Supplemental Information

Table S1 (supplementary information) Renewable natural gas (RNG) market price data. The RNG price is the sum of the wholesale fossil natural gas price and the D3 RIN price. Data are presented as the minimum (min), maximum (max), and average (avg) dollars per gallon gasoline equivalent, dollars per million British thermal units (MMBtu), dollars per cubic meter of biogas, and dollars per metric ton (Mg) of rye. RNG production was calculated assuming a biogas yield of 0.315 m^3 CH_4 kg^{-1} volatile solids for rye containing 94% volatile solids (VS).

Data	$ per gallon gasoline equivalent	$ MMBtu^{-1}	$ m^{-3}	$ Mg^{-1}	Date range	Data source
D3 RIN price	Min: $1.92 Max: $3.09 Avg: $2.47	Min: $22.52 Max: $36.24 Avg: $29.00	Min: $0.80 Max: $1.28 Avg: $1.03	Min: $236.88 Max: $379.01 Avg: $304.98	12/28/2020 - 5/24/2021	[82]
Fossil natural gas price	--	Min: $1.63 Max: $5.35 Avg: $2.49	Min: $0.06 Max: $0.19 Avg: $0.09	Min: $17.77 Max: $56.26 Avg: $26.65	1/1/2019 - 6/1/2021	[83]

Table S2 (supplementary information) Aboveground biomass reported by rye planting method (drilled after corn harvest, broadcast and overseeded into R6 corn, and broadcast and incorporated after corn harvest) and by fertilizer nitrogen application rate (N rate) (0, 60, 120 kg N ha^{-1}) reported in [37]. Estimated harvestable biomass was determined by [37] as biomass minus 0.75 Mg assumed left in the field to maintain soil ecosystem services based on [34]. Overall, rye biomass production in this study was similar to ranges reported in Alabama, United States [33] and Maryland, United States [84] and exceeded production in Nebraska, United States [85,86] and Kentucky, United States [18].

Factor / Level		2018	2019
Planting Method	Drilled	5.9 (1.0)	5.2 (1.8)
	Overseeded	5.2 (1.0)	6.2 (1.5)
	Incorporated	7.2 (0.9)	5.3 (1.4)
N Rate	0 kg N ha^{-1}	5.9 (1.3)	4.1 (1.0)
	60 kg N ha^{-1}	6.3 (1.1)	5.9 (1.3)
	120 kg N ha^{-1}	6.1 (1.4)	6.6 (1.4)

Table S3 (supplementary information) Mean values (with standard deviation) for rye crude protein (CP), available protein (CP minus acid detergent insoluble crude protein), rumen degradable protein (RDP), rumen undegradable protein (RUP), acid detergent fiber (ADF), neutral detergent fiber (NDF), lignin, relative feed value (RFV), total digestible nutrients (TDN), net energy for lactation (NEL), net energy for gain (NEG) and net energy for maintenance (NEM) for the two growing seasons, 2018 and 2019. Data are reported by rye planting method (drilled after corn harvest, broadcast and overseeded into R6 corn, and broadcast and incorporated after corn harvest) and by interaction between planting method and fertilizer nitrogen application rate (N rate) (0, 60, and 120 kg N ha^{-1}).

Forage quality constituent	**2018**					**2019**				
	Drilled	**Overseeded**	**Incorporated**	***p***	**Planting Method x N Rate**	**Drilled**	**Overseeded**	**Incorporated**	***p***	**Planting Method x N Rate**
CP (%)	10.58 (1.70) a	11.19 (0.95) b	10.74 (1.32) ab	*	**	10.38 (1.81) ab	9.83 (1.81) a	11.01 (2.14) b	**	ns
Available P (%)	10.16 (1.63) a	10.76 (0.88) b	10.28 (1.34) ab	*	**	9.94 (1.67) ab	9.35 (1.71) a	10.54 (2.01) b	***	ns
RDP (%)	76.22 (3.02) ab	78.11 (3.03) b	75.50 (3.29) a	*	ns	75.94 (1.59)	74.22 (2.37)	75.22 (2.62)	ns	ns
RUP (%)	23.78 (3.02) ab	21.89 (3.03) a	24.50 (3.29) b	*	ns	24.06 (1.59)	25.78 (2.37)	24.78 (2.62)	ns	ns
ADF (%)	42.85 (1.14)	41.77 (1.23)	42.39 (1.32)	ns	ns	44.60 (1.37)	45.61 (1.73)	44.51 (1.77)	ns	ns
NDF (%)	64.83 (1.92)	64.21 (2.17)	64.92 (1.95)	ns	ns	68.33 (1.85) ab	69.59 (1.45) b	67.44 (1.68) a	**	ns
Lignin (%)	5.48 (0.60)	5.59 (0.60)	5.38 (0.47)	ns	ns	5.21 (0.76) a	5.71 (0.43) b	5.32 (0.45) ab	*	ns
RFV (%)	79.61 (3.53)	81.94 (4.11)	80.33 (3.77)	ns	ns	73.78 (3.08) b	71.39 (2.81) a	74.94 (3.21) a	**	ns
TDN (%)	57.61 (1.82)	58.33 (1.14)	58.00 (1.08)	ns	ns	55.61 (1.38) ab	54.50 (1.10) a	55.78 (1.35) b	*	ns
NEL (%)	4.50 (0.25)	4.59 (0.22)	4.53 (0.21)	ns	ns	4.08 (0.24) ab	3.90 (0.17) a	4.18 (0.20) b	**	ns
NEG (%)	2.35 (0.23)	2.43 (0.17)	2.41 (0.15)	ns	ns	2.06 (0.19) ab	1.90 (0.15) a	2.10 (0.19) b	*	ns
NEM (%)	4.69 (0.25)	4.77 (0.19)	4.75 (0.17)	ns	ns	4.37 (0.21) ab	4.20 (0.16) a	4.42 (0.20) b	*	ns

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns: not significant.

Different letters indicate significant differences for a constituent within a specific year identified by the Tukey-Kramer post hoc test at α=0.05 level.

Table S4 (supplementary information) Mean values (with standard deviation) for rye revenue potential for the two growing seasons, 2018 and 2019. Data are reported for winter rye in a bioenergy system producing RNG and a high protein feed coproduct (RNG system) for a range of RNG prices (low estimate to high estimate) by rye planting method (drilled after corn harvest, broadcast and overseeded into R6 corn, and broadcast and incorporated after corn harvest) and by fertilizer nitrogen application rate (N rate) (0, 60, and 120 kg N ha^{-1}).

Factor	Level	2018		2019	
		RNG system (low estimate) *$ Mg^{-1}*	**RNG system (high estimate)** *$ Mg^{-1}*	**RNG system (low estimate)** *$ Mg^{-1}*	**RNG system (high estimate)** *$ Mg^{-1}*
Planting Method	Drilled	308.37 (3.59)	488.99 (3.59)	314.73 (5.59)	495.35 (5.59)
	Overseeded	305.66 (4.90)	486.29 (4.90)	317.11 (7.80)	497.73 (7.80)
	Incorporated	306.67 (3.83)	487.29 (3.83)	315.22 (7.70)	495.85 (7.70)
	p	ns	ns	ns	ns
N Rate	0 kg N ha^{-1}	306.78 (4.67)	487.4 (4.67)	307.93 (3.58) a	488.55 (3.58) a
	60 kg N ha^{-1}	306.99 (3.89)	487.61 (3.89)	317.91 (4.29) b	498.53 (4.29) b
	120 kg N ha^{-1}	306.94 (4.30)	487.56 (4.30)	321.22 (4.71) b	501.84 (4.71) b
	p	ns	ns	***	***
Planting Method x N Rate		ns	ns	ns	ns

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns: not significant.
Different letters indicate significant differences within column identified by the Tukey-Kramer post hoc test at α=0.05 level.

Figure S5 (supplemental information) Equations used to calculate net greenhouse gas emissions (GHG) in Figure 3 for fertilized and unfertilized rye in a renewable natural gas (RNG) bioenergy system.

Variables used in equations

a = Rye biomass yield (Mg ha^{-1}) reported in [37].

b = 94% biomass volatile solids (VS) content reported in [26] for triticale.

c = 0.315 m^3CH_4 kg^{-1} VS reported in [26] for triticale.

d = 26.7%; residual biomass remaining as digestate reported in [26] and validated in bench-scale experiments with winter rye in PA.

e = 41.2% carbon in digestate (measured in bench-scale anaerobic digestion experiments with winter rye in PA).

f = kg C ha^{-1} from Figure 6 in [11] for winter rye following corn / 0.27 kg C per kg CO_2.

g= kg C ha^{-1} from Figure 6 in [11] for fertilized rye following corn / 0.27 kg C per kg CO_2.

h = Mg ha^{-1} reported in [11] for winter rye following corn.

i = Mg ha^{-1} reported in [11] for fertilized rye.

j = average rye yield (Mg ha^{-1}) for the 2018 harvest year reported in [37].

k = average rye yield (Mg ha^{-1}) for the 2019 harvest year reported in [37].

Net GHG emissions (kg CO_2-eq ha^{-1}) =

$$\{Emissions\ from\ the\ combustion\ of\ RNG\ + \\ Emissions\ from\ digester\ energy\ requirements\ + \\ GHG\ emissions\ modeled\ in\ FEAT\ (except\ fertilizer\ N2O) + \\ emissions\ from\ fertilizer\ N2O\} - \{carbon\ stored\ in\ digestate\ + \\ carbon\ stored\ in\ soil\ +\ fossil\ natural\ gas\ emissions\ offset\ by\ RNG\}$$

Fertilizer N_2O emissions (kg CO_2-eq ha^{-1}) were modeled in the Farm Energy Analysis Tool (FEAT) [55]. See [37] for more details.

GHG emissions (except fertilizer N_2O) (kg CO_2-eq ha-1) modeled in FEAT. See [37] for more details.

Emissions from the combustion of Renewable natural gas (RNG) (kg CO_2-eq ha^{-1}) =

$$a\ x\ \left(\frac{1\ kg}{0.001\ Mg}\right) x\ b\ x\ c\ x\ \frac{35.3147\ ft^3}{m^3}\ x\ \frac{1027\ BTU}{ft^3}\ x\ x\ \frac{MMBTU}{10^6\ BTU} x \frac{52.91\ kg\ CO_2}{MMBTU}\ \ ;$$

$Where$ 52.91 $kg\ CO_2\ per\ MMBTU\ is\ reported\ in\ U.S.EIA$ (2021) [56]

$which\ is\ equivalent\ to$ 50.1 $kg\ CO_2\ GJ^{-1}\ because$ 1 $MMBTU\ =\ 1.0551\ GJ$

and 1,027 $BTU\ per\ ft^3\ is\ reported\ for\ natural\ gas\ by$ [87]

Fossil natural gas emissions offset by RNG (kg CO_2-eq ha^{-1}) = emissions from combustion of RNG (see above as RNG and fossil natural gas have identical emissions during combustion).

Emissions from digester energy requirements (kg CO_2-eq ha^{-1}) =
$a\ x\ b\ x\ c\ x$ 0.06 $kg\ CO_2m^{-3}\ methane$;

Where 0.06 $kg\ CO_2m^{-3}\ methane$ = external energy requirements for operating a 1200 m^3 digester [79].

Carbon stored in digestate (digestate) (kg CO_2-eq ha^{-1}) = $-d\ x\ a\ x\ e\ x\ 1{,}000 \frac{kg}{Mg} x \left(\frac{1\ kg\ CO_2}{0.27\ kg\ digestate\ C}\right)$

Soil carbon unfertilized rye (kg CO_2-eq ha^{-1}) = $\frac{\left\{\left(\frac{(f\ x\ j)}{h}\right)+\left(\frac{(f\ x\ k)}{h}\right)\right\}}{2}$

Soil carbon fertilized rye (kg CO_2-eq ha^{-1}) = $\frac{\left\{\left(\frac{(g\ x\ j)}{i}\right)+\left(\frac{(g\ x\ k)}{i}\right)\right\}}{2}$

Table S6 (supplemental information) Forage quality indicators of composite winter rye samples before (day 0) and after (day 21) twenty-one days of digestion in bench-scale experiments from winter rye harvested in PA, including crude protein (CP) (%), acid detergent fiber (ADF) (%), neutral detergent fiber (NDF) (%), total digestible nutrients (TDN) (%), net energy for lactation (NEL) (%), net energy for maintenance (NEM) (%), net energy for grain (NEG) (%), relative feed value (RFV) (%), and lignin (%). Bench-scale digesters were inoculated on day 0 with digested material (digestate) from an acclimated switchgrass digester. The digestate used as inoculum had a higher % lignin than % lignin measured in fresh rye samples collected in IA because the material is already digested and because the material is digestate from a digester fed with mature, lignocellulosic switchgrass.

Bench-scale digester experiment day and description	Dry Matter (%)	Crude Protein (CP) (%)	ADF (%)	NDF (%)	TDN (%)	NEL (%)	NEM (%)	NEG (%)	RFV (%)	Lignin (%)
Day 0 (Fresh material)	99.9	22.0	36.8	51.2	49.0	0.48	0.40	0.15	110	17.2
Day 21 (Digested)	99.9	29.4	34.9	42.1	50.0	0.52	0.43	0.18	136	24.2
Percent decrease or increase		33.6	-5.2	-17.8	2.0	8.3	7.5	20.0	23.6	40.7

This section (SI 7 to SI 9) provides supplemental information on the multiple linear regression analysis used for the hedonic pricing [49] of winter rye digestate as feed. Since a market for winter rye digestate does not exist in the field experiment study area (Iowa), we modeled the relationships between national weekly feedstuff wholesale prices for alfalfa hay, wheat straw, soybean meal, and corn gluten feed sold in Iowa and St. Louis, Missouri (reported in [52] from September 2020 to September 2021 and the average forage quality (crude protein (CP), net energy for lactation (NEL), and acid detergent fiber (ADF) reported for field samples between 2020 and 2021 of four forage crops: alfalfa hay, wheat straw, soybean meal, and corn gluten meal [53]. This allowed us to use hedonic pricing to assign an economic value to the leftover digestate material as a feed protein coproduct.

The multiple regression model for predicting wholesale feed prices from their estimated CP, NEL, and ADF was Price ($\$ \text{ ton}^{-1}$ dry basis) = 4.24*CP (%) + 1266.0*NEL (Mcal Lb-1) + 13.4*ADF (%) – 1029.7 and had an R squared of 0.88. All coefficients were significant at $p < 0.1$ ($p = 0.0086$ for CP, $p = 0.0814$ for NEL, and $p = 0.0273$ for ADF). Other forage quality measures were also considered for the regression but were not found to be significant.

Similar approaches have previously been used to estimate the economic value of feeds or compare feed value based on nutritional composition, including:

1. The University of Wisconsin-Madison's FeedVal v6.0 decision support tool developed by V. E. Cabrera, L. Armentano, and R. D. Shaver [50] calculates the predicted value of feed ingredients using rumen degradable protein, rumen undegradable protein, neutral detergent fiber, and net energy for lactation.

2. North Dakota State University's combined Feed Value (FV) and Protein and Energy (P&E) Calculator [88] estimates and compares the cost per unit of protein or energy at various prices and nutritional compositions.

3. South Dakota State University Extension's feed value calculator [89] is a tool producers can use to evaluate feed value based on its nutritional content.

4. Penn State Extension's feed value calculator [90] calculates the economic value of forages and concentrates based on price and average quality. That tool is available for download at https://extension.psu.edu/feed-value-calculator-spreadsheet;

5. The University of Wisconsin's 'feed cost calculator' [91] calculates the protein, total digestible nutrients, and energy cost per ton so producers can find the most economical feed.

These tools use single static values for price data that are only representative of a particular date and therefore do not capture or consider the seasonal variation in market fluctuations; furthermore, these models were developed using input values from outside of the study region. The hedonic price estimation described above uses prices and composition data from Iowa and Missouri that represent real fluctuations over time. All composition parameter estimates in the model are significant at $p < 0.1$, strongly suggesting that the estimated value of livestock feed as a function of feed composition for the region is robust.

The actual market price data for alfalfa hay, wheat straw, soybean meal, and corn gluten feed versus the prices predicted by the regression model are shown in plot SI 7. Alfalfa hay is shown as red circles, wheat straw is shown as orange squares, soybean meal is shown as blue triangles, and corn gluten feed is shown as green triangles. SI 8 shows the actual and the regression estimated prices for alfalfa hay, wheat straw, soybean meal, and corn gluten feed, the upper and lower bounds of the 95% mean confidence intervals for the estimated price, and the average hedonic price estimates for digestate (average across planting method and fertilizer nitrogen rate). SI 9 shows model residuals and parameter estimates and their significance.

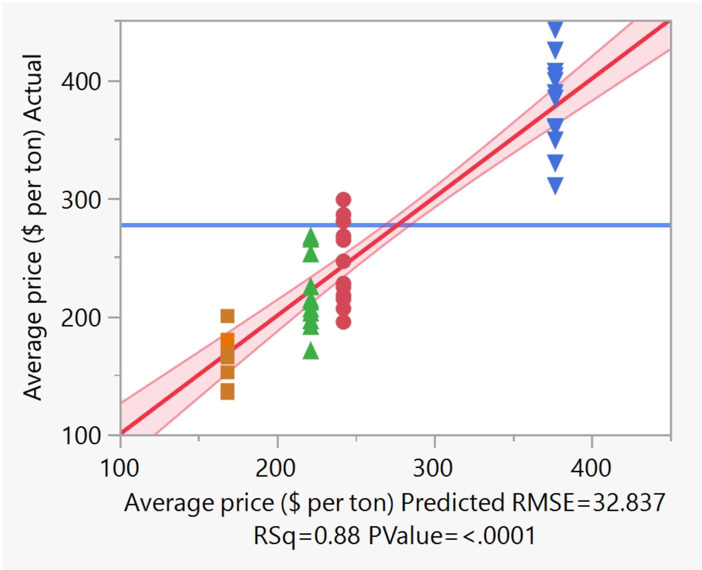


Figure S7 (supplemental information) Actual feed price compared to price predicted by regression. Alfalfa hay, wheat straw, soybean meal, and corn gluten feed are shown as red circles, orange squares, blue triangles, and green triangles, respectively. The estimated regression was *price ($ ton^{-1} dry basis) = 4.24*CP (%) + 1266.0*NEL (Mcal Lb^{-1}) + 13.4*ADF (%) – 1029.7*, which had an R squared of 0.88 and root mean square error (RMSE) of $32.83. Spreads on the actual prices represent overall feed market fluctuations, which primarily affect the intercept but not the slope of the regression. Predicted prices are based on the mean price during the period the regression data were collected. The 95% confidence interval is shown as the shaded pink region around the red regression equation, with the solid line and confidence interval bounds illustrated for the mean price.

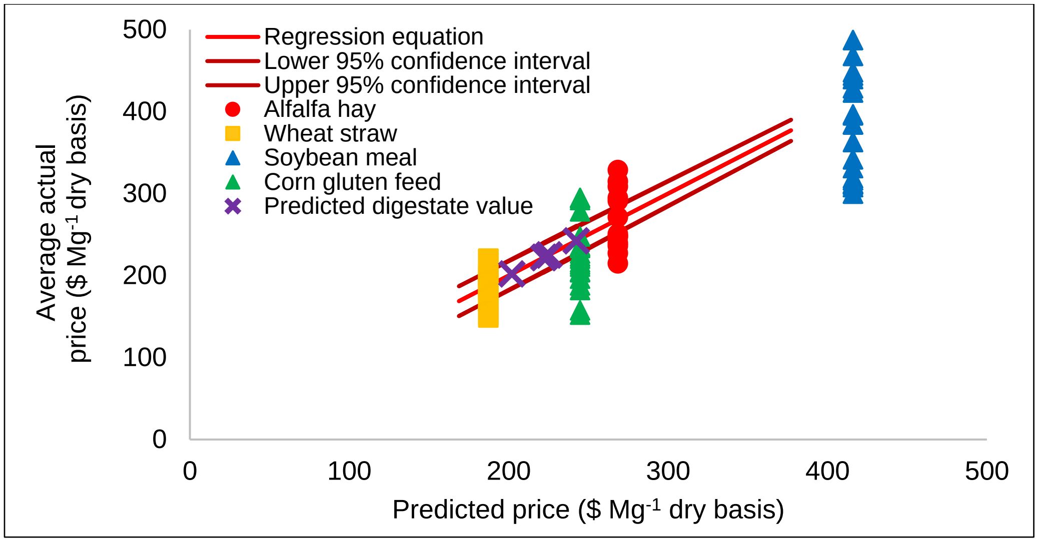
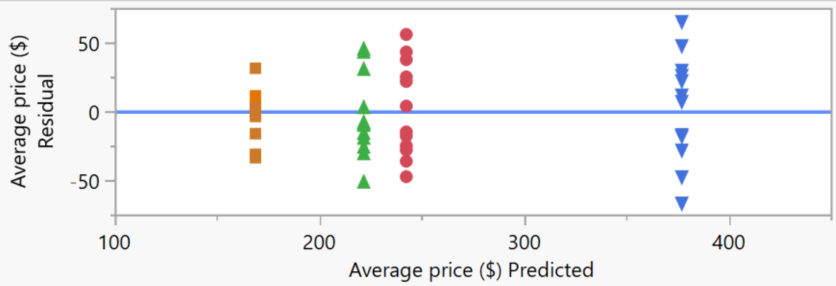
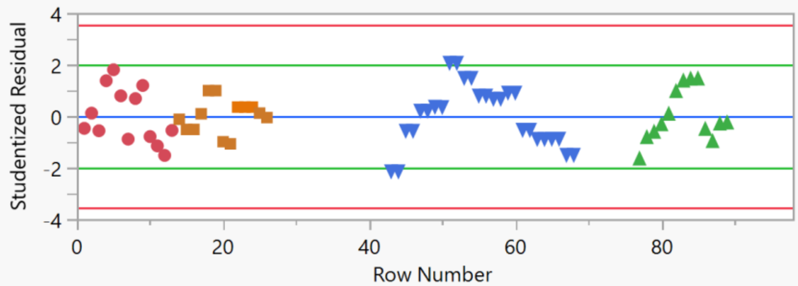


Figure S8 (supplemental information) Actual and predicted feed prices ($ Mg^{-1}) for feeds (alfalfa hay, wheat straw soybean meal, and corn gluten feed) modeled by regression, and average estimated price for winter rye digestate for each planting method and nitrogen fertilizer application rate. Alfalfa hay, wheat straw, soybean meal, and corn gluten feed are shown as red circles, orange squares, blue triangles, and green triangles, respectively. Predicted digestate values are shown as purple crosses. The lower and upper bounds for the 95% confidence interval are shown in maroon around the red regression equation, illustrated for the mean price).

Residual by Predicted Plot



Studentized Residuals



Externally studentized residuals with 95% simultaneous limits (Bonferroni) in red, individual limits in green.

Parameter Estimates

Term		Estimate	Std Error	t Ratio	Prob>|t|
Intercept	Biased	-1029.667	584.4038	-1.76	0.0831
CP	Biased	4.2399646	1.560551	2.72	0.0086*
NEL	Biased	1266.0039	714.4729	1.77	0.0814
ADF	Biased	13.36752	5.911259	2.26	0.0273*
NDF	Zeroed	0	0	.	.
(CP-31.1252)*(NEL-0.7152)	Zeroed	0	0	.	.
(CP-31.1252)*(ADF-20.1756)	Zeroed	0	0	.	.
(CP-31.1252)*(NDF-24.4082)	Zeroed	0	0	.	.
(NEL-0.7152)*(ADF-20.1756)	Zeroed	0	0	.	.
(NEL-0.7152)*(NDF-24.4082)	Zeroed	0	0	.	.
(ADF-20.1756)*(NDF-24.4082)	Zeroed	0	0	.	.
(CP-31.1252)*(NEL-0.7152)*(ADF-20.1756)	Zeroed	0	0	.	.
(CP-31.1252)*(NEL-0.7152)*(NDF-24.4082)	Zeroed	0	0	.	.
(CP-31.1252)*(ADF-20.1756)*(NDF-24.4082)	Zeroed	0	0	.	.
(NEL-0.7152)*(ADF-20.1756)*(NDF-24.4082)	Zeroed	0	0	.	.
(CP-31.1252)*(NEL-0.7152)*(ADF-20.1756)*(NDF-24.4082)	Zeroed	0	0	.	.

Figure S9 (supplemental information) Regression residuals by predicted plot, studentized residuals with 95% simultaneous limits (shown in red) and individual limits (shown in green), and model parameter estimates and their significance. Alfalfa hay, wheat straw, soybean meal, and corn gluten feed are shown as red circles, orange squares, blue triangles, and green triangles, respectively. Crude protein (CP), net energy for lactation (NEL) and acid detergent fiber (ADF) were significant at $p < 0.1$ ($p = 0.0086$ for CP, $p = 0.0814$ for NEL, and $p = 0.0273$ for ADF. Neutral detergent fiber (NDF) and interactions between terms were not significant.