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Nitrogen and Phosphorus Requirements of Teff Grown Under Dryland Production System

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Abstract

Nitrogen and phosphorus are key limiting nutrients in teff [*Eragrostis tef* (Zucc.) Trotter] production. The crop is particularly sensitive to N fertilization, and as a result forage and grain yields are influenced. We conducted four site-year studies to determine N and P requirement of teff grown under a dryland production system. Studies were located in central Oklahoma. Treatments included nine N and P combinations. Commonly grown varieties 'Quick-E' and 'Tiffany' were used in 2009 and 2010, respectively. Experiments were arranged in a randomized complete block design with three replications. Data were subject to statistical analysis using Statistical Analysis Software (SAS). Analysis of variance (ANOVA), orthogonal polynomial or paired contrasts and non-linear regressions were used to determine the effect of treatments on teff forage and grain yields and quality. Results showed that for central Oklahoma, optimum fertilizer N rate was 67 kg/ha which corresponded with a 1.1 Mg/ha yield goal. Forage crude protein increased with N rate. In addition, N and P influenced some teff mineral and forage quality parameters such as Ca, Fe, acid detergent fiber, and crude protein. Recommendations provided here will serve as a benchmark for N and P fertility guidelines for producers in Oklahoma and semi-arid regions who want to grow teff in a niche market.

Teff is Becoming an Important Crop in the United States

Teff [*Eragrostis tef* (Zucc.) Trotter] is an annual grass native to Ethiopia (2,19,20); it has a short growing cycle, reaching maturity in approximately 90 to 100 days after emergence during normal years (37). Teff yield remains reasonable in low or excessive moisture conditions, while that of other cereals is depressed significantly under these conditions (17). Teff grows well on a range of soils, including Veritsols, which can become saturated by high precipitation (20). Teff requires only a modest amount of fertilizer (20,40), and because it experiences few insect and disease problems, even in its native land, it requires little pesticide input. In addition, Teff has a high regrowth potential after harvesting (14). Because of teff's high grain price and niche market, small farmers may be encouraged to include it in their overall cropping system.

As food for human consumption, teff has unique qualities in that it contains high levels of several minerals, such as Fe, Mg, Ca, P, and thiamine (28,31). It is also an excellent source of essential amino acids, particularly lysine, which is deficient in common grain foods such as wheat and millet (23) and is low in gluten, providing an important dietary option for many gluten-intolerant people (36,37). Teff also provides excellent quality hay (17,33,40), with forage qualities that are comparable to Timothy grass (29), and can provide feed for cattle, horses, and small ruminants (5,38).

Teff is becoming known as a "health" food in many areas, increasing the demand for the grain (6,30). For example, east African restaurants and cuisines that use teff flour for bread are becoming increasingly popular all over the United States and the market is expanding (6). Many teff distributors are losing their market for lack of continuous supply of teff grain and are exploring avenues for local production of teff to meet the demand. Achieving sustainable supplies of teff flour for immigrant communities, industries (health and baby food), and local residents requires producing the crop locally rather than obtaining it by the less reliable imports (6). Teff is a potential rotation crop in certain environments where rotational crops (1) and late summer feed are limited (35).

It is well known that fertilization is essential for improving the nutrient-use efficiency of teff (12), in addition to other factors such as proper selection of teff cultivars and crop management practices (42). Nitrogen and P are the primary nutrients affecting teff forage and grain yields as well as quality. Nitrogen fertilization is particularly critical because teff has a weak stem that is susceptible to lodging [though some of this is due to inherent factors such as the shallow root system of the crop (42) and not soil fertility]. More importantly, excess N can incur unnecessary cost to the producer, as the application may neither translate to increased economic yield nor increased nutrient-use efficiency.

The response of teff forage or hay to N application has been examined in several north central and northwestern states of the United States. For example, Roseberg et al. (35) reported mixed results of N fertilization on teff forage; teff forage responded to N input rates lower than 90 kg/ha but not to higher input. In New York, Hunter et al. (18) found that teff forage yield increased with N fertilization except when land had been fertilized with manure or rotated with legumes in the preceding years. Furthermore, they found that the protein content of teff forage increased with the application of 56 kg N/ha across 1, 2 and 3 cut systems; with the multi-cut system, however, this level of N fertilization reduced neutral detergent fiber. Finally, moisture availability and frequency of cutting are important factors that determine the N requirements in forage/hay teff (15).

Limited information is available on the response of teff to P fertilization. In the United States, most teff producers do not apply P, and some producers base their P recommendations on soil test results developed for other crops. However, such recommendations are approximate. Phosphorus availability to crops is a function of several factors, including soil moisture, ambient available P, and the nature of clay (3,9).

In the dryland farming systems of the south central United States, teff fertilizer requirements are not well documented for yield and quality of both forage and grain. The majority of nutrient requirement studies have focused on forage production, and few report on the influence of P on teff grain quality. Developing a recommendation for dual-purpose teff is more difficult than it is for teff that is intended for grain only or hay only. However, the recommendations must reflect the total amount of nutrient inputs needed for both systems simultaneously. Therefore, this study was designed to develop N and P input requirements to maximize teff forage and grain yield as well as quality. In identifying the major nutrient requirements of teff for growth in central Oklahoma, we aimed to introduce teff as an alternative crop to create economic and ecological opportunities.

Field Trials Over Four Site-Years

Trials were conducted in Oklahoma at Hennessey (Shellabarger sandy loam fine-loamy, mixed, thermic Udic Argiustoll) and Sumner (Kirkland silt loam-fine, mixed, superactive, thermic Udertic Paleustolls) in 2009, and at Sumner and Lake Carl Blackwell (Port silt loam-fine-silty, mixed, thermic Cumulic Haplustolls) in 2010. The initial soil test results for NO_3-N, P, K, and pH are presented in Table 1 for all site-years. In 2009, treatments included a control (no fertilizer), four levels of N input (0, 45, 67, and 90 kg/ha) each at fixed levels of 25 kg/ha P_2O_5 and K_2O, topdress N (45 kg N/ha), only P (50 kg

P_2O_5/ha), and only K (69 kg K_2O/ha). In 2010, two additional N input rates, 23 and 112 kg N/ha were added. The K treatment was removed from the experiment in 2010 because the soil had adequate K and because it did not influence the results in 2009. All rates were adjusted for preplant soil N and P levels.

Table 1. Soil chemical properties determined prior to start of trials from surface soil samples (0 to 30 cm) at four site-years in 2009 and 2010 in Oklahoma.

Site, year	**pH**	**NO_3-N** (kg/ha)	**P_2O_5** (kg/ha)	**K_2O** (kg/ha)
Hennessey, 2009	6.10	30.1	61.3	421
Sumner, 2009	5.68	23.6	51.2	399
Lake, 2010	5.67	17.2	37.2	472
Sumner, 2010	6.53	14.8	40.7	449

pH was determined using pH probe from 1:1 soil:water paste.

The experimental design was a randomized complete block (RCB) with a plot size of 3 m × 6 m. Each treatment was replicated three times. The 'Quick-E' and 'Tiffany' varieties of teff were planted in 2009 and 2010, respectively, at a seeding rate density of 12 kg/ha; the two varieties have similar growth habits. Teff was seeded into conventional or reduced-till fields with a John Deere 450 Series grain drill (Deere & Company, Moline, IL). In 2009, seeds were planted on 2 June and 5 June at Sumner and Hennessey, respectively, and emerged in late June. In 2010, seeds were planted on 21 May and 24 May at Lake Carl Blackwell and Sumner, respectively. One third of the N rates and all of the P and K (if applicable) were applied at the time of planting. The remaining N (including the topdress N treatment) was applied prior to booting. Broadleaf weeds were controlled with 2,4-D amine applied at a rate of 1.2 liter/ha during the 4 to 5-leaf growth stage. Grass weeds were controlled with a post-emergence application of 1.2 liter/ha pinoxaden (Axial XL, Syngenta, Basel, Switzerland), an experimental herbicide for teff , at the 4 to 5-leaf growth stage using SRS-540 Propack rechargeable electric backpack sprayers (Shurflo, Cypress, CA). Measurements included preplant soil N, P and K, plant height, days to flowering, percent lodging, forage and grain yields, grain protein and grain mineral content.

Four 0- to 30-cm-depth soil samples, each averaged from 12 soil cores, were collected with a bucket auger prior to planting. Samples were dried at 60°C for 72 h and ground to pass through a 2-mm sieve. Next, soil NO_3-N was extracted with 1 M KCl solution and quantified by a Flow Injection Autoanalyzer (21). Available P and K were extracted using Mehlich III solution (26).

Teff was harvested for forage yield estimation from a randomly selected 1 m^2 plot from each plot using a manual sickle. After harvesting, forage samples were dried at 60°C in a forced-air oven for 96 h and then ground to pass through a 1-mm screen using a Wiley Mill (Thomas Scientific, Swedesboro, NJ).

Total N was determined using a dry combustion N Analyzer (LECO Truspec, 41). Crude protein was determined by multiplying total N by 6.25 for all samples. Acid detergent fiber (ADF) and total digestible nutrients (TDN) were determined with an Ankom Fiber Analyzer (Ankom Technology, MacEdon, NY) using the method developed by Goering and Van Soest (13). Mineral content of the forage was analyzed with a Spectro CirOs ICP (SPECTRO Analytical Instruments GmbH, Deutschland) following wet digestion extraction (41). When the teff was mature, a 1.5 m^2 plot was harvested using sickles to estimate final teff grain yield. In 2009 and 2010, teff was harvested on 5 September (at Hennessey and Sumner) and 30 September (Lake Carl Blackwell and Sumner), respectively. Samples were dried for 72 h at 60 °C, threshed using a custom-made belt thresher (Oklahoma State University) and cleaned with an air-screen cleaner (Westrup Inc., Plano, TX) to determine final grain yield. Grain yield samples were then washed with de-ionized water, dried at 60˚C for 3 days, ground to pass through a 1-mm mesh, and sent to the Soil, Water and Forage Analytical Laboratory (Plant and Soil Sciences Department, Oklahoma State University) for analysis of total C, N, crude protein, and minerals. The same methods described for forage above were used for total C, N, and crude protein and minerals.

Data were analyzed with ANOVA using the general linear model (GLM) and mixed model (MIXED) procedures in SAS (SAS Institute Inc., Cary, NC). Following the results of omnibus ANOVA, polynomial orthogonal contrasts were used to analyze trends and other hypotheses of interest. Significance was set at $P < 0.05$ for all variables unless specified. The relationship between certain measured variables was also evaluated by correlation. A linear-plateau model was fit to the grain yield data on N input rate for the fertilizer rate study in 2010 (both sites).

Teff Yields and Quality Are Affected by N and P Fertilization

2009 forage and grain yields. Quick-E forage and grain yields were not significantly affected by N, P, and K rates in 2009. The only exception was for forage and grain yields at Sumner, which increased linearly with P input rate (Table 2). Forage yield was not different between sites; average forage yield was 7.0 and 6.8 Mg/ha at Hennessey and Sumner, respectively. Average grain yield at Hennessey and Sumner was 740 and 638 kg/ha, respectively (significantly different $P < 0.05$). Although not statistically significant, grain and forage yields at both Hennessey and Sumner followed a quadratic trend; yields peaked at 67 kg N/ha (Table 2). Previous studies on teff forage response to N have shown that applications of approximately 90 kg N/ha over a season may achieve optimum forage yield and quality (32). However, other environmental factors influence the optimum N rate for different environments; thus, our results suggest a different optimum N rate. Application of 45 kg/ha N as topdress resulted in 0.7 Mg/ha and 386 kg/ha more forage and grain yields, respectively, compared with a 45 kg N/ha split application (1/3 preplant and 2/3 topdress) at Hennessey in 2009. This suggests that applying N as topdress before booting increased yields compared to splitting the same N input rate between preplant and topdress. We attribute this result to poor utilization of preplant N by teff seedlings. Because of precipitation and warm temperatures after planting, some of the N applied preplanting would have volatilized from the soil. At Sumner, this difference was not significant.

Table 2. Means and effect of N, P, and K rates on grain yield (kg/ha), forage yield (Mg/ha), and plant height (cm) at Hennessey and Sumner, OK, in 2009.

	Hennessey			Sumner		
N rate (kg/ha)	**Forage yield**	**Grain yield**	**Height**	**Forage yield**	**Grain yield**	**Height**
0	6.6	708	79.7	7.3	649	89.3
45	7.3	614	101.7	7.8	650	87.2
67	8.6	823	99.7	7.8	656	87.4
90	8.3	786	98.3	6.8	594	93.2
Linear	ns	ns	ns	ns	ns	ns
Quadratic	ns	ns	ns	ns	ns	ns
P rate (kg/ha)						
0	6.5	789	84.7	5.5	612	77.3
25	6.6	708	79.7	7.8	649	89.3
50	5.2	627	79.7	8.5	697	88.9
Linear	ns	ns	ns	*	$P < 0.1$	ns
Quadratic	ns	ns	ns	ns	ns	ns
K rate (kg/ha)						
0	6.5	789	84.7	5.5	612	77.3
69	5.3	680	79.3	6.0	675	86.1
Prob.	ns	ns	ns	ns	ns	ns
Paired contrast for split N (Preplant and topdress) versus only topdress						
Split N	7.3	614	101.7	7.8	650	87.2
Topdrss N	8.9	1000	103.3	6.7	585	84.9
Prob.	*	*	ns	ns	ns	ns

* Significant at $P < 0.05$ probability level; ns = non-significant at $P < 0.05$ probability level.

2010 forage and grain yields. In 2010, N input rate had a significant effect on forage, grain yield, and height at Lake Carl Blackwell; however, only grain yield was significant at Sumner. Similar to the 2009 results, grain yield was maximized at 67 kg N/ha N inputs at both sites (Table 3). Average forage yield in 2010 was 11 Mg/ha across sites. Forage yield and plant height showed a linear trend as the N input rate increased at Lake Carl Blackwell. The forage yield obtained in this study was within the range of the best production environments in the United States; teff forage yields between 10 and 15 Mg/ha have been reported in Oregon, Idaho, and New York (14,18,35). The recommended N input rate for forage yield potential was between 56 and 112 kg/ha. The average height of teff was 86 and 72 cm at Lake Carl Blackwell and Sumner, respectively. A strong (positive) correlation was observed among lodging, N input rate and plant height (correlation coefficients ranged 0.72 to 0.84). The correlation results suggests that N input rate in excess of plant requirements may exacerbate lodging in teff. Lodging is a major setback for grain yield production in teff (20). In our study, lodging ranged from 0 (in control plots) to 65% with N input rates greater than 67 kg/ha (*data not shown*).

Table 3. Means and effect of N rate on grain yield (kg/ha), forage yield (Mg/ha) and plant height (cm) at two sites in 2010.

	Lake Carl Blackwell			**Sumner**		
	Forage yield	**Grain yield**	**Height**	**Forage yield**	**Grain yield**	**Height**
N rate (kg/ha)						
0	8.6	835	75.2	10.3	856	77.7
22	10.2	847	86.4	10.7	992	71.0
45	11.3	968	81.7	12.7	1142	76.6
67	12.5	1199	91.8	12.7	1260	70.8
90	14.0	1167	90.0	9.9	1139	68.9
112	15.7	1011	92.3	11.1	1124	75.5
Linear	***	***	***	ns	ns	ns
Quadratic	ns	*	ns	ns	*	ns
Split vs. topdress N	ns	ns	ns	ns	ns	ns
P rate (kg/ha)						
0	9.0	828	82.5	9.3	670	72.9
25	8.6	835	75.2	10.3	856	70.7
50	8.3	996	74.8	11.2	1100	72.9
P linear	ns	*	*	ns	*	ns
P quadratic	ns	ns	ns	ns	ns	ns

* and *** Significant at $P < 0.05$ and $P < 0.001$ levels of probability, respectively; ns = non-significant at $P < 0.05$.

In 2010, pooled over the two sites, teff grain yield data fit well ($R^2 = 0.74$) to a linear plateau model of N input rates. The same critical N rate as from the individual sites was obtained (Fig. 1). The critical level shows that growers can add N at a rate of 4.7 kg/ha for N rates between 0 and 67 kg/ha, beyond which it is no longer advantageous to apply N for a grain yield goal of 1.1 Mg/ha, although the yield goal is certainly a function of many yield-limiting factors. The teff grain yield obtained in this study was less than its potential yield in a controlled environment (up to 3.2 Mg/ha, *unpublished data*) and the yield reported in other states (32); this could most likely be due to a combined effect of heat and low moisture, as well as lodging. In both years of the study, prolonged heat in June-July resulted in significant growth reduction and flower abortion. Figs. 2a and b illustrates the daily maximum temperature and precipitation patterns in 2009 and 2010, respectively, at the nearest Mesonet weather station for each site.

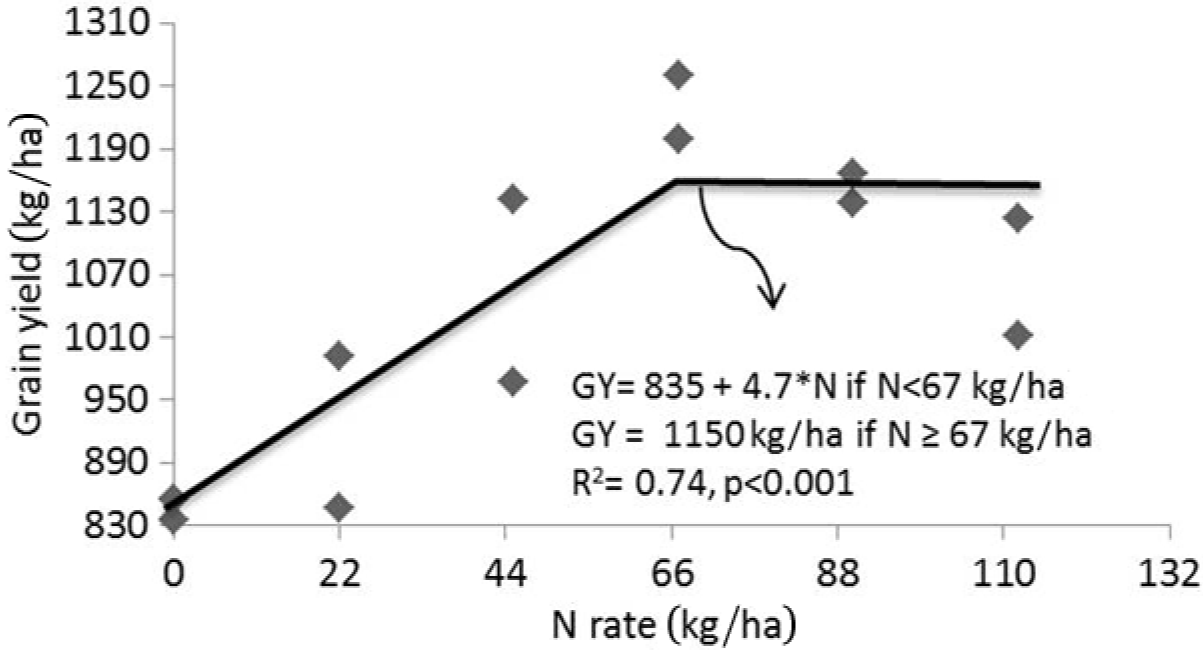

Fig. 1. General N fertilizer recommendation for central Oklahoma. Nitrogen fertilizer should be adjusted for yield goal.

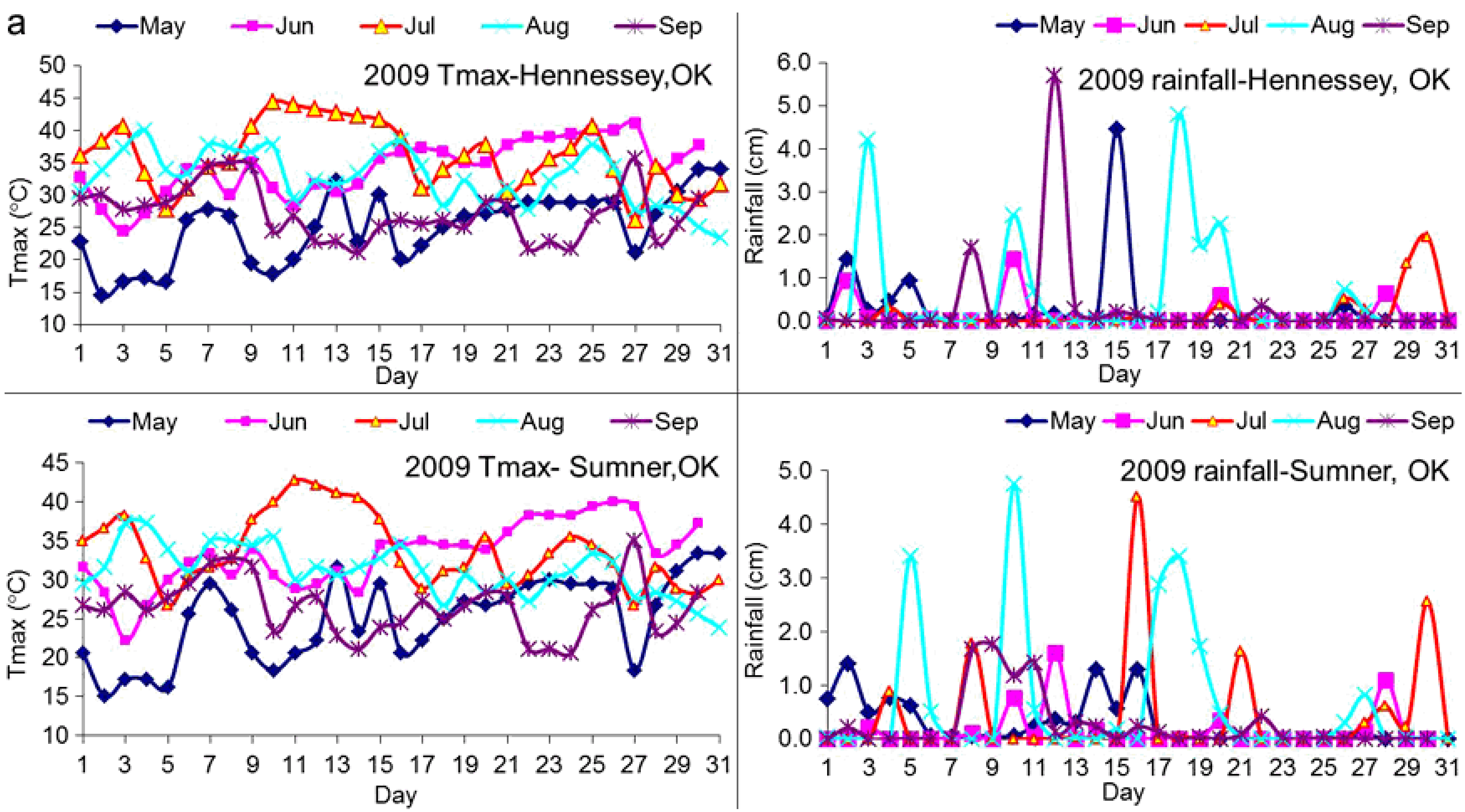

Fig. 2a. T_{max} and rainfall at closest weather stations to Hennessey (Marshall Mesonet station) and Sumner (Stillwater Mesonet station), in 2009.

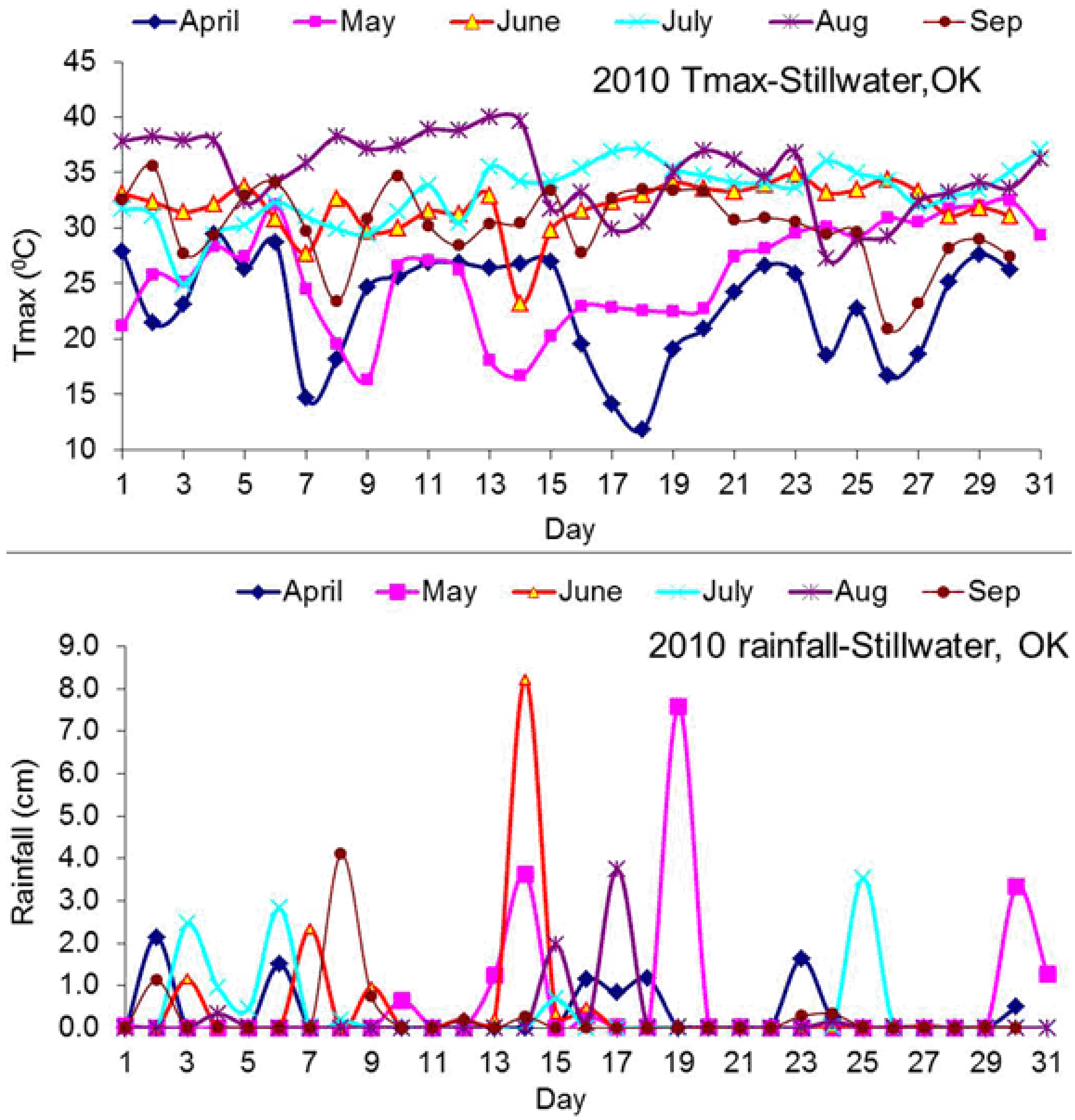

Fig. 2b. T_{max} and rainfall at closest weather stations to Sumner and Lake Carl Blackwell (Stillwater Mesonet station) in 2010.

For both sites, the 45 kg/ha topdress treatment and the split-N treatment (between preplanting and topdress) were not significantly different in terms of yield and plant height (Table 3). These data suggest that topdress N would be the preferred application method. However, to ensure adequate N for root and shoot development and growth, it is crucial to apply N fertilizer if the ambient total inorganic N at planting is considerably low.

Teff grain yield increased linearly with increasing P input rates from 0 to 50 kg N/ha at both sites (Table 3). Based on the Mehlich III soil test P index and response of teff grain yield to P, the recommendations developed for growing weeping lovegrass (*Eragrostis curvula*) in Oklahoma (16,43) could be adopted for teff. Using existing calibration curves avoids the need to develop a new calibration for determining P requirement of teff.

2010 forage and grain quality. Forage crude protein ranged from 9 to 17%. In 2010, sites differed in crude protein content; 11% at Lake Carl Blackwell and 16% at Sumner (*data not shown*). The average forage crude protein obtained in this study was slightly higher than or comparable to what has been reported in the literature (15,18,35). Other forage quality measurements, such as ADF (43.4

and 40.1% at Lake and Sumner, respectively) and TDN (55.1 and 57.7% at Lake and Sumner, respectively), did not differ across sites. At Lake, ADF reached a maximum at an application of 67 kg N/ha, whereas TDN peaked at an application of 90 kg N/ha (Table 4). Hunter et al. (18) reported a decrease in ADF as N input rate increased from 0 to 112 kg/ha, although this result was only marginally significant. Roseberg et al. (35) also found a decrease in ADF with the addition of N. In the current study, ADF peaked at 67 kg N/harate and then decreased at higher input rates. The relatively higher ADF in this study compared with what has been reported in previous studies could be attributed to forage harvest time (stage). The Cu content of teff forage at Lake Carl Blackwell increased linearly as the N input rate increased. Across all sites, crude protein increased linearly with an increase in N input rate.

Table 4. Effect of N rate on selected teff forage quality and mineral content at Lake Carl Blackwell (Lake) and Sumner, OK, in 2010.

N rate (kg/ha)	**Lake**	**Sumner**		
	ADF	**TDN**	**Cu** (ppm)	**Zn** (ppm)
0	44.1	54.1	6.53	26.2
22	44.0	54.6	6.70	26.7
45	43.1	56.3	7.52	33.7
67	46.3	53.6	7.47	28.7
90	40.7	54.6	8.83	31.6
112	40.5	55.3	8.73	25.9
Mean	43.1	55.0	8.7	25.9
Linear	*	$P < 0.1$	*	*
Quadratic	*	*	ns	ns

* Denotes significance at $P < 0.05$ level of probability; ns = non-significant at $P < 0.05$.

Phosphorus fertilization did not affect forage quality. Likewise, comparisons between crude protein obtained with topdress only and with split N treatments at 45 kg N/ha did not reveal differences. The lack of significance could be due to the N supplied as organic matter that serves as starter N and that all N inputs can be topdressed later in the season. Topdressing could provide a significant saving in N fertilizer in particular for dual-purpose crop systems.

At Sumner, Ca content in teff grain increased linearly with N input rate until approximately 67 kg N/ha and reached its peak at 90 kg/ha (Table 5). With high N input rates and favorable conditions for nitrification, NO_3- ions may interfere with Ca uptake of crops (4), which may explain this linear-plateau trend. Alternatively, this trend could be because teff grain accumulated adequate Ca. The Ca content in teff grain can reach 0.2% (11,28). The Mn content of teff grain was 143 mg/kg at 0 kg N/ha and decreased to 105 mg/kg with the application of 90 kg N/ha. Contradicting results were observed in Bengal gram (*Cicer arietinum*), where Mn accumulation was positively correlated with N availability (7).

Table 5. Effect of N rate on selected mineral content of teff grain at Lake Carl Blackwell (Lake) and Sumner, OK in 2010.

N rate (kg/ha)	**Lake**	**Sumner**			
	Mn (ppm)	**Ca** (%)	**Zn** (ppm)	**Cu** (ppm)	**Protein** (%)
0	146.3	0.155	46.4	9.09	12.90
22	133.9	0.165	44.9	9.21	13.91
45	131.7	0.166	50.1	9.73	13.52
67	120.7	0.178	47.5	9.11	15.93
90	105.4	0.181	57.7	11.09	17.07
112	.	0.181	54.6	11.03	15.98
Means	127.6	0.171	50.2	9.876	14.88
Linear	**	*	*	*	ns
Quadratic	ns	ns	ns	ns	*

* and ** Denote significance at $P < 0.05$ and $P < 0.01$ levels of probability; ns-non-significant at $P < 0.05$.

Over all the sites, teff grain and forage Fe content decreased as P input rate increased from 0 to 52 P_2O_5 kg/ha (Fig. 3). Forage and grain Fe content ratios decreased as P input rate increased from 3:1 to 1.5:1, suggesting that Fe remobilization from forage to grain reached its peak with no P fertilization. A previous study on barley (*Hordeum vulgare* L.) showed that Fe content was greater at low P vs. high P soil levels (22). At low P levels, Fe uptake and mobilization to shoots improves and consequently translates to improved grain Fe content. Other studies have also underscored the effect of P on Fe content of plants (8,10,24,34). In bengal gram, a similar result was reported (7); Fe content tends to be high in plants with low P content. Excess P in soils tends to result in the formation of insoluble iron phosphate ($FePO_4$), fixing Fe in the soil and subsequently reducing Fe uptake and accumulation in grain. Likewise, teff forage Fe content showed similar results. When available P in the soil is excessively high, uptake of Fe can be reduced, resulting in poor growth (24,25).

Grain crude protein decreased as the P input rate increased when the data were averaged over the sites in 2010 (Fig. 3). According to Mehrvarz and Chaichi (27), the increase in P fertilizer (as triple superphosphate) from 0 to 60 kg/ha (at 30 kg/ha) decreased the percent grain crude protein by 0.017%.

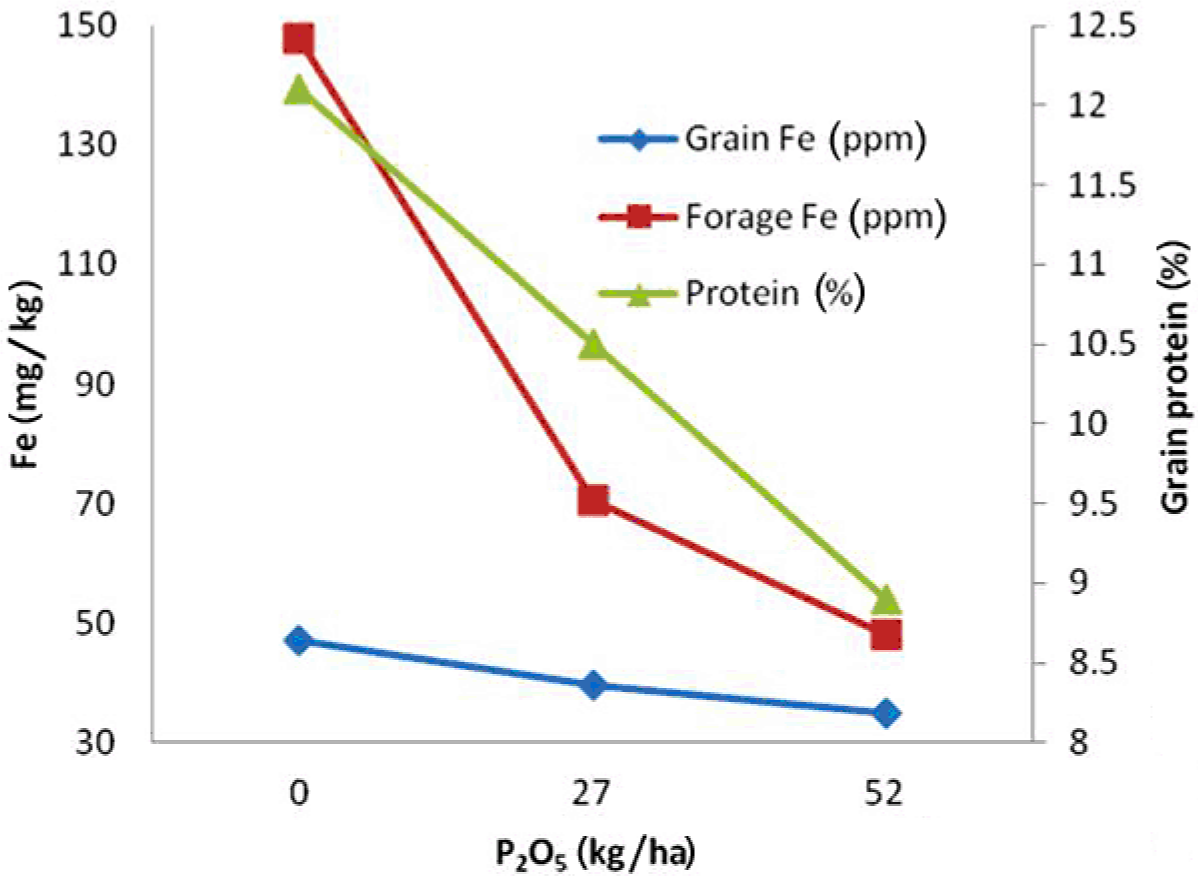

Fig. 3. Teff grain and forage iron content and grain protein as affected by P rates averaged over two years and two sites. Polynomial orthogonal contrasts for grain protein and forage Fe content were significant at $P < 0.05$, and Grain Fe content at $P < 0.05$.

Conclusions and Recommendations

The results of this study suggest that for central Oklahoma, optimum fertilizer N rate is about 67 kg/ha which corresponds with a 1.1 Mg/ha grain yield goal. Forage yield response to N was significant but not consistent. Nitrogen rates between 67 and 112 kg/ha were adequate for teff taking into consideration soil and visual deficiencies. It would be preferable to topdress instead of applying N preplant. Phosphorus should be applied based on soil test index and percent sufficiency. The existing recommendation developed for weeping love-grass can be used to recommend P for teff. The crop is sensitive to lodging, and fertilization is at the center of all crop management practices for minimizing lodging. Forage crude protein increased with increasing N rate. Nitrogen and P influenced some teff mineral and forage quality parameters such as Ca, Fe, ADF, and crude protein. Our recommendations will serve as a benchmark for N and P fertility guidelines for central Oklahoma and semi-arid regions producers who would want to grow teff as a niche market driven alternative grain and forage crop.

Acknowledgements

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