

Article

Native Warm-Season Grass Response to Nitrogen Fertilization

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Abstract: The identification of appropriate nitrogen (N) rates for native warm-season grasses (NWSG) is needed to inform forage management in the southeastern United States. Experiments were conducted in Knoxville and Springfield, TN, from 2015 to 2019, to evaluate dry matter (DM) yield, forage nutritive value (FNV), the influence of temperature and precipitation on yield, and partial factor productivity (PFP) responses. Three NWSG species (big bluestem [BB; *Andropogon gerardii* Vitman], switchgrass [SG; *Panicum virgatum* L.], and eastern gamagrass [EG; *Tripsacum dactyloides* L.]) were grown at each location and harvested twice annually. Five N rates in the form of urea were applied annually in split applications. The yields for all species responded positively to nitrogen ($p < 0.001$) and the time of harvest ($p < 0.001$) at both sites, except for BB yield at Springfield; no consistent N effects were observed over years. Nitrogen affected the FNV ($p < 0.001$) of all species, increasing CP by three to five percentage points ($p < 0.001$). Yields across all species and locations responded positively to precipitation ($p < 0.001$) and temperature ($p < 0.001$). A moderate N amendment ($< 135 \text{ kg N ha}^{-1} \text{ yr}^{-1}$, based on PFP) can enhance the productivity of NWSG, but responses were site-dependent and influenced by temperature and precipitation.

Keywords: big bluestem; dry matter yield; eastern gamagrass; forage nutritive value; nitrogen; native warm-season grass; partial factor productivity; switchgrass; United States (U.S.)



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1. Introduction

Native warm-season grasses (NWSG), including big bluestem [BB; *Andropogon gerardii* Vitman], switchgrass [SG; *Panicum virgatum* L.], and eastern gamagrass [EG; *Tripsacum dactyloides* (L.) L.], have gained attention due to their potential contribution to forage and bioenergy production [1–3]. These species have long been known for various desirable attributes, including their broad adaptation [4–6], drought tolerance [7,8], and conservation potential [9]. In addition, NWSG offset reductions in the quantity and quality of available forage during summer in grazing systems dominated by cool-season grasses [10,11].

In addition to supporting forage-based beef and dairy enterprises, these NWSG are important for maintaining biodiversity and providing other ecosystems services like soil conservation [12], wildlife habitats [9,13], and carbon sequestration [2,14]. Yet, grasslands dominated by these native species have been declining and remain at risk, especially in the humid southeastern United States (U.S.) [15]. Currently, this region is dominated by tall fescue [TF; *Lolium arundinaceum*], a cool-season grass that requires more fertilization, relative to NWSG, and is under stress due to a pattern of severe summer droughts and higher than normal temperatures. Although average precipitation increased slightly (ca. 1%) between 1981 and 2023, the annual mean temperature increased by about 0.18 °C per decade since 1981, with the 10 warmest years on record all occurring since 2010 [16,17].

Such climatic conditions are weakening TF in the southeastern U.S., therefore leading to an encroachment of non-native warm-season grasses such as bermudagrass [BG; *Cynodon dactylon*, (L.) Pers.]. However, BG requires substantially more fertilization than TF, and thus has a larger carbon footprint for forage production. Furthermore, BG is not a high-quality forage and, without intensive fertilization, is less productive [18,19]. The need to provide high quality and productive summer forage that can withstand more extreme climatic conditions without negative environmental impacts is becoming a critical concern for sustainable forage production.

The NWSG, in contrast to the aforementioned introduced species, have been considered to have relatively low nutrient requirements for productivity [20–22]. Regardless, soil fertility and harvest management can exert a strong influence on forage productivity, as well as the nutritive value of NWSG [23–25]. Past studies have evaluated yield responses to N under biomass harvest scenarios for BB [22,26], SG [21,27,28], and EG [22,26,29]. In addition, research has been conducted on N responses in forage production scenarios in the Great Plains on mixed NWSG swards on marginal [30] and productive [31] soils and monoculture stands of BB, SG, and EG on productive soils [32]. However, in the southeastern U.S., data on yield responses and nutritive values from the N fertilization of NWSG are limited. The few studies conducted within this region have been on marginal soils, including reclaimed surface mines [6], on soils over deep sands within the Coastal Plain [22,33], and on a site with a fragipan [20]. Although both studies were conducted for two years, the fragipan study [20] evaluated SG only while the Coastal Plain studies [22,33] examined BB, SG, and EG. In comparison, our experiment evaluated BB, SG, and EG for five years, and assessed the influence of local precipitation and temperature, factors that could influence the efficacy of N amendments [34].

Understanding N responses in the context of phosphorous (P) and potassium (K) is important, but previous studies of NWSG conducted on soil with low available P and K have presented conflicting results. Some found a minimal yield increase for SG beyond the lowest rates of P and K, or that P had no influence on SG biomass yield [35]. Contrastingly, other studies found that treatments combining N, P, and K, produced the most SG [36,37], BB, and IG [37] yields. Yet, other studies conducted on the yield responses of SG to N, P, and K reported that only N provided consistent positive responses [35,38].

In light of the aforementioned critical need for high-quality summer forage, there is also need for improved resilience to extreme weather events, reduced environmental impacts associated with N fertilization, improved soil carbon balances, and for providing improved habitats for at-risk wildlife. To better understand the responses of NWSG to N fertilization, we conducted an experiment at two locations to evaluate their response across a range of N rates. Our specific objectives were to evaluate dry matter (DM) yield, forage nutritive values [FNV; crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF)], and partial factor productivity (PFP) for BB, SG, and EG in response to N fertilization. Our secondary objective was to explore the influence of temperature and precipitation during the growing season on yield responses at each location. We hypothesized that the yield asymptote for all three grasses would be low [20,21], but would be greater for EG than the other two species [23]. We also hypothesized that increased N levels would result in greater CP concentrations [24,25].

2. Materials and Methods

2.1. Site Description

Experiments were conducted on two sites: East Tennessee AgResearch and Education Center–Plant Science Unit (35.8984°, –83.9569°) in Knoxville, TN, and Highland Rim AgResearch and Education Center (36.4747°, –86.8379°) in Springfield, TN. The soil series at Knoxville was a Corryton–Townley complex (Corryton-loam and Townley-silt loam; fine, mixed, semiactive, thermic Typic Hapludults). This site previously grew turfgrasses, predominantly bermudagrass [*Cynodon dactylon* (L.) Pers.]. The soil series at Springfield was a Crider silt loam (fine-silty, mixed, active, mesic Typic Paleudalfs) and Staser silt

loam (fine-loamy, mixed, active, thermic Cumulic Hapludolls). Prior to planting NWSG, the field was managed with a mixed cool-season sward for hay production. Initial soil testing indicated an average pH of 5.7 and 6.4 at Knoxville and Springfield, respectively. On average, P and K were 18.3 kg ha⁻¹ and 143.6 kg ha⁻¹, respectively, at Knoxville, while at Springfield they were 86.4 kg ha⁻¹ and 118.7 kg ha⁻¹, respectively, and no soil P and K amendments were added for the study period. Annual soil samples (0–15 cm) were collected to determine pH, P, and K levels. The soil pH target for the study was ≥ 5.0 . Because annual mean soil pH over the 5-year study was 5.8 (range, 5.1–6.0) and 5.8 (range 5.4–6.1) at Knoxville and Springfield, respectively, no amendments were made for pH. At Knoxville, mean soil P was 15.1 $\pm$ 1.08 kg ha⁻¹, while K was 86.1 $\pm$ 1.92 kg ha⁻¹. At Springfield, means were 83.6 $\pm$ 1.9 kg P ha⁻¹ and 105.36 $\pm$ 6.6 kg K ha⁻¹ (Mehlich-1). Supplemental P and K were not applied to plots during the experimental period, owing to limited NWSG response to P and K in previous work [35,36,39,40] and our interest in evaluating N responses in environments where fertility was low [40,41].

2.2. Experimental Design

The three NWSG (BB, SG, and EG) were planted in 2011 in a randomized complete block design with a split-plot treatment arrangement and three replicates. Species represented the whole plot, and urea N rate was the split-plot factor. Grasses were planted at both sites using a 7-row, no-till plot drill (Hege Equipment Inc., Colwich, KS, USA) with 18 cm row spacing. Big bluestem, SG, and EG were seeded based on the University of Tennessee extension recommended rates of 10, 7, and 14 kg ha⁻¹ pure live seed, respectively [42]. Six N [urea (46-0-0 [CH₄N₂O])] application rates (Table 1) selected based on rates applied to alternative warm-season forages in the region, and a range wide enough to have surpassed the maximum yield response for that species. Urea was hand-broadcasted onto each of the 1.5 by 7.6 m plots in split applications (Figures 1, A1 and A2). From 2015 to 2019, N was applied with the first application after green-up (after plants were 30 cm tall, in late April), and the second application occurred two weeks after the first harvest (June).

Rep I		Rep II		Rep III					
1.5 meters									
106 SG 34	116 BigBlue 67	126 E.Gama 269	206 BigBlue 34	216 E.Gama 404	226 SG 269	316 SG 67	326 BigBlue 202	336 E.Gama 404	
1 meter alley									
105 SG 269	115 BigBlue 0	125 E.Gama 0	205 BigBlue 269	215 E.Gama 67	225 SG 202	315 SG 34	325 BigBlue 269	335 E.Gama 269	
1 meter alley									
104 SG 67	114 BigBlue 135	124 E.Gama 202	204 BigBlue 202	214 E.Gama 135	224 SG 202	314 SG 135	324 BigBlue 67	334 E.Gama 135	
1 meter alley									
103 SG 202	113 BigBlue 202	123 E.Gama 67	203 BigBlue 67	213 E.Gama 202	223 SG 135	313 SG 0	323 BigBlue 135	333 E.Gama 202	
1 meter alley									
102 SG 135	112 BigBlue 269	122 E.Gama 404	202 BigBlue 135	212 E.Gama 269	222 SG 269	312 SG 34	322 BigBlue 34	332 E.Gama 67	
1 meter alley									
101 SG 0	111 BigBlue 34	121 E.Gama 135	201 BigBlue 0	211 E.Gama 0	221 SG 67	311 SG 0	321 BigBlue 0	331 E.Gama 0	

Figure 1. Map of plots used for urea experiment. Top number in box is plot number, bottom number is nitrogen rate applied to that plot. SG is switchgrass, BB is big bluestem, EG is eastern gamagrass.

Table 1. Nitrogen rates ($\text{kg ha}^{-1} \text{yr}^{-1}$) for big bluestem, switchgrass, and eastern gamagrass.

Big Bluestem	Switchgrass	Eastern Gamagrass
0	0	0
34	34	67
67	67	135
135	135	202
202	202	269
269	269	404

2.3. Data Collection

Big bluestem, SG, and EG were harvested twice annually from 2015 to 2019 at both locations (Table 2), using a Carter forage harvester (Carter Manufacturing Company, Inc., Brookston, IN, USA) with a 91.4 cm cutting width and a 20.3 cm cutting height. Because multiple annual harvests could reduce plant vigor, a single growing-season harvest was conducted some years to ensure treatments could continue over a five-year period without stand degradation [2]. Post-dormancy harvests were conducted only in years with just a single growing-season harvest to capture yield produced following the first cut.

Table 2. Harvest dates of big bluestem (BB), switchgrass (SG), and eastern gamagrass (EG), 2015–2019.

Year	Springfield		Knoxville	
	First Cut	Second Cut	First Cut	Second Cut
2015	27 May [†]	7 December	2 June	30 July
2016	7 June	3 August	25 May	1 August
2017	7 June	28 November	2 June	11 December
2018	28 June	11 December	15 June	6 September
2019	8 July	5 December	14 June	19 August

[†] All species (BB, SG, and EG) were harvested on the same date for both cuts at both locations within a year.

Sub-samples from each plot of each NWSG were collected, weighed, and dried at 55 °C in a forced-air oven (Wisconsin Oven Corporation, East Troy, WI, USA and Oven King, Seattle, WA, USA at Knoxville and Springfield, respectively) for at least 72-h, or until no weight change was observed; then, samples were re-weighed to determine percent moisture to calculate DM yield.

Forage nutrient concentrations (CP, ADF, and NDF) were determined using data from Knoxville only, from 2017 to 2019. The dried sub-samples used to determine yield were ground using a Wiley Mill (Thomas-Wiley Laboratory Mill Model 4, Arthur H. Thomas Co., Philadelphia, PA, USA) to pass through a 2 mm mesh screen [43]. Additional drying of the prepared sample in a forced air oven at 55 °C was completed to ensure consistent moisture for scanning on a near infrared spectrometer (NIRS) for less variability in predicted results across all samples [44]. The samples were scanned on a Foss DS2500F using ISIS scan Nova v. 8.0.6.2 (Foss North America, Eden Prairie, MN, USA). The global and neighborhood statistical tests were monitored and analyzed for accuracy across all predictions, with the entire data set fitting the calibrations within the H limit of fit (<3.0), and were reported accordingly [43,45]. Units of measurement for nutritive analyses and calculated parameters were presented at 100% DM across the entire data set. The NIRS nutritive value predictions were provided by the Grass Hay calibrations (2018–2019) developed by the NIRS Consortium (NIRSC, Berea, KY, USA). The UT Beef & Forage Center Forage Nutrition Laboratory was used for this analysis, and is certified by the National Forage and Testing Association (NFTA, Stuart, FL, USA).

2.4. Statistical Analysis

Data were analyzed separately by species and location due to differences in N-rates applied per species and different harvest dates at each location. Dry matter yield and FNV were analyzed under an ANOVA model in SAS v9.4 [46] using PROC MIXED, and significant differences were declared at $\alpha = 0.05$ using Fisher's least significance difference (LSD) test [47]. Fixed effects for yield were treatments (N rates) and year (to be able to detect cumulative effects of treatments over the 5-year study period) with block being a random effect. Fixed effects for FNV models were N treatments and harvest time (first or second harvest), and block was a random effect. Where indicated, due to non-normality and unequal variances of residuals, data were transformed, and models were re-run using ranked data. Untransformed means were reported in all cases.

For each species, PFP ($\text{Mg ha}^{-1} \text{ kg}^{-1} \text{ N}$) was calculated per N rate using a modified formula based on previous studies [48,49] below:

$$\text{PFP} = (\text{Yield}_{N_0} + (\text{Yield}_{N_x} - \text{Yield}_{N_0})) / \text{Kg}_{N_i} \quad (1)$$

where N_x was N rate > 0 , and N_0 was N rate $= 0$, Kg_{N_i} was kg N applied and yield was DM values per N rate.

To determine the relationship between NWSG yields and precipitation (mm) and temperature ($^{\circ}\text{C}$), we used ANCOVA with each of the environmental variables and their interactions entered as covariates, while block, year, species, and N rate were treated as random effects in the model. As was the case with the models for DM yield, each location was analyzed separately. However, because NWSG did not differ ($p = 0.607$), nor did they interact with either precipitation ($p = 0.284$) or temperatures ($p = 0.639$) in a preliminary model, we pooled them for the final model to improve model sensitivity. For the first harvest, data for precipitation and temperature included a 30–35-day period preceding each harvest (Table 2). For the second harvest, precipitation from the period after the first harvest but preceding the second was included. Because, in Tennessee, NWSG begin senescence in late September, this was the last month used for precipitation and temperature for post-dormancy harvests. Weather data were collected at weather stations located on site at Knoxville and Springfield and were compared to 30-year means per location [50,51].

3. Results and Discussion

3.1. Environmental Conditions at Knoxville and Springfield

During the study, monthly precipitation remained near the 30-year means for both locations with few exceptions (Figure 2a,b). At Knoxville, increased precipitation was observed in July 2015 and 2019, August 2017, and August and September 2018. Months well below the 30-year mean precipitation included May 2015, August–September 2016, September 2017, and August–September 2019. In Springfield, 2016 and 2019 had more precipitation than normal. Precipitation levels below the 30-year mean was observed at that location in 2015 (May, August, and September), 2018 (July), and 2019 (May and September). Temperatures, on the other hand, for both Knoxville (Figure 2c) and Springfield (Figure 2d) remained close to the 30-year mean, with no substantial deviations.

3.2. NWSG' Yield Response to Inorganic-N

At Knoxville, N rate affected ($p < 0.001$) yields for all three species, but at Springfield only SG ($p < 0.001$) and EG ($p = 0.002$) responded to N amendments (Table 3), whereas BB did not ($p = 0.150$).

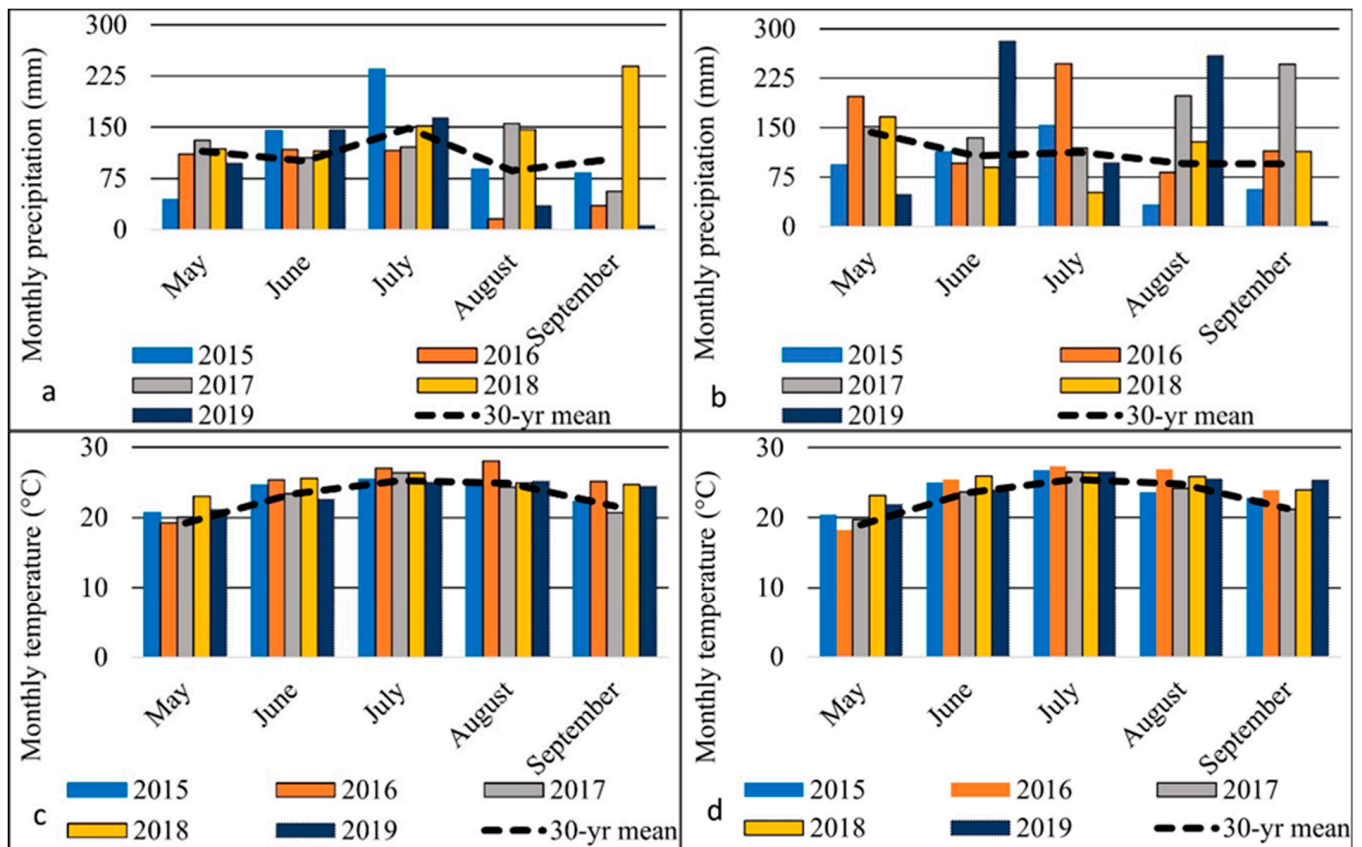


Figure 2. Mean monthly precipitation (mm) and 30-year mean for east Tennessee ((a); Knoxville, TN, USA) and Highland Rim ((b); Springfield, TN, USA), 2015–2019. Mean monthly temperature (°C) and 30-year mean for east Tennessee ((c); Knoxville, TN, USA) and Highland Rim ((d); Springfield, TN, USA), 2015–2019.

Table 3. Results from ANOVA model for dry matter yield for big bluestem, switchgrass, and eastern gamagrass at east Tennessee (Knoxville) and Highland Rim (Springfield), 2015–2019.

Effect	Knoxville		Springfield	
	F Value	p > F	F Value	p > F
Big bluestem				
Nitrogen	15.57	<0.001	1.70	0.150
Year	52.97	<0.001	19.08	<0.001
Year × Nitrogen	0.36	0.993	0.44	0.977
Switchgrass				
Nitrogen	11.94	<0.001	19.25	<0.001
Year	44.87	<0.001	7.88	<0.001
Year × Nitrogen	0.84	0.657	0.93	0.551
Eastern gamagrass				
Nitrogen	36.03	<0.001	5.74	0.002
Year	117.66	<0.001	35.05	<0.001
Year × Nitrogen	2.93	0.008	0.86	0.631

Clearly, N played a key role in increasing NWSG yields. Mean yields were always least at 0 kg N ha^{−1} yr^{−1}, with the exception of BB at Springfield, for which there was no difference among N rates (Table 4). The responses of the other two species to N amendments were similar to those previously reported [6,20,23], and support the use for N fertilization to improve NWSG yields. The greatest DM yield for SG was attained when fertilizing

with 202 kg N ha⁻¹ yr⁻¹ at Springfield, while the greatest yields at Knoxville were at 67 kg N ha⁻¹ yr⁻¹, indicating possible differences in sites. The year × N-rate interaction at Knoxville for EG ($p = 0.008$) may have been a result of greater precipitation in some years (e.g., 2015, 2018) that led to increased yields relative to other years. Regardless, 135 kg N ha⁻¹ yr⁻¹ produced the greatest DM yield for EG at both sites (Table 4).

Table 4. Mean dry matter yields (Mg ha⁻¹) for big bluestem (BB), switchgrass (SG) and eastern gamagrass (EG) per N rate at east Tennessee (Knoxville) and Highland Rim (Springfield), 2015–2019.

N Rate	Knoxville			Springfield		
	BB	SG	EG	BB	SG	EG
0	5.92 d [†]	4.78 c	6.77 b	6.14	6.50 c	5.46 c
34	8.13 c	6.26 c	-	6.25	7.24 c	-
67	9.03 bc	9.01 ab	7.99 b	5.32	8.28 b	5.67 bc
135	11.31 ab	10.36 ab	10.82 a	5.79	8.38 b	6.87 a
202	12.33 a	9.44 b	11.46 a	6.32	9.75 a	5.85 bc
269	11.22 a	10.73 a	12.87 a	5.94	10.32 a	6.63 ab
404	-	-	12.46 a	-	-	7.42 a

[†] Means for each location and species with at least one common letter were not different ($p < 0.05$).

For all species, except BB and SG at Springfield, 135 kg ha⁻¹ yr⁻¹ was enough to produce the greatest yield, a rate similar to that identified in recent research in Arkansas [20]. Therefore, for low-input production scenarios, our study suggests N rates of no more than 135 kg N ha⁻¹ yr⁻¹ for EG at Springfield or 67 kg N ha⁻¹ yr⁻¹ for SG, and no more than 135 kg N ha⁻¹ yr⁻¹ for BB and EG at Knoxville. These rates appear to be sufficient for forage production in the southeastern U.S. These results also make it clear that species and site characteristics both play a role in fertilization decisions for NWSG forage production. These results are similar to those previously reported [26,52], which concluded that optimum yields required similar N rates or lower and varied by species.

Studies have also reported that although N applications increased NWSG yield, the increase varied by harvest frequency. For instance, an Arkansas study evaluating switchgrass concluded that for a two-cut system, 252 kg N ha⁻¹ yr⁻¹ was optimal [20]. While a study of six NWSG under four harvest intervals with five N rates reported that more nitrogen was needed with more frequent harvests [22]. However, even with 224 kg N ha⁻¹ yr⁻¹, sustaining high yields required stand rest from constant defoliations. Our results indicate lower N requirements than suggested by the above studies [20,22], but this could be due to different soil types between Mississippi, Arkansas, and Tennessee, or differing harvest regimes, including those post-dormancy harvests in our case, and the duration of the studies (two years versus five years in the current study).

3.3. The Temporal Effects on DM Yield of NWSG

For all species at both sites, the year influenced the annual DM yield ($p < 0.001$; Table 3). The greatest mean DM yields at Knoxville were achieved in 2018 with BB, SG, and EG averaging 15.21, 14.53, and 17.53 Mg ha⁻¹, respectively, and were different from the mean yields of all other years for all three species (Table 5). Similarly, at Springfield, the greatest mean yields were also observed in a single year (2016) for all three species, with BB, SG, and EG yielding 7.37, 9.29, and 9.73 Mg ha⁻¹, respectively, and differing from other years, with the exception of SG, where 2015 and 2017 were similar to 2016.

Table 5. Mean dry matter yields (Mg ha^{-1}) for big bluestem (BB), switchgrass (SG), and eastern gamagrass (EG) at east Tennessee (Knoxville) and Highland Rim (Springfield), 2015–2019.

Year	Knoxville			Springfield		
	BB	SG	EG	BB	SG	EG
2015	12.27 b [†]	9.72 b	11.30 b	6.91 b	9.22 a	4.74 c
2016	5.68 d	4.69 d	6.94 d	7.37 a	9.29 a	9.73 a
2017	7.01 c	5.21 d	6.44 e	5.68 c	8.82 a	6.10 b
2018	15.21 a	14.53 a	17.53 a	4.75 d	7.50 b	6.12 b
2019	7.81 c	8.54 c	9.87 c	5.08 c	7.47 b	4.90 c

[†] Means for each location and species with at least one common letter were not different ($p < 0.05$).

In contrast, patterns for lowest yields were not as clear. At Knoxville, the yields were lowest for BB and SG (5.68 and 4.69 Mg ha^{-1} , respectively) during 2016. At Springfield, the lowest yields were from 2018 for BB and 2019 for SG and EG. The yield variations from year-to-year have been documented by previous studies and attributed to seasonal variations in precipitation, temperatures, annual variations, species' cultivar, and sites [23,28,53]. In the current study, the influence of weather as a contributing factor in these variations was supported by our regression analysis (Table 6). Indeed, in 2018, Knoxville had rainfall levels at (May, June, and July) or above (August and September) the 30-year mean, while 2016 precipitation was near (May and June) or well below the 30-year means for the rest of the season (Figure 2a).

Table 6. Precipitation (mm) and temperature ($^{\circ}\text{C}$) relationships, and their interactions based on ANCOVA model for native warm-season grass yields at Knoxville and Springfield, 2015–2019.

	Knoxville			Springfield		
	Coefficients	t-Value	$p > t$	Coefficients	t-Value	$p > t$
Precipitation	0.036	7.14	<0.001	0.016	6.65	<0.001
Temperature	0.195	2.80	<0.001	−0.043	−1.21	<0.001
Temperature $\times$ Precipitation	−0.000	−0.01	0.993	−0.005	−5.36	<0.001

Overall, however, the absence of any $\text{N} \times \text{Year}$ interactions (Table 3) indicate that fertilization rates were not associated with long-term trends in yield; no consistent increase or decrease in yields was observed over the course of our study. This lack of cumulative impact in response to N over five years has not, to our knowledge, been previously documented in the literature. However, a 2019 study of five NWSG for two years reported that only EG was able to maintain its yield, but other species' yields varied between years [22], a finding they attributed to harvest frequency rather than N fertilization.

3.4. Precipitation and Temperature Effects on NWSG Yield

At Knoxville, each additional unit of precipitation (mm) increased yield 0.036 Mg ha^{-1} ($p < 0.001$), and each additional unit of temperature ($^{\circ}\text{C}$) increased yield 0.195 Mg ha^{-1} ($p < 0.001$); however, precipitation and temperature did not interact ($p = 0.993$) (Table 6, Figure 3a,b). Thus, the expected yield at Knoxville with 0 N and 44 mm precipitation was 1.9 Mg ha^{-1} , whereas, at that same N rate and greatest precipitation value of 189 mm, the expected yield increased to 5.8 Mg ha^{-1} . A difference of 3.9 Mg ha^{-1} was noted, which is slightly smaller than the yield at $135 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ (4.2 Mg ha^{-1}) and 44 mm precipitation. Conversely, the expected yield at the mean precipitation value (122 mm) and $67 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ was only slightly lower than the yields at $135 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ at 44 mm precipitation (3.9 vs. 4.2 Mg ha^{-1}), suggesting further caution in making decisions on appropriate N rates for forage production with these species. At Knoxville, the increase in temperature also increased yield but not by the same magnitude. For instance, at $0 \text{ kg N ha}^{-1} \text{ yr}^{-1}$, in the expected yield from the lowest temperature (19.2°C) to the

highest (26.2 °C), there was not enough difference to substitute for even the lower N rate of 67 kg N ha⁻¹ yr⁻¹, since it increased only slightly from 1.65 to 1.93 Mg ha⁻¹.

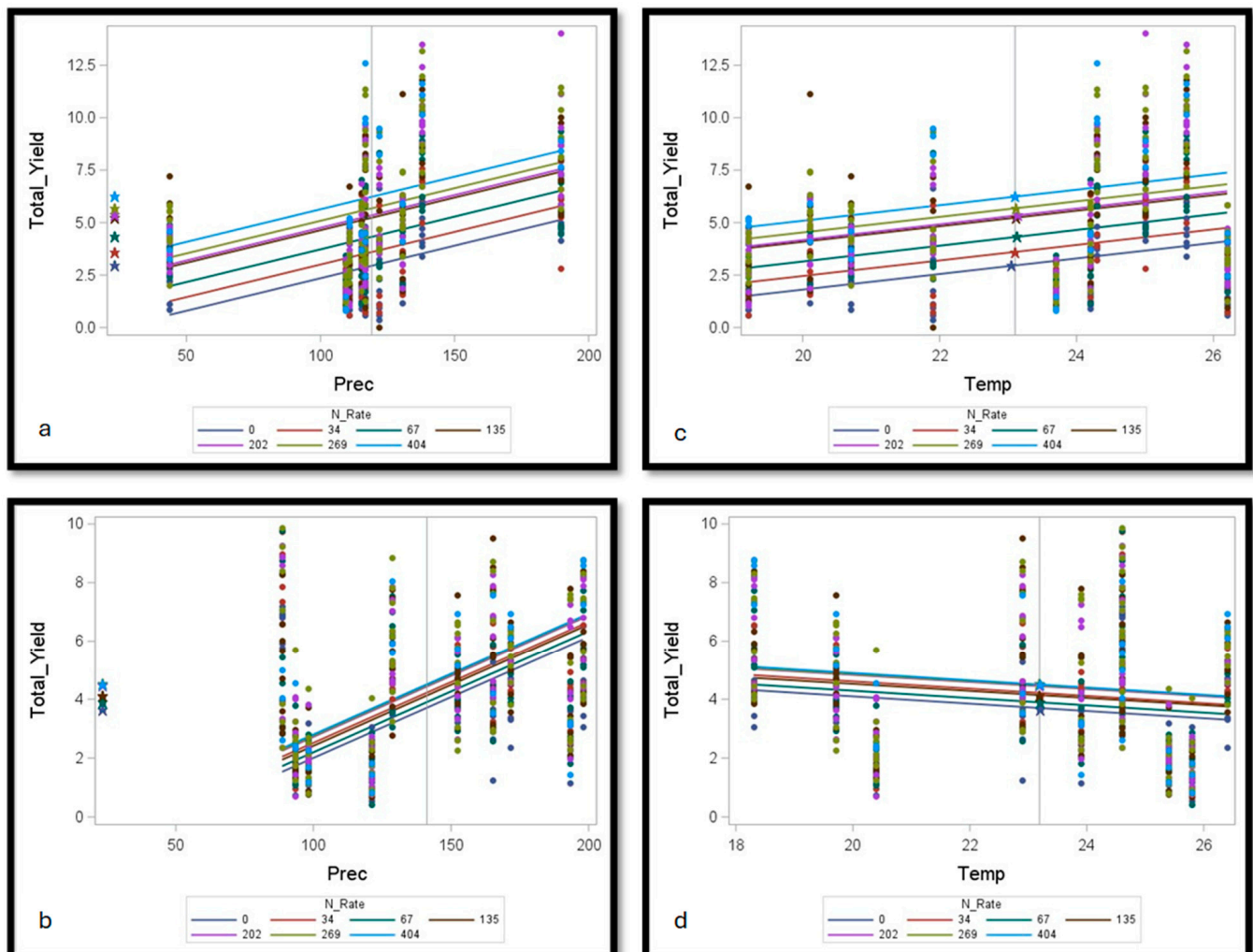


Figure 3. Relationship between N rate and precipitation (mm) (a,b) and temperature (°C) (c,d), at Knoxville and Springfield, respectively. Stars indicate covariate adjustment of raw means for precipitation (a,b) and temperature (c,d) at Knoxville and Springfield, respectively. Vertical lines indicate observed means for temperature and precipitation at Knoxville and Springfield, respectively. Colored dots are yield points at each N rate and precipitation or temperature levels. Temp is temperature, Prec is Precipitation.

At Springfield, precipitation increased yield ($p < 0.001$), but temperature decreased yield ($p < 0.001$), and an interaction was observed between temperature and precipitation at Springfield ($p < 0.001$) (Table 6, Figure 3c,d). The interaction had an inverse relationship whereby, increasing both precipitation and temperature by one unit (mm and °C), respectively, decreased yields by 0.005 Mg ha⁻¹ ($p < 0.001$). At 0 N rate, yield increased from the least to greatest precipitation (88.7 vs. 197.9 mm); the difference was 1.58 Mg ha⁻¹, but at that rate, from the lowest to highest temperature (18.3 vs. 26.4 °C), yield decreased more than it increased with precipitation (−1.84 Mg ha⁻¹). It should be noted that NWSG produce their maximum yields at higher temperatures (29.5–35 °C) than experienced during the growing periods of this research (18.3–26.2 °C) (Figure 2c,d), with Springfield experiencing slightly lower temperatures (18.3, 19.2, and 20.3 °C) relative to Knoxville (19.2, 20.7, and 21.9 °C) during the first harvests. Since the site location of the Springfield experiment was at a lower slope position, this may have created longer periods with soil saturation

under lower than optimal temperatures for these species and may have contributed to the negative interaction. Additionally, four of the five years of the study at Springfield were harvested post-dormancy, which may have reduced the influence of both our covariates.

To our knowledge, this is the first study to investigate the effects of temperatures and precipitation on NWSG including BB and EG, especially in the southeast US. Skinner et al. [54] found that, in Wyoming, a NWSG, blue grama (*Bouteloua gracilis* [H.B.K] Lag. Ex Steud.), was responsive to supplemental summer precipitation and additional irrigation, whether grazed or non-grazed, but this was not the case with the cool-season grasses used in the study to compare with the native grass. Bransby et al. [55] reported that annual and seasonal precipitation accounted for 45% and 10% of SG yield, while Fike et al. [56] reported some SG yield response from precipitation early in the season but no response in the summer. We found no interactions between N and precipitation (F -Value = 0.25, $p > 0.958$) or N and temperature (F -Value = 0.25, $p > 0.958$) at either location, and they were not included in the model.

Clearly, in dry conditions, the value of N amendments declines substantially. The timing of N amendments with respect to predicted rainfall at each location means that managers have some ability to exploit this relationship, whereas temperature is beyond their control. However, our study indicates a relationship between temperature and precipitation, suggesting further caution in making decisions on appropriate N amendments for forage production. The need for precipitation and aforementioned optimal temperatures working together has been proposed previously as a necessity for the maximum production of NWSG [57], and in our study, precipitation was close to the 30-year mean, but temperatures were well below the optimal required for maximum NWSG performance (Figure 2).

3.5. Forage Nutritive Values

Nitrogen rate influenced CP, ADF, and NDF for all three species, with the exception of ADF in BB, which had a weak effect in both cases (Table 7). In addition, harvest time effected CP, ADF, and NDF for all species. Crude protein increased with increasing N rate and reached peak concentration at or just below the greatest N rates for each species (Table 8). The magnitude of the increase was approximately three percentage points for BB and SG, while for EG it was above five percentage points. However, at N rates producing the greatest yield ($135 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ for BB and EG and $67 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ for SG), increases were two percentage points (BB and EG) or one percentage point (SG). For SG only, N and harvest time interacted, with greater CP in the first than the second harvest. This was an expected result, because SG tends to mature and become stemmier faster than BB and EG as the season progresses [11], causing SG to decline in quality more rapidly [58].

Concentrations of ADF for SG and NDF for BB and SG were greatest at $34 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ and decreased as N rates increased. In the case of EG, the greatest concentrations for NDF were at $67 \text{ kg N ha}^{-1} \text{ yr}^{-1}$, and increasing N did not reduce NDF concentration until the greatest N rate ($404 \text{ kg N ha}^{-1} \text{ yr}^{-1}$). The variation in ADF and NDF across N rates was small, a finding consistent with previous reports within EG studies [24,59].

The time of harvest influenced ($p < 0.001$) CP, ADF, and NDF in all three species, with similar trends within each species (Table 9). For BB and SG, early harvests were consistently higher in CP than during the late harvest. However, for EG, there was not a consistent pattern.

Table 7. Results from ANOVA model for forage nutritive value parameters for big bluestem, switchgrass, and eastern gamagrass at Knoxville, TN, 2017–2019. Harvest time was June and late summer (either August or September); no dormant-season harvests were included.

Effect	BB		SG		EG	
	F Value	p > F	F Value	p > F	F Value	p > F
CP [†]						
Nitrogen	44.37	<0.001	57.96	<0.001	61.57	<0.001
Harvest time	71.02	<0.001	85.35	<0.001	20.76	<0.001
Nitrogen × Harvest time	1.60	0.094	3.22	0.003	0.66	0.848
ADF						
Nitrogen	2.39	0.051	4.34	<0.001	5.40	<0.001
Harvest time	133.72	<0.001	100.23	<0.001	43.60	<0.001
Nitrogen × Harvest time	1.10	0.384	1.25	0.255	0.65	0.852
NDF						
Nitrogen	3.37	0.011	2.66	0.032	3.32	0.011
Harvest time	75.20	<0.001	115.93	<0.001	140.65	<0.001
Nitrogen × Harvest time	0.89	0.603	1.09	0.384	0.57	0.916

[†] CP, Crude Protein; ADF, Acid Detergent Fiber; NDF, Neutral Detergent Fiber.

Table 8. Mean percent concentrations for crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) for big bluestem (BB), switchgrass (SG), and eastern gamagrass (EG) for each N rate (kg N ha^{−1} yr^{−1}) at Knoxville, TN, 2017–2019.

N Rate	CP			ADF			NDF		
	Native Warm-Season Grass Species								
	BB	SG	EG	BB	SG	EG	BB	SG	EG
0	7.2 d [†]	7.7 d	7.3 e	37.9	37.5 ab	38.8 a	68.4 ab	66.1 b	67.3 bc
34	7.2 d	7.6 d	-	38.9	38.1 a	-	69.9 a	67.9 a	-
67	8.6 c	8.8 c	8.0 d	37.8	36.8 bc	39.3 a	67.8 b	66.5 b	68.0 a
135	9.4 b	9.6 b	9.7 c	37.4	36.9 b	38.8 a	67.3 b	66.3 b	68.8 a
202	10.3 a	10.5 a	9.9 c	37.7	35.8 c	38.9 a	67.4 b	65.6 b	68.2 a
269	10.4 a	10.8 a	10.7 b	37.1	36.5 bc	38.6 a	66.9 b	66.6 ab	68.4 a
404	-	-	12.6 a	-	-	36.9 b	-	-	66.4 b

[†] Means for each nutrient and species with at least one common letter were not different ($p < 0.05$).

Table 9. Mean percent concentrations for crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) for big bluestem (BB), switchgrass (SG), and eastern gamagrass (EG) per harvest time at Knoxville TN, 2017–2019.

Year	CP			ADF			NDF		
	Native Warm-Season Grass Species								
	BB	SG	EG	BB	SG	EG	BB	SG	EG
2017_1 [†]	9.4 b [‡]	10.4 a	9.9 b	36.1 c	33.8 c	37.5 b	67.6 c	64.2 b	68.8 c
2018_1	9.2 b	9.6 b	8.9 c	38.6 b	38.5 b	41.1 a	71.3 b	71.3 a	73.5 a
2018_2	6.3 d	6.7 d	8.5 c	43.6 a	41.5 a	40.6 a	73.4 a	71.9 a	70.2 b
2019_1	10.6 a	10.3 a	10.4 ab	32.8 d	33.0 c	36.7 b	63.5 d	63.7 b	67.2 d
2019_2	8.7 c	8.8 c	10.9 a	37.9 b	37.8 b	36.8 b	64.1 d	61.3 c	59.6 e

[†] Numbers following year indicate harvest time; 1 is first harvest (June) and 2 is second harvest (August–September).

[‡] Means for each nutrient and species with at least one common letter were not different ($p < 0.05$).

Additionally, EG had less variations for all nutritional values. For instance, in years with two harvests (2018 and 2019), the early harvest had a lower ADF than late harvests in both BB and SG, but these values did not differ for EG. This is similar to a three-year study at two locations in Tennessee that found no differences in any FNV parameters between

grazing horizons or harvests from different months for EG [60]. In the case of BB and SG, these findings were also expected based on trends in plant maturity [61]. Additionally, Rushing et al. [62] evaluated the costs of feeding with weaned beef steers as being impacted by the hay yield and quality of several warm-season perennial grasses, including EG. They found that more frequent harvests (30-day intervals) provided greater digestible fibers, similar to in early harvests in the current study. Comparable results were found in another study [33], which evaluated harvest frequency and NWSG species' influence on nutritive value and reported greater digestibility with early harvests.

3.6. Partial Factor Productivity

At Knoxville, PFP was greatest at the lowest applied N rates (34 kg N ha⁻¹ yr⁻¹ for BB and SG and 67 kg N ha⁻¹ yr⁻¹ for EG; Figure 4). With the exception of SG at Springfield, the pattern for PFP was consistent for all species and locations. For SG at Springfield, the decline in productivity followed a similar pattern, but with a greater productivity for each N-level. This could indicate that SG is somewhat more responsive to N than BB or EG. Despite differences in soils, soil nutrients, temperature and precipitation, and harvest management at the two sites, the consistency in response to N suggests that, in most circumstances, applying N at lower rates will typically be the best approach. In addition, reduced N inputs present an opportunity to provide high-quality forage with less fertilization, which could be more environmentally suitable. Previous studies reached similar conclusions [63] after they found high rates of N fertilization decreased both the richness and evenness of diazotrophic communities that promote biological N fixation.

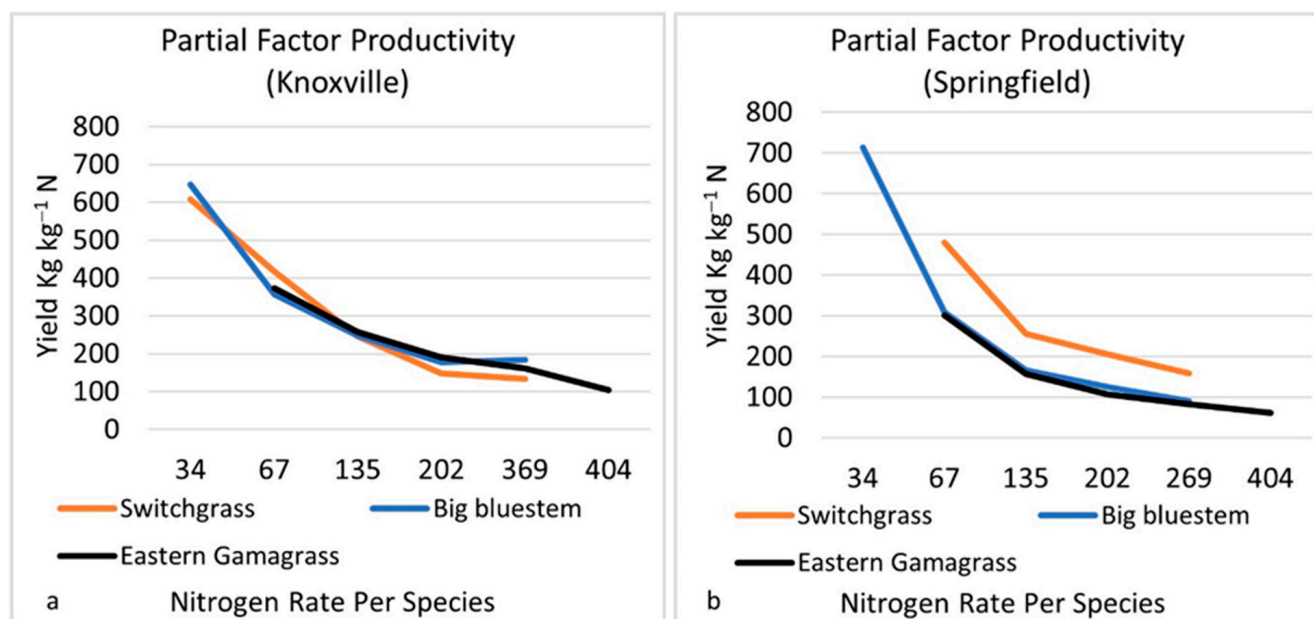


Figure 4. Partial factor productivity as affected by N amendment at Knoxville (a) and Springfield (b). Data is pooled across years (2015–2019) for each species.

4. Conclusions

This study documented the N rates producing the greatest yield for three native forage species. No single N rate performed the same for all NWSG species at both sites, but all NWSG responded to fertilization; the N rate that produced the greater yield for each species was site-specific, but overall a maximum of 135 kg ha⁻¹ N produced the greatest yields, with the Knoxville site requiring only 67 kg ha⁻¹ N. Clearly, these species do benefit from N amendments, but at lower rates than the alternative non-native forages available in this region. A consistent improvement in CP concentration with increased N inputs for each species was also observed. Additionally, early harvests provided more CP and lower fiber

contents than the later harvests. The other FNVs analyzed (ADF and NDF) demonstrated more modest responses to fertilization. The PFP assessment further substantiated that NWSG can be productive with moderate levels of N application, generally at or below $67 \text{ kg N ha}^{-1} \text{ yr}^{-1}$. This study also documented a strong relationship between precipitation, temperature, and N application rates for yields at Knoxville, with precipitation seemingly having a bigger impact on the ability of nitrogen to effect yield. Precipitation also positively influenced N at Springfield, but temperature seemed to weaken the N effect on yield. Yet, because of the interaction at Springfield, caution is warranted in reaching a definitive conclusion, as our suspicion is that the slope position at this site was a factor. In any case, this experiment indicates that temperatures and rainfall are important aspects of how N effects NWSG yield. Despite five years of N amendments, we found no cumulative effect of nitrogen application.

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Appendix A



Figure A1. Knoxville plots.



Figure A2. Springfield plots.

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