34.5	1.62	22.0	0.64	29.5	1.35	4.54	0.283	5.6	0.44	13.5	1.05
2017															
May 24	Elongation	41.1	1.89	21.8	1.18	19.4	0.74	20.5	1.23	0.71	0.152	7.0	0.37	19.0	0.90
May 29	Boot	49.3	1.83	26.9	1.20	22.3	0.63	25.2	1.11	1.29	0.120	7.2	0.19	17.1	0.50
June 2	Late boot	51.5	4.72	28.6	3.67	23.0	1.07	26.2	3.10	1.80	0.517	7.2	0.15	16.3	2.18
June 8	Early anthesis	61.1	2.86	35.6	2.44	25.5	0.67	32.2	2.09	2.97	0.323	7.1	0.33	10.2	1.43
June 23	Watery seed	65.2	1.01	40.5	0.46	24.7	0.65	35.9	0.43	4.05	0.070	5.0	0.17	13.7	0.36
June 30	Soft dough	59.5	0.46	36.9	0.30	22.7	0.26	32.4	0.35	4.07	0.109	4.6	0.14	16.3	1.18

¹Mean and SD based on 5 field replications on each harvest date for 2016 and 4 field replications for 2017.

nents on a whole-plant basis. Similar observations have been reported for a wide range of cereal grain forages in Michigan (Helsel and Thomas, 1987) and California (Meyer et al., 1957).

Ash. Concentrations of ash generally declined with plant development, yielding higher-ordered models in 2017 compared with 2016, but each exhibited a close relationship ($R^2 \geq 0.907$) with growth stage (Figure 4) or GDD (Table 4). The negative relationship between whole-plant ash concentrations and plant development has been observed with fall-grown oat, wheat, and triticale (Coblentz and Walgenbach, 2010), with concentrations ranging between 12.3 and 15.8% in mid-September when plants were in the vegetative or early stem elongation stages of growth. Similarly, spring growth of oat, triticale, wheat, and barley exhibited sharply declining concentrations of K, Ca, P, and Mg as plants matured from the flag leaf stage to 28 d postappearance of the first awns or floret (Cherney and Marten, 1982a). In the present study, ash exceeded 10.2% through the May 25 harvest date during 2016 but was less on similar dates in 2017 ($\leq 7.2\%$). Ash does not contribute to overall energy estimates (NRC, 2001), and high concentrations of ash have depressed estimations of energy within immature fall oat forages (Coblentz et al., 2013b).

WSC. The relationships between concentrations of WSC and growth stage or GDD were complex and were explained by a quartic ($P < 0.001$) model in all cases (Figure 5; Table 4). Generally, the relationship between WSC and growth stage exhibited 3 inflection points, which can be described as (1) an increase in WSC reaching an apex at the late stem elongation/early boot stage, (2) a subsequent decline reaching a minimum at early anthesis, and (3) an increase following anthesis that reached a plateau at the soft dough stage of growth. During both 2016 and 2017, there was an approximate 9-percentage-unit differential in WSC concentrations between late stem elongation and anthesis (Table 3), which likely occurred as cells expanded rapidly and forage plants partitioned carbohydrate into rapid plant growth. Increases in WSC after anthesis are likely associated with the cessation of rapid plant growth and initiation of grain fill. However, WSC also may decline as carbohydrate (particularly starch) is partitioned into the filling grain head at advanced growth stages. This has been illustrated for wheat, oat, and barley forages harvested at milk and dough stages of growth; respective concentrations of WSC declined by 39.2, 43.2, and 53.6% during this time interval (Bergen et al., 1991). Regardless, the soft dough stage of growth has often been considered desirable for harvest of cereal grain forages as silage (Helsel and Thomas, 1987; Acosta et al., 1991; McDonald et al., 1991). Despite the higher-

Table 4. Summary of statistics for regressions of nutritive value on growing degree days >5°C¹ for triticale forages harvested at Marshfield, Wisconsin, during 2016 and 2017

Item, ² % of DM unless noted	No.	Model type	Model	$P > F^3$	Dependent mean	RMSE ⁴	R ²
2016							
NDF	30	Quadratic	$Y = -0.000189x^2 + 0.219x + 3.9$	<0.001	52.9	2.34	0.946
ADF	30	Quadratic	$Y = -0.000125x^2 + 0.149x - 3.7$	<0.001	30.4	1.87	0.935
ADL	30	Quadratic	$Y = -0.0000150x^2 + 0.0208x - 2.46$	<0.001	2.81	0.410	0.920
Ash	30	Quadratic	$Y = -0.00000711x^2 - 0.0165x + 14.3$	<0.001	9.1	0.67	0.907
WSC	30	Quartic	$Y = -0.0000000612x^4 + 0.0000115x^3 - 0.00736x^2 + 1.91x - 155.5$	<0.001	11.6	1.58	0.836
CP	30	Cubic	$Y = -0.000000189x^3 + 0.000333x^2 - 0.201x + 50.8$	<0.001	14.4	1.37	0.956
ADICP, % of CP	30	Linear	$Y = 0.00425x + 2.51$	<0.001	4.22	0.64	0.676
TDN	30	Quadratic	$Y = 0.0000757x^2 - 0.0863x + 84.4$	<0.001	65.3	1.41	0.876
NE _L , Mcal/kg	30	Quadratic	$Y = 0.00000186x^2 - 0.00212x + 1.95$	<0.001	1.48	0.035	0.876
2017							
NDF	24	Quadratic	$Y = -0.000243x^2 + 0.287x - 18.6$	<0.001	54.6	2.46	0.926
ADF	24	Quadratic	$Y = -0.000153x^2 + 0.189x - 18.4$	<0.001	31.7	1.91	0.928
ADL	24	Quadratic	$Y = -0.0000181x^2 + 0.0255x - 4.94$	<0.001	2.48	0.259	0.967
Ash	24	Cubic	$Y = 0.0000000579x^3 - 0.000101x^2 + 0.0497x - 0.2$	<0.001	6.3	0.24	0.963
WSC	24	Quartic	$Y = -0.0000000265x^4 + 0.00000551x^3 - 0.00398x^2 + 1.16x - 97.6$	<0.001	15.4	1.27	0.859
CP	24	Cubic	$Y = -0.000000168x^3 + 0.000310x^2 - 0.201x + 52.3$	<0.001	11.0	0.99	0.957
ADICP, % of CP	24	Linear	$Y = 0.00928x + 0.18$	<0.001	4.54	0.503	0.924
TDN	24	Quadratic	$Y = 0.000122x^2 - 0.144x + 104.9$	<0.001	68.1	1.14	0.937
NE _L , Mcal/kg	24	Quadratic	$Y = 0.00000298x^2 - 0.00353x + 2.45$	<0.001	1.55	0.028	0.937

¹Growing degree days accumulated since January 1 using 5°C as a base temperature; data are summarized in Table 1.

²WSC = water-soluble carbohydrates; ADICP = acid detergent insoluble CP.

³ $P > F$ for the overall regression model.

⁴Root mean squared error for the regression model.

Figure 3. Regression relationships for ADL on growth stage for triticale forages harvested during 2016 and 2017 at Marshfield, Wisconsin. Regression equations were as follows: 2016, $Y = -0.00114x^2 + 0.195x - 3.73$, $R^2 = 0.917$, root mean squared error (RMSE) = 0.416%; 2017, $Y = -0.0000778x^3 + 0.0129x^2 - 0.590x + 8.99$, $R^2 = 0.986$, RMSE = 0.170%. The overall model for each regression was significant at $P < 0.001$.

ordered (quartic) character of regressions of WSC on growth stage or GDD, more variability was found in these relationships than for most other measures of nutritive value. Respective R^2 statistics for 2016 and 2017 were 0.776 and 0.839 when growth stage was the independent variable and 0.836 and 0.859 for GDD.

Figure 4. Regression relationships for whole-plant ash on growth stage for triticale forages harvested during 2016 and 2017 at Marshfield, Wisconsin. Regression equations were as follows: 2016, $Y = -0.104x + 14.4$, $R^2 = 0.907$, root mean squared error (RMSE) = 0.65%; 2017, $Y = 0.00000776x^4 - 0.00170x^3 + 0.133x^2 - 4.39x + 59.0$, $R^2 = 0.958$, RMSE = 0.26%. The overall model for each regression was significant at $P < 0.001$.

Figure 5. Regression relationships for water-soluble carbohydrates (WSC) on growth stage for triticale forages harvested during 2016 and 2017 at Marshfield, Wisconsin. Regression equations were as follows: 2016, $Y = -0.0000368x^4 + 0.00866x^3 - 0.726x^2 + 25.4x - 300.7$, $R^2 = 0.776$, root mean squared error (RMSE) = 1.85%; 2017, $Y = -0.0000173x^4 + 0.00422x^3 - 0.365x^2 + 13.0x - 143.6$, $R^2 = 0.839$, RMSE = 1.36%. The overall model for each regression was significant at $P < 0.001$.

CP. Many studies evaluating cereal grain forages have described reduced concentrations of N or CP as functions of growth stage or GDD (Cherney and Marten, 1982a; Coblenz et al., 2001; Gibson et al., 2007). Unlike other measured plant components that reflect dynamic changes in various carbohydrate pools during plant development, concentrations of CP in leaf blade, leaf sheath, stem, and inflorescence all decline with maturity (Cherney and Marten, 1982b). Generally, these responses have been curvilinear in nature, with the rate of CP decline slowing at advanced growth stages (Cherney and Marten, 1982a,b; Khorasani et al., 1997) or with greater accumulations of GDD (Gibson et al., 2007). Means for specific harvest dates (Table 5) and our regression responses to advancing growth stage and accumulated GDD (Figure 6; Table 4) are consistent with previous studies; concentrations of CP declined cubically ($P < 0.001$) and quadratically ($P < 0.001$) with growth stage in 2016 and 2017, respectively, with excellent fits in each case ($R^2 \geq 0.946$). Similarly, close cubic responses ($P < 0.001$) to accumulated GDD were found during both years ($R^2 \geq 0.956$). Although concentrations of CP in triticale forages are increased by N fertilization rate (Gibson et al., 2007), the modest spring rate of N fertilization applied in the present study (52 kg of N/ha) yielded forages with CP concentrations of about 15% at boot stage, but CP declined to about 5% by the soft dough stage of growth. These

comparisons of CP concentrations represent a clear trade-off for producers between DM yield and quality; however, it is unlikely that producers would prioritize the magnitude of CP concentrations in harvest timing decisions. Rather, a decision to maximize yield by delaying harvest until the soft dough stage of growth should be made with the clear knowledge that CP supplementation with other forages or feedstuffs will be necessary to meet the needs of virtually all livestock classes.

ADICP. The relationship between ADICP and growth stage or GDD has not often been discussed, but one study (Coblenz et al., 2001) showed that ADICP (% of CP) increased with plant maturation in wheat, rye, and oat forages, but these increases were heavily associated with declining overall concentrations of CP rather than significant changes in the concentration of ADICP expressed on a DM basis. Concentrations of ADICP have implications for dairy nutrition with respect to availability of CP pool for ruminant digestion (Van Soest, 1982) as well as being a required input for calculation of energy by the summative approach, where truly digestible CP = $CP \times e^{[-1.2 \times (ADICP/CP)]}$ (Weiss et al., 1992; NRC, 2001). In the present study, triticale forages exhibited quadratic ($P < 0.001$) and cubic ($P < 0.001$) increases in ADICP (% of CP) with growth stage during 2016 and 2017 (Figure 6), respectively. These relationships were characterized by an

excellent fit for 2017 ($R^2 = 0.945$) but much poorer fit ($R^2 = 0.711$) for 2016, mostly due to greater variability for individual replicates at the vegetative and stem elongation stages of growth, which was not observed in more mature forages. Unlike regressions on growth stage, use of GDD as the independent variable (Table 4) yielded simple linear ($P < 0.001$) responses in both years, although the coefficient of determination was again poorer for 2016 ($R^2 = 0.676$) than 2017 ($R^2 = 0.924$). Overall, increases in ADICP were substantial; mean concentrations approximately doubled between the boot and soft dough stages of growth, reaching 6.18 and 7.11% of CP (Table 5) at the latter growth stage during 2016 and 2017, respectively.

TDN and NE_L . Overall, triticale was a relatively energy-dense forage, with mean energy estimates ranging between 60.4 and 74.9% TDN ($NE_L = 1.36$ and 1.72 Mcal/kg) on specific harvest dates across 2 production years (Table 5). As such, concentrations of TDN were comparable with corn silage (68.8%; NRC, 2001) through the stem elongation stage of growth in 2016 (70.2%) and through the late boot stage in 2017 (69.5%). Much as discussed for WSC, energy estimates declined as plants matured, reaching a minimum at the anthesis stage of growth before increasing thereafter in response to increased concentrations of WSC or starch within the filling grain head; however, these responses to grain fill were muted somewhat by competing effects of increased lignification (Figure 3) that occurred concurrently. Although these general characteristics were similar across years, quadratic ($P < 0.001$) models best fit responses for TDN and NE_L regressed on growth stage for 2016, but cubic ($P < 0.001$) models were selected for the second year of the trial (Figure

7). Regardless, growth stage effectively explained the variability in energy estimates ($R^2 \geq 0.858$). Regressions of energy estimates on GDD (Table 4) exhibited a quadratic ($P < 0.001$) relationship in all cases, also with very high coefficients of determination ($R^2 \geq 0.876$). Based on energy considerations, triticale forages should be harvested at boot stage for lactating cows, but harvests can be delayed until anthesis for gravid heifers with reduced energy requirements (NRC, 2001). However, management decisions attempting to match nutrient value with the requirements of specific livestock classes must be weighed against other factors, such as potential effects on DM yield or the urgency to remove triticale forages before establishing a subsequent double crop.

Comments on GDD >5°C

Generally, our results suggest that it will take about 300 GDD from January 1 for triticale forages to reach the boot stage of growth in central Wisconsin. To reach the soft dough stage, 750 to 800 GDD are required. One noticeable difference between regressions on growth stage compared with GDD was that those on growth stage were frequently higher ordered; of the 20 response variables regressed on both growth stage or GDD over 2 yr, 10 exhibited a higher-ordered model when a linear growth stage model was used as the independent or predictor variable. In 7 cases, regression models maintained the same number of polynomial terms, whereas regressions of whole-plant ash and ADICP for 2016 as well as CP for 2017 were more complex with GDD as the independent variable. It is important to note that GDD and growth stage are closely related to chrono-

Table 5. Concentrations of CP, neutral detergent insoluble CP (NDICP), acid detergent insoluble CP (ADICP), TDN, and NE_L for triticale forages harvested at Marshfield, Wisconsin, during 2016 and 2017

Harvest date	Descriptive growth stage	CP, % of DM		NDICP, % of CP		ADICP, % of CP		TDN, % of DM		NE _L , Mcal/kg	
		Mean ¹	SD ¹	Mean	SD	Mean	SD	Mean	SD	Mean	SD
2016											
May 12	Vegetative	23.9	1.12	13.8	0.89	3.41	0.905	69.4	0.65	1.58	0.016
May 19	Elongation	19.1	1.62	14.4	0.57	3.91	0.857	70.2	0.68	1.60	0.017
May 25	Boot	15.4	1.24	13.3	1.57	3.50	0.346	65.4	2.48	1.48	0.061
May 31	Heading	12.3	1.04	11.4	0.47	3.89	0.377	61.8	0.54	1.39	0.013
June 9	Anthesis	9.6	0.57	11.1	0.88	4.42	0.459	60.4	0.88	1.36	0.021
July 1	Soft dough	5.9	0.58	13.8	0.51	6.18	0.545	64.4	1.36	1.46	0.033
2017											
May 24	Elongation	18.0	0.58	10.0	0.22	2.70	0.325	74.9	0.92	1.72	0.023
May 29	Early boot	13.7	0.89	9.5	0.67	2.94	0.282	71.1	0.59	1.62	0.014
June 2	Boot	12.1	1.10	11.0	1.29	3.52	0.707	69.5	2.47	1.58	0.060
June 8	Early anthesis	10.4	1.21	11.3	0.46	4.55	0.615	64.5	1.15	1.46	0.028
June 23	Watery seed	6.0	0.12	11.9	2.57	6.41	0.545	63.4	0.29	1.43	0.007
June 30	Soft dough	5.7	0.43	12.4	2.03	7.11	0.600	65.2	0.14	1.48	0.003

¹Mean and SD based on 5 field replications of each harvest date for 2016 and 4 field replications for 2017.

Figure 6. Regression relationships for CP (top) and acid detergent insoluble CP (ADICP; bottom) on growth stage for triticale forages harvested during 2016 and 2017 at Marshfield, Wisconsin. Regression equations for CP were as follows: 2016, $Y = -0.000174x^3 + 0.0335x^2 - 2.31x + 66.2$, $R^2 = 0.950$, root mean squared error (RMSE) = 1.46%; 2017, $Y = 0.00262x^2 - 0.562x + 33.7$, $R^2 = 0.946$, RMSE = 1.09%. Regression equations for ADICP were as follows: 2016, $Y = 0.00127x^2 - 0.0980x + 5.45$, $R^2 = 0.711$, RMSE = 0.617% of CP; 2017, $Y = -0.0000715x^3 + 0.0131x^2 - 0.663x + 12.84$, $R^2 = 0.945$, RMSE = 0.448% of CP. The overall model for each regression was significant at $P < 0.001$.

logical time but not in identical ways; for GDD, these relationships were linear for both 2016 ($GDD = 14.1x - 55.0$; $R^2 = 0.997$) and 2017 ($GDD = 13.6x - 73.5$; $R^2 = 0.995$), where x = days from May 15. In contrast, the relationship between growth stage and days for this time period was quadratic for 2016 ($Y = -0.017x^2 + 2.6x - 11$; $R^2 = 0.999$) and 2017 ($Y = -0.012x^2 + 2.2x - 12$; $R^2 = 0.987$), where the rate of morphological

development slowed as a function of time, particularly between the anthesis and soft dough stages of growth.

Kinetics of IVDMD

Fractions A, B, and C. Means for various regression parameters describing kinetics of IVDMD for triticale forages harvested from the stem elongation

through soft dough stages of growth during 2016 are summarized in Table 6. The regressions of A, B, and U pools on growth stage (Figure 8) depict dynamic rather than static relationships between various DM pools as plants develop morphologically. Overall, fraction A declined with plant maturity in a close ($R^2 = 0.980$), quartic ($P < 0.001$) relationship with growth stage;

however, slight increases were observed after anthesis in response to greater concentrations of WSC (Figure 5) and the initiation of grain fill. Fraction B exhibited a quadratic ($P < 0.001$) response across growth stages, increasing to >50% of total plant DM during the heading and anthesis stages of growth in response to plants partitioning increased percentages of DM into struc-

Figure 7. Regression relationships for TDN and NE_L on growth stage for triticale forages harvested during 2016 and 2017 at Marshfield, Wisconsin. Regression relationships for TDN were as follows: 2016, $Y = 0.00820x^2 - 1.05x + 94.5$, $R^2 = 0.858$, root mean squared error (RMSE) = 1.51%; 2017, $Y = 0.000251x^3 - 0.0358x^2 + 1.27x + 63.1$, $R^2 = 0.962$, RMSE = 0.90%. Regression equations for NE_L on growth stage were as follows: 2016, $Y = 0.000201x^2 - 0.0257x + 2.20$, $R^2 = 0.858$, RMSE = 0.037 Mcal/kg; 2017, $Y = 0.00000616x^3 - 0.000878x^2 + 0.0313x + 1.42$, $R^2 = 0.963$, RMSE = 0.022 Mcal/kg. The overall model for each regression was significant at $P < 0.001$.

Figure 8. Changes in DM pools as affected by growth stage for triticale forages harvested in Marshfield, Wisconsin, during 2016, where A = pool that disappears at a rate too fast to measure, B = pool that disappears at a measurable rate, and U = pool that is indigestible in buffered rumen fluid. All pool sizes were determined via in vitro procedures for DM disappearance. Regression curves were defined as follows: A = $-0.0000448x^4 + 0.0107x^3 - 0.905x^2 + 31.3x - 327.9$, $R^2 = 0.980$, root mean squared error (RMSE) = 1.70%; B = $-0.0160x^2 + 1.92x - 6.2$, $R^2 = 0.907$, RMSE = 1.55%; U = $-0.000433x^3 + 0.0707x^2 - 3.16x + 53.0$, $R^2 = 0.980$, RMSE = 1.24%. The overall regression model for each fraction was significant at $P < 0.001$.

Figure 9. Changes in in vitro DM disappearance rate (K_d) of fraction B (defined as pool that disappears at a measurable rate) as a function of growth stage for triticale forages harvested at Marshfield, Wisconsin, during 2016. Regression equation was defined as follows: $K_d = 0.0000176x^2 - 0.00275x + 0.142$, $R^2 = 0.917$, root mean squared error = 0.0043/h. The overall regression was significant at $P < 0.001$.

Figure 10. Regression relationship between lag time and growth stage of triticale forages harvested in Marshfield, Wisconsin, during 2016. Lag time was estimated from in vitro DM disappearance kinetics. Regression equation was defined as follows: lag time = $-0.00252x^2 + 0.222x + 1.54$, $R^2 = 0.788$, root mean squared error = 0.805 h. The overall regression was significant at $P < 0.001$.

Figure 11. Regression of apparent in vitro DM disappearance after 30-h (IVDMD30) or 48-h (IVDMD48) incubations as determined from nonlinear regressions of DM remaining on incubation time for triticale forages harvested in Marshfield, Wisconsin, during 2016. Regressions were defined as follows: IVDMD30 = $0.000641x^3 - 0.0958x^2 + 3.66x + 42.7$, $R^2 = 0.982$, root mean squared error (RMSE) = 1.75%; IVDMD48 = $0.000619x^3 - 0.0974x^2 + 4.12x + 35.4$, $R^2 = 0.984$, RMSE = 1.51%. Both overall regression equations were significant at $P < 0.001$.

Table 7. Summary of statistics for regressions of parameter estimates from kinetics of in vitro DM disappearance and apparent in vitro DM disappearance after 30 or 48 h of incubation on growing degree days $>5^{\circ}\text{C}^1$ for triticale forages harvested at Marshfield, Wisconsin, during 2016

Item ^{2,3}	No.	Model type	Model	$P > F^4$	Dependent mean	RMSE ⁵	R ²
Fraction A	24	Quadratic	$Y = 0.000210x^2 - 0.259x + 98.1$	<0.001	33.9	1.98	0.970
Fraction B	24	Cubic	$Y = 0.00000239x^3 - 0.000482x^2 + 0.291x - 4.3$	<0.001	45.6	1.51	0.916
Fraction U	24	Cubic	$Y = -0.000000471x^3 + 0.000620x^2 - 0.187x + 26.3$	<0.001	20.5	1.13	0.983
K _d , /h	24	Quadratic	$Y = 0.00000205x^2 - 0.000273x + 0.121$	<0.001	0.049	0.0043	0.917
Lag time, h	24	Linear	$Y = -0.00668x - 8.28$	<0.001	5.32	0.912	0.715
IVDMD, 30 h	24	Quadratic	$Y = 0.000189x^2 - 0.248x + 129.6$	<0.001	64.9	2.28	0.969
IVDMD, 48 h	24	Cubic	$Y = 0.000000586x^3 - 0.000733x^2 + 0.189x + 75.3$	<0.001	72.9	1.32	0.988

¹Growing degree days accumulated since January 1 using 5°C as a base temperature; data are summarized in Table 1.

²Fraction A = DM disappearing at a rate too fast to measure; fraction B = DM disappearing at a measurable rate; fraction U = DM indigestible in buffered rumen fluid. K_d = in vitro disappearance rate of fraction B per hour. IVDMD, 30 h and IVDMD, 48 h = in vitro DM disappearance calculated after 30 and 48 h of incubation, respectively.

³Units for each dependent regression variable are expressed as percentage of DM unless otherwise indicated.

⁴ $P > F$ for the overall regression model.

⁵Root mean squared error for the regression model.

from 5.2 to 9.8 percentage units on individual harvest dates (Table 6). For both incubation times, relationships with growth stage were explained by cubic ($P < 0.001$) models with very high coefficients of determination ($R^2 \geq 0.982$). Generally, mean apparent IVDMD30 and IVDMD48 were very high during stem elongation ($\geq 82.3\%$; Table 6) and then declined steadily through the anthesis stage of growth ($\leq 61.5\%$) before increasing slightly in response to grain fill. Two key summary points are important: (1) triticale forages are highly digestible at the stem elongation or boot stages of growth, which is consistent with many studies including a variety of cereal grain forages (Cherney and Marten, 1982a; Walker et al., 1990; Coblenz et al., 2000), and (2) the DM digestibility of triticale stabilizes, and may even increase, during grain fill. This latter response has been described for other cereal grain forages (Walker et al., 1990; West et al., 1991); however, the final collective effect of grain fill is dependent on species (Helsel and Thomas, 1987; Coblenz et al., 2000) as well as the competing effects of increased lignification and reduced digestibility of leaf, leaf sheath, and stem juxtaposed against the accumulation of highly digestible carbohydrate within the seed head (Cherney and Marten, 1982b; Walker et al., 1990).

Regressions on GDD. While regressions of DM yield, concentrations of N, and total N uptake on GDD for triticale grown in Iowa have been reported (Schwarte et al., 2005; Gibson et al., 2007), similar regressions on parameter estimates for DM disappearance kinetics have not. These relationships are included (Table 7), and generally they exhibit very high coefficients of determination ($R^2 \geq 0.916$) for all parameters except lag time ($R^2 = 0.715$). Although the most appropriate polynomial model varies somewhat from regressions on growth stage, in part because the 2 independent variables have different relationships with chronological time, growth stage and GDD are obviously interrelated and both depict similar changing patterns in digestibility characteristics as GDD accumulate or as plants mature.

CONCLUSIONS

From a management perspective, the nutritional characteristics of triticale forages are heavily influenced by 2 competing processes. These include the normal maturation effects that reduce the quality of most forages juxtaposed against the physiological process of grain fill, which can dilute concentrations of forage fiber components, increase energy density, and improve DM digestibility at advanced plant growth stages. Despite this juxtaposition of competing physiological processes, nutritive characteristics of triticale harvested at the

boot stage of growth are more favorable for lactating cows compared with those harvested at later stages of maturity, primarily due to avoidance of the most negative aspects of the normal maturation process, such as increased concentrations of fiber components and reduced concentrations of CP. However, an approximately 70% yield drag also can be associated with this management choice. Furthermore, a comparison of respective energy yields for 2016 (2,488 vs. 8,141 kg of TDN/ha) and 2017 (1,033 vs. 3,520 kg of TDN/ha) suggests that yields of energy are mostly driven by the differential in DM yield. Despite these differences, an informed management decision for lactating cows may still favor a boot-stage harvest because of superior nutritional characteristics, a need to plant a corn double crop expeditiously, or both. Harvest timing of triticale forages for other livestock classes would appear to be more flexible, but prioritizing a double crop of corn, soybeans, or sorghum may reduce the negative effects on DM yield to a secondary consideration.

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