EVALUATING THE RESPONSE OF TEFF [*Eragrostis tef* (Zucc.) Trotter] AND HARD RED WINTER WHEAT (*Triticum aestivum* L.) TO YIELD LIMITING FACTORS IN OKLAHOMA

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Title of Study: EVALUATING THE RESPONSE OF TEFF [*Eragrostis tef* (Zucc.) *Trotter*] AND HARD RED WINTER WHEAT (*Triticum aestivum* L.) TO YIELD LIMITING FACTORS IN OKLAHOMA

Major Field: Plant Science/ Crop Physiology and Production

Abstract: **Scope and Method**: Weather conditions such as temperature and precipitation are the most important crop growth limiting factors in Oklahoma. Less precipitation is available for crop growth during the summer months due to high evapotranspiration attributed to high temperature. In some years, the winter is dry affecting performance of winter crops. Soil applied phosphate fertilizers use efficiency in winter wheat is low because of soil and weather related factors. Therefore, control and field experiments were established to determine teff growth and yield. The growth chamber teff study comprised three temperature regimes, four levels of soil moisture, three times of watering intervals, and two photoperiods. Treatments for the field study included four levels of irrigation and two watering intervals. Foliar phosphorus improves P use efficiency of crops. However, no effective foliar products are available on the market. The objective of the phosphite study was to evaluate Nutri-phite, a foliar phosphorous product on winter wheat yield, quality and nutrient use efficiency in five fields over two years. Treatments for the foliar P study included application of a Nutri-phite at two growth stages of winter wheat. Nutri-phite was applied with and without N at 100 and 75% of crop need and P at 100 and 80% of P sufficiency a long a check (no fertilizer) and standard (farmer practice) treatments.

Findings and Conclusions: In the control study, teff biomass and grain yields increased with increasing soil moisture and decreased with increasing temperature and photoperiod. Grain yield was more affected by high temperature and drought than biomass yield in the growth chamber study. In the field experiment, biomass and grain yield were highly related to water amount. Teff produced acceptable biomass and grain yields under rainfall treatment. The Nutri-phite product improved grain yield of wheat in some fields, especially when rainfall is not limiting during the growing season. In addition, Nutri-phite was more efficient in increasing grain phosphorus concentration compared with the check treatment. Thus, application of Nutri-phite might improve the wheat growth and yield if weather conditions are normal, and the right amount of Nutri-phite is used.

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CHAPTER I

GENERAL INTRODUCTION

This dissertation presents results of two independent experiments. The first experiment evaluated teff [*Eragrostis tef* (Zucc.) Trotter] as an alternative forage and grain crop in the State of Oklahoma in controlled and field situations in 2011 and 2012. Teff is a principal warm season annual grass crop grown in Ethiopia. It is tolerates low water stress and endures moderate water logging. It is grow in some African countries as livestock forage. Teff was introduced into the US by the missionaries and expatriates from Ethiopia in 1916 to the State of California (Ketema, 1997). It is growing as forage grass in 25 states in the US (Davison et al., 2011).

In Oklahoma, during the last five years, many producers showed interest in growing teff. However, its establishment, growth and yield are influenced by day length, temperature, and soil moisture. Although the crop is drought tolerant, like any crop, it requires a certain level of soil moisture particularly given the high heat index in Oklahoma. This project is designed to establish the relationship between day length, temperature and soil moisture with teff growth parameters and yield. The controlled study was conducted in the growth chambers and comprised three temperature regimes, four levels of soil moisture, three times of watering intervals, and two photoperiods. Treatments for the field study included four levels of irrigation and two watering intervals.

The second experiment evaluated foliar phosphite on hard red winter wheat (*Triticum aestivum* L.) at Perkins, Perry and Morison, OK over 2009 and 2010. The major problem of soil applied fertilizers has been low nutrients use efficiency, especially nitrogen and phosphorous. To improve grain quality and nutrient use efficiency, we proposed foliar application of P. However, effective formulations that can be easily absorbed by cereal crop leaves are lacking. Nutri-phite® is a phosphite foliar fertilizer formulation that purportedly absorbed through leaf tissues. In this experiment, Nutri-phite was applied at two growth stages of winter wheat with and without soil applied nitrogen and phosphorus.

In general, the two experiments are organized into four chapters including this General Introduction. Chapter II covers the controlled teff study entitled “Teff growth and yield as affected by day length, temperature and soil moisture”. Chapter III deals with the teff study conducted in the field entitled “Response of teff biomass and grain yield to soil water availability and watering interval”. The last chapter, Chapter IV covers the work conducted in winter wheat entitled “Response of winter wheat growth, grain yield, and phosphorus and nitrogen uptake to foliar phosphite fertilization”. All three chapters are strategically addressing environmental and management constraints for successful production of teff and red hard winter wheat in Oklahoma.

CHAPTER II

TEFF GROWTH AND YIELD AS AFFECTED BY DAY LENGTH, TEMPERATURE AND SOIL MOISTURE

ABSTRACT

Teff [*Eragrostis tef* (Zucc.) Trotter] is an annual dual-purpose grass crop. Although the crop is drought tolerant, teff morphological and yield responses to different soil moisture regimes, day length period and temperature are not well understood. Therefore, a controlled environment growth chamber experiment was initiated in 2011 and 2012. Experimental design was a split-plot arrangement and a completely randomized with three replications. A factorial combination of three levels of watering interval (3, 5 and 7 days) as main plot and four levels of field capacity (FC) (100%, 75%, 50%, or 25% of FC) as sub-plot, was treated with two day lengths (14 light /10 dark or 16 light /8 dark hours) and three day/night temperature regimens (24/19, 27/16, and 30/24 C day/night). Tiller number, plant height, and leaf area were decreased by increasing water deficit, temperature, and day length. The lowest tiller number and plant height (≈ 2 and 43 cm) were recorded at the combination of 25% FC with a 7-day watering interval. The greatest leaf area was 47 cm^2 at day length 14/10 hours. Biomass and grain yield were decreased at high water and temperature stress. Changing day length from 14/10 to 16/8 hours resulted in 14% decrease in biomass yield. Grain yield decreased by 13% at the combination of FC$_{25}$ + I3 days compared to FC$_{100}$ + I3 days. Grain yield response to water treatments was (R^2=0.87 and 0.58) at (14/10 and 16/8 hours respectively). Photosynthetic assimilation rate (A) and stomatal conductance to water vapor (g_{ws}) were correlated to the combination of FC with watering intervals (R^2= 0.76, 0.45, and 0.40) and (R^2= 0.90, 0.47, and 0.67) of 24/19°C, 27/16°C and 30/19°C respectively at (14/10 and 16/8 hours respectively). Teff growth and yield were tightly correlated to water availability, temperature, and photoperiod.

INTRODUCTION AND LITERATURE REVIEW

Most of the crops introduced into the US for food and fodder purposes were brought here by the immigrant communities from all parts of the world. Some of these crops and herbs are well accepted by local populations for alternative uses, thus creating a common interest and demand for those crops. One such crop is teff [*Eragrostis tef* (Zucc.) Trotter]. Teff is an annual warm grass indigenous to Ethiopia (Ketema, 1997). It is a tetraploid crop with 2n =40 chromosomes (Tavassoli 1986). Teff seeds are small in size, and weight of 1000 seeds is 0.3 to 0.4g, and teff produces massive fibrous root in early season growth (Stallknecht et al., 1993).

Teff grain contains high levels of several minerals such as iron, magnesium, calcium, phosphorus, and thiamine (National Research Council, 1996; Mengesha, 1965). It is an excellent source of essential amino acids, especially lysine, the amino acid that is most often deficient in common grain foods including wheat and millet (Lovis, 2003; Spaenij-Dekking et al., 2005). Unlike common cereals (wheat, corn, and barley), teff has balanced nutrition but is low in gluten, which makes a good diet source for gluten intolerant people (Stallknecht et al., 1993). Teff forage contains high amount of proteins; a field trial research in Montana reported 9.6 to 13.7% hay protein and the same Relative Feed Quality (RFQ) as full-bloom alfalfa, which ranged from 78 to 108 in research from Oregon and Washington (Stallknecht et al., 1993; Norberg et al., 2009).

Temperature, soil moisture, planting depth and soil texture are some of challenges to established teff. Though teff can be grown in a wide range of soil moisture conditions extending from highly drought to highly waterlogged soil, but the early season growth is weak until a very good root system is established (Hunter et al., 2007; Millar, 2010). A preliminary green house study conducted in 2010 suggested that teff can well thrive if moisture level is over 15% water content (weight of water/weight of soil) and relative humidity (RH) of 65% or lower (Ali and Girma personal observation). Girma (2009) reported that teff produced 5 to 12 ton ha^{-1} of total biomass in central Oklahoma under optimal soil moisture. Drought soil conditions reduce grain yield, especially if the stress occurs during the vegetative growth stage, and grain yield reduction of 40% and 85.1% reported under greenhouse grown soil drought conditions (Ayale, 1993; Takele, 1997 & 2001; Teferra et al., 2000). Likewise, tiller number, plant height and both yield of biomass and grain yield of all teff genotypes decreased under soil moisture stress compared to non-stress condition (Takele, 1997; Admas and Belay, 2011). In U.S.A, highest forage yield (9 to 13.5 ton/ha) was recorded dependent upon soil moisture levels ranged from dry to well irrigation (Boe et al. 1986; Eckhoff et al. 1993).

In another study that compared the interaction of seed treatment and temperature on teff seedling vigor, Ghebrehiwot et al. (2008) showed that temperature was not a critical factor when temperatures range from 25 to 38.9°C. Generally, at 15°C teff should grow well. Soil temperature less than 18.4°C inhibits teff growth (Stallknecht, 1997; Millar, 2010). Debelo (1992) reported that low germination of teff seed was recorded at low temperatures 15/15° and 15/25°C compared to high temperatures 25/25°, 35/35°, 15/35°, and 25/35°C. Highest yields (700 to 1600 kg ha^{-1}) are typically obtained in its native country, Ethiopia, under a range of temperature from 10° to 29°C (Stallknecht, 1997; Hunter et al., 2007; Millar, 2010).

Teff is a photoperiod sensitive plant, and optimal day length (12 hours) is appropriate to induce flowering in teff. Shorter day lengths (8 hours) and longer day lengths (16 hours) reduce and delay flowering of teff (Katema, 1997; Roseberg et al., 2005). Growing teff in early season (low temperature at less than 10°C) can lead to more weed problems as it is very sensitive and less tolerant to frost and freezing (Stallknecht, 1997; Millar, 2010). Teff forage yield is more sensitive to day length and decreased yield at short day lengths, especially in fall season (Katema, 1997).

Photosynthetic efficiency of teff is also affected by temperature. Carbon exchange rate of teff increased with increasing the temperature from 18 to 42°C and then decreased at temperatures above that. In the same time intercellular CO_2 concentration was not significantly affected by temperature but in general intercellular CO_2 concentration level decreased at the temperature in which it was optimal to carbon exchange rate. Stomatal conductance increased as temperature increased (Kebede et al., 1989). Net photosynthetic assimilation and respiration rates of teff decreased by 92.8% and 60% respectively at very high water stress less than 75% of soil water availability. Water stress during the vegetative growth stage decreased a photosynthesis rate, and water stress had a significant effect on stomatal conductance (Dejene, 2009).

In Oklahoma, teff is a new crop and farmers are interested in growing teff to produce hay during summer, but its management is not well understood. More importantly, establishment, erratic rainfall, and summer heat make production difficult. The objective of this study was to determine the effect of day length, temperature, soil moisture level and watering intervals on growth and yields of teff. The specific objectives of this project were:

(1) Evaluate teff response to the interaction of water quantity (field capacity), and watering interval.
(2) Determine the interaction of day lengths, and temperature on growth and yield of teff under controlled environment.

MATERIALS AND METHODS

Six controlled environment growth chambers at the Control Environmental Research Laboratory (CERL) facility of Oklahoma State University were used to accommodate six day length by temperature combinations. Two day lengths were evaluated 14/10 (short day, SD), and 16/8 (long day (LD) light/dark hours to mimic Oklahoma day length during summer. Three temperature regimes were evaluated (1) 24/19°C day/night chosen to represent an ambient ideal temperature (IT), (2) 27/16°C day/night which mimicked the 10- years average temperature of Oklahoma during May to August as minimum temperature (MT) , and (3) 30/24°C day/night as high temperature (HT) in which the temperature was set to 30°C in the first month, 35°C in the second month with an increase in temperature of 1°C every 4 days until reached 35°C and a decrease in temperature from 35°C in the third month at a rate of 1°C every 4 days. The last temperature regime was designed to mimic a severe summer in Oklahoma. Relative humidity of growth chambers was set to 50/50, 55/50, 55/50 % day/night for 24/19°, 27/16°, and 30/24°C temperature, respectively, to mimic the Oklahoma environmental conditions during summer. The trial was repeated over 2011 and 2012.

In each growth chamber, a factorial combination of four soil water levels and three levels of watering interval were implemented. Soil moisture levels were maintained at 25, 50, 75 and 100% of field capacity (FC_{100}, FC_{75}, FC_{50}, and FC_{25}) corresponding to 12.5, 25, 37.5 and 50 (v/v of soil/water), respectively. Field capacity was measured depending on the field soil at Agronomy Research Station at Stillwater and as described by Anderson and Ingram (1993). Dominant soil type at this location is a norge fine-silty, mixed, active, thermic udic apleustolls. Watering intervals were watering every 3, 5, and 7 days (I3, I5, and I7). Water requirement was obtained by weighing pots before and after irrigation to measure the amount of water needed according to field capacity and soil weight.

The experimental design within a growth chamber was split-plot arrangement and completely randomized within three replications. Main plots were watering interval and sub-plots were field capacity. Each growth chamber contained 36 small pots (12.7 cm depth by 15.3 cm diameter). Each pot was filled with 2 kg of soil (silty clay loam) from the Agronomy Research Station. Soil water amount (table 1.1) and watering interval treatments were treated 10 days after planting and were continued until physiological maturity. The 10 days delay after planting ensured complete emergence of teff. About 15 seeds of teff were planted in each pot and each pot had 65 kg N h^{-1} and 50 kg P h^{-1} available to plant growth, accounting for residual N and P in the soil. Two-third of nitrogen was applied before jointing.

Planting date was August 3, 2011 and February 2, 2012. Teff was harvested manually at physiological maturity with scissors on November 15, 2011 for all the growth chambers except the 30/24°C and 16/8 hours chamber, which was harvested on October 25. In 2012 the harvest date was on May 20 for all growth chambers except the 30/24°C chambers which were harvested on April 30.

Number of seedlings, plant height (cm) from the soil surface until the end of panicle, leaf numbers per plant, and leaf area were measured at 3-4, 6-8, and 10-11 weeks after planting. Number of tillers were measured during tillering stage (4-5 weeks from the planting date) and at final harvest (11-12 weeks from the planting date). Aboveground biomass, and grain yield was measured at physiological maturity. After harvest teff was dried in an oven (42°C) for 7 days, and then was weighted for biomass yield and threshed by hand and cleaned to determine grain yield.

Leaf area was measured using LI-3000 leaf area meter (LI-COR, Lincoln, Nebraska USA). Physiological variables including photosynthetic CO_2 assimilation A (μmol CO_2 m^{-2} s^{-1}), stomatal conductance to water vapor (g_{ws}) (mol H_2O m^{-2} s^{-1}), and intercellular CO_2 concentration C_i (μmol CO_2 mol air^{-1}) were measured with a *LI-6400* portable photosynthesis system (LI-COR, Lincoln, Nebraska USA). A CO_2 cylinder was used to supply CO_2 (400 μL L^{-1}) in CO_2 injection system during the measurement, and light source (6400-02 LED) was used to supply 1500 μmol m^{-2} s^{-1} of photosynthetically active radiation (PAR). The temperature of the leaf cuvette chamber was set depending upon the growth chamber temperature. The measurement was repeated weekly, beginning 20 days after emergence (six times).

A polynomial model was used to estimate the effect of treatments on the relationship of grain yield to biomass yield, the effect of treatment on *A*, and the response of *A* to g_{ws} and C_i ;

$$Y= y0 + ax + bx^2$$

Raw data we analyzed with PROC MIXED and PROC REPEATED statistical procedures of SAS statistical software program (SAS 9.3). Least squares means and tests of effect slices of treatment were used for mean separations at 5% level of significance probability. Linear contrast of treatments was also measured for biomass and grain yields.

Table 1.1. Total amount of water (ml) added to each pot of teff plant based on field capacity, watering interval, temperature and day length. The pots were watered between 9 and 10 AM. at growing seasons 2011 and 2012 at the control experiment.

Treatment	Growing season 2011						Growing season 2012					
	Day length (light/ dark) hours						Day length (light/ dark) hours					
	14/10 hours			16/8 hours			14/10 hours			16/8 hours		
	24/19°C	27/16°C	30/24°C	24/19°C	27/16°C	30/24°C	24/19°C	27/16°C	30/24°C	24/19°C	27/16°C	30/24°C
3 Days												
25%FC	3092	3123	3241	3196	3102	3349	3002	3100	3201	3106	3129	3334
50%FC	6142	6146	6369	6246	6289	6410	6049	6112	6263	6156	6219	6400
75%FC	9170	9171	9493	9299	9356	9499	9095	9201	9339	9108	9350	9402
100%FC	12348	12368	12685	12488	12591	12699	12151	12212	12400	12488	12570	12592
5 Days												
25%FC	2255	2240	2385	2242	2292	2344	2342	2349	2398	2392	2392	2416
50%FC	4493	4485	4562	4500	4509	4579	4500	4499	4527	4594	4509	4629
75%FC	6599	6618	6794	6797	6730	6797	6528	6598	6690	6702	6613	6742
100%FC	8986	8982	8984	8974	8999	9095	8809	8882	8914	8998	8915	9015
7 Days												
25%FC	1610	1609	1700	1675	1699	1710	1649	1669	1709	1775	1700	1787
50%FC	3247	3279	3303	3290	3316	3405	3240	3279	3310	3391	3324	3435
75%FC	4848	4863	4902	4899	4525	4988	4852	4897	4900	4912	4937	4518
100%FC	6495	6495	6601	6500	6545	6698	6401	6485	6521	6581	6555	6607

RESULTS

Morphological Variables

None of watering regimes evaluated affected number of seedlings (Table 1.2). Number of tillers per plant was significantly affected by the combination of Field capacity and watering interval treatments (Figure 1.1 and Table1.3) at ($P \leq 0.05$). Combination of water quantity (%field capacity) with watering interval had no significant effect on tiller number at 24/19°C at either measurement time (4-5 and 11-12 weeks). A similar effect was also observed with the 27/16°C temperature regimen at the tillering stage (4-5 weeks). However, at 27/16°C, a significant effect was recorded with the combination of water quantity (FC_{75} and FC_{100}) with watering interval at harvesting (11-12 weeks) under the effect of day length (SD). Thus, tillers per plant decreased (3.6) of the combination of FC_{75} + I7 compared with 5 and 4.8 tillers per plant of FC_{75} + I3 and FC_{75} + I5 days, respectively. Also, at the combination of FC_{100} + I5 and FC_{100} + I7 treatments, tillers number per plant were 4 and 3, respectively compared with 5.4 tillers per plant of the combination FC_{100} + I3 day of watering interval. The same results were also obtained at 30/24°C at tillering and harvesting stages. The number of tiller per plant was decreased of the combination FC_{75} + I3 and FC_{75} + I7 treatments (2.8 and 2.8 tillers per plant) compared to FC_{75} + I5 treatment (4 tillers per plant) at LD setting. Also, tiller number decreased of the combination FC_{100} + I5 and FC_{100} + I7 treatments (2.7 and 2.8 tillers per plant) compared with a 3.3 tillers per plant at FC_{100} + I3 treatment. In general, tiller number per plant decreased with decreasing soil moisture level, and it was affected by temperatures more than day length in which tiller number decreased with increasing temperature.

Table 1.2. Statistical analysis (PROC MIXED with repeated measurement) of teff seedling numbers per pot as affected by the combination of each field capacity (%) with watering intervals (day) treatments under the effect of the combination of temperature (°C) with day length (hour) treatments in growth chamber studies in 2011 and 2012

Day Length (14/10 hours) light/dark							
Effect	Num DF	Temperature (24/19°C)		Temperature (27/16°C)		Temperature (30/24°C)	
		F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
FC%[†]	3	1.35	0.27	1.45	0.24	0.36	0.78
25	2	0.23	0.80	0.53	0.59	0.44	0.65
50	2	1.60	0.21	1.56	0.22	0.28	0.76
75	2	0.66	0.52	1.21	0.31	0.35	0.71
100	2	0.04	0.96	0.10	0.91	1.63	0.20
WIdays[‡]	2	0.79	0.46	0.76	0.48	1.40	0.26
3	3	0.55	0.65	0.55	0.65	0.16	0.92
5	3	0.29	0.83	1.16	0.34	0.53	0.66
7	3	1.67	0.18	1.51	0.22	0.53	0.66
FC*WIdays[§]	6	0.58	0.75	0.88	0.51	0.43	0.85

Day Length (16/8 hours) light/dark							
Effect	Num DF	Temperature (24/19°C)		Temperature (27/16°C)		Temperature (30/24°C)	
		F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
FC%	3	1.75	0.17	1.54	0.21	0.48	0.70
25	2	0.14	0.87	0.62	0.54	0.86	0.43
50	2	2.43	0.10	0.75	0.48	0.6	0.55
75	2	1.41	0.25	0.19	0.83	0.15	0.86
100	2	3.04	0.06	0.89	0.42	0.50	0.61
WIdays	2	0.85	0.43	1.36	0.27	0.09	0.92
3	3	1.32	0.28	0.24	0.87	0.51	0.67
5	3	3.92	0.01	0.68	0.57	0.42	0.74
7	3	0.62	0.61	1.35	0.27	0.90	0.45
FC*WIdays	6	2.06	0.07	0.36	0.90	0.68	0.67

† FC%= Field capacity (%).
‡ WIdays= Watering intervals (day).
§ FC*WIdays= Interaction of field capacity and watering interval.

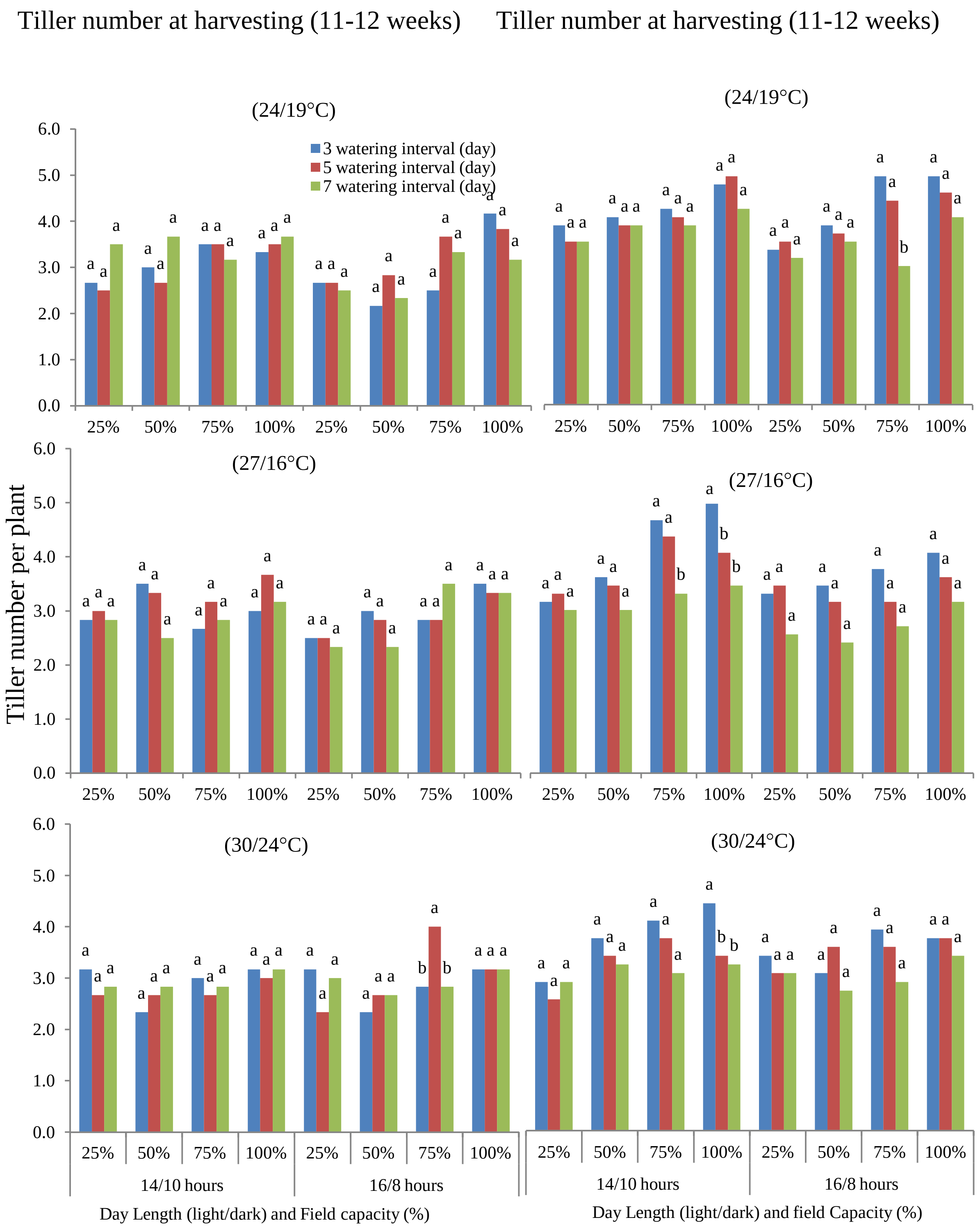

Figure 1.1. Teff tillers number per plant at 4-5 weeks and at 11-12 weeks after emergence as affected by the combination of field capacity (%) with watering intervals (day) treatments. Each combination of field capacity with watering interval treatments compared individually and bars with the same letter are not statistically different at $p \leq 0.05$ level of least square means.

Table 1.3. Statistical analysis (PROC MIXED with repeated measurement) of teff tillers number per plant as affected by the combination of each field capacity (%) with watering intervals (day) treatments under the effect of the combination of temperature (°C) with day length (hours) treatments in growth chamber studies in 2011 and 2012.

Day Length (14/10 hours) light/dark

Effect	Num DF	Temperature (24/19°C)		Temperature (27/16°C)		Temperature (30/24°C)	
		F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
Date[†]	1	15.29	0.0002	56.01	<.0001	9.96	0.002
FC%[‡]	3	4.21	0.007	5.49	0.002	2.74	0.047
+Date	3	0.35	0.789	3.54	0.017	2.23	0.089
WIdays[§]	2	0.23	0.792	7.34	0.001	2.34	0.101
+Date	2	2.06	0.132	3.15	0.047	1.76	0.177
FC*WIdays[¶]	6	0.67	0.677	0.54	0.777	0.5	0.807
DATE*FC*WIdays[#]	6	0.32	0.926	1.42	0.213	0.57	0.751

Day Length (16/8 hours) light/dark

Effect	Num DF	Temperature (24/19°C)		Temperature (27/16°C)		Temperature (30/24°C)	
		F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
Date	1	21.45	<.0001	15.03	0.0002	4.88	0.03
FC%	3	11.09	<.0001	3.71	0.01	3.12	0.03
+Date	3	0.57	0.64	0.39	0.76	0.23	0.88
WIdays	2	3.93	0.02	3.5	0.03	1.38	0.26
+Date	2	2.13	0.12	2.67	0.07	1.09	0.34
FC*WIdays	6	0.69	0.66	0.42	0.86	1.31	0.26
DATE*FC*WIdays	6	1.59	0.16	0.28	0.95	0.78	0.59

†Date Time to measure the Tiller Number per plant (teller and harvesting stages).

‡ FC%= Field capacity (%).

§ WIdays= Watering intervals (day).

¶ FC*WIdays= Interaction of field capacity and watering interval.

Date*FC*WIdays= Interaction of date, field capacity and watering interval.

Teff plant height (cm) was significantly affected ($P \leq 0.05$) by the combination of field capacity and watering interval (Tables 1.4 and 1.5). Plant height at 4 weeks was affected by the combination of water quantity (% field capacity) with watering interval affected regardless of temperatures at the SD (14/10 hours light/dark). At LD (16/8 hours light/dark), however, the combination of FC_{75} + I3 treatment grew to 63 cm height as compared to 43 and 49 cm height for the combination of FC_{75} + I5 and FC_{75} + I7 treatments.

At eight weeks, the combination of water quantity with watering interval significantly affected plant height. Differences among the treatments for plant height were more common at LD compared with short day length (14/10 hours). The greatest difference for plant height were associated with the combination of FC_{75} and FC_{50} + I3 and FC_{75} and FC_{50} + I7 treatments were 19 and 18 cm, respectively compared to 12 and 7 cm height of the combination of FC_{25} and FC_{100} + I3 and FC_{25} and FC_{100} + I7 treatments under the effect of LD (16/8 hours) and temperature 27/16°C.

The same results were obtained of 11-12 week measurements of plant height, which were affected by the combination of water quantity (field capacity) with watering interval. A greater effect of treatments on plant height was recorded at day length 16/8 hours, and the greatest difference of 30 cm was between the combination of FC_{25} + I3 and FC_{25} + I7 treatments at the effect of temperature 24/19°C. However, plant height decreased under the effect of low and high temperature (24/19° and 30/24°C) and increased at temperature 27/16°C. Also it increased with increasing time of water from 3 to 7 days.

Overall, plant height increased with increasing soil water availability and at day length 16/8 hours (light/dark) and decreased with increasing temperatures regimen.

Table 1.4. Teff plant height (cm) at 4, 8 and 12 weeks after emergence as affected by the combination of field capacity (%) with watering intervals treatments. Each combination of field capacity with watering interval treatments compared individually and treatments means with the same letter are not statistically different at $p \leq 0.05$ level of least square means.

Measurement time	Field capacity %	Watering interval (day)	Day length (light/ dark) hours					
			DL (14/10)[†]			DL (16/8)		
			Temp.[‡] 24/19°C	Temp. 27/16°C	Temp. 30/24°C	Temp. 24/19°C	Temp. 27/16°C	Temp. 30/24°C
			--------------cm----------------			-------------cm----------------		
4 weeks from emergence	25	3	14 a[§]	32 a	26 a	40 a	24 a	33 a
		5	13 a	35 a	27 a	37 a	29 a	38 a
		7	11 a	32 a	25 a	29 b	24 a	30 a
	50	3	17 a	38 a	35 a	40 a	30 a	40 a
		5	20 a	38 a	27 a	38 a	33 a	48 a
		7	16 a	37 a	25 a	42 a	24 a	40 a
	75	3	19 a	42 a	37 a	63 a	29 a	45 a
		5	26 a	39 a	35 a	43 b	36 a	43 a
		7	19 a	36 a	29 a	49 b	23 a	39 a
	100	3	22 a	41 a	31 a	51 a	33 a	24 b
		5	27 a	32 a	35 a	50 a	30 a	38 a
		7	22 a	30 a	30 a	52 a	31 a	31 a
8 weeks from emergence	25	3	30 a	56 a	28 a	53 a	51 a	34 b
		5	25 a	57 a	30 a	52 a	53 a	43 a
		7	18 b	55 a	22 a	40 b	39 b	41 a
	50	3	44 a	66 a	39 a	61 a	62 a	50 a
		5	35 a	63 a	35 a	65 a	54 ab	56 a
		7	25 b	58 a	36 a	59 a	44 b	48 a
	75	3	44 a	75 a	49 a	78 a	67 a	59 a
		5	43 a	72 a	35 a	67 b	66 a	54 a
		7	38 a	67 a	39 a	65 b	48 b	56 a
	100	3	43 a	81 a	45 a	71 a	67 a	61 a
		5	48 a	68 b	42 a	63 a	66 a	58 ab
		7	40 a	68 b	34 a	71 a	60 a	52 b
11-12 weeks from emergence	25	3	62 a	64 a	27 a	79 a	66 a	10 a
		5	56 a	67 a	33 a	67 a	68 a	18 a
		7	43 b	62 a	27 a	49 b	59 a	15 a
	50	3	80 a	79 a	41 b	87 a	78 a	30 a
		5	66 b	76 a	51 a	76 ab	72 a	30 a
		7	52 c	72 a	46 ab	69 b	55 b	18 b
	75	3	83 a	90 a	65 a	93 a	88 a	33 a
		5	78 a	81 b	64 a	86 ab	80 ab	28 a
		7	77 a	79 b	58 a	82 b	68 b	33 a
	100	3	84 a	96 a	81 a	92 a	89 a	32 a
		5	89 a	87 a	73 a	89 a	85 a	31 a
		7	80 a	86 a	58 b	90 a	74 b	33 a

†DL= day length (14/10 and 16/8 hours light/dark).

‡ Temp.= Temperature treatments.

§ Combination of each field capacity (%) with water interval (day) individually followed by the same letter are not statistically different at $p \leq 0.05$ level of least square means.

Table 1.5. Statistical analysis (PROC MIXED with repeated measurement) of teff plant height (cm) as affected by the combination of each field capacity (%) with watering intervals (day) treatments under the effect of combination of temperature (°C) with day length (hour) in growth chamber studies in 2011 and 2012.

Day Length (14/10 hours) light/dark

Effect	Num DF	Temperature (24/19°C)		Temperature (27/16°C)		Temperature (30/24°C)	
		F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
Date[†]	2	255.26	<.0001	275.16	<.0001	79.8	<.0001
FC[‡]	3	18.07	<.0001	12.02	<.0001	19.52	<.0001
+Date	6	1.94	0.079	4.12	9E-04	10.91	<.0001
Widays[§]	2	6.05	0.004	3.92	0.03	3.1	0.05
+Date	4	1.48	0.2	0.18	0.95	0.8	0.5
FC*WIdays[¶]	6	0.85	0.5	0.72	0.64	0.5	0.8
Date*FC*WIdays[#]	12	0.29	1.0	0.12	1.00	1.2	0.3

Day Length (16/8 hours) light/dark

Effect	Num DF	Temperature (24/19°C)		Temperature (27/16°C)		Temperature (30/24°C)	
		F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
Date	2	182.24	<.0001	325.4	<.0001	17.36	<.0001
FC	3	26.38	<.0001	9.38	<.0001	3.94	0.01
+Date	6	0.79	0.6	1.9	0.09	0.79	0.58
Widays	2	8.37	0.001	13.02	<.0001	0.62	0.54
+Date	4	1.46	0.2	2.64	0.04	0.11	0.98
FC*WIdays	6	2.01	0.08	0.64	0.70	0.3	0.93
Date*FC*WIdays	12	0.7	0.8	0.41	0.96	0.15	1.00

†Date Time to measure the Tiller Number per plant (teller and harvesting stages).
‡ FC%= Field capacity (%).
§ WIdays= Watering intervals (day).
¶ FC*WIdays= Interaction of field capacity and watering interval.
# Date*FC*WIdays= Interaction of date, field capacity and watering interval.

The combination of water quantity with watering interval affected leaf number per plant (Tables 1.6 and 1.7). The effect of the combination of water quantity (field capacity) with watering interval had no effect on leaf number at 3 weeks, especially at day length (14/10 hours light/dark) over all temperatures levels. More significant impact on leaf number was obtained from the effect of day length (16/8 hours light/dark) and the greatest leaf number was 17 at the combination of FC_{75} + I3 treatment at temperature (24/19°C). On the other hand, opposite effect of the combination of water quantity with watering interval was observed at 6 weeks compared to 3 weeks leaf number measurements under the effect of day lengths. At day length (14/10 hours), some of the treatments showed a significant effect on leaf number, especially at the combinations of FC_{25} and FC_{50} with watering interval at temperature treatments (24/19°C and 30/24°C, respectively). In general, statistically most of the combination of water quantity with watering interval had no effect in leaf number at day length (14/10 hours light/dark), and leaf number increased with increasing the soil moisture level. Some combinations (FC_{25} and FC_{50} with watering interval) affected the leaf number at day length (16/8 hours). Leaf number of the combination of FC_{25} + (I3, I5 and I7 days) treatments was (11, 10 and 7 leaf/plant respectively) at temperature (24/19°C) and was (10, 10 and 7 leaf/plant respectively) at temperature (27/16°C) in which leaf number decreased with decreasing soil moisture level. In general the number of leaves ranged between 4 to 17 leaves per plant, and the effect of temperatures was consistent in leaf number compared to the effect of soil moisture levels in which it decreased leaf number at low level of soil moisture and increased leaf number at high level of soil moisture.

Table 1.6. Leaf number per teff plant at 3, 6 and 9-10 weeks after emergence as affected by the combination of field capacity treatments (%) with watering intervals treatments. Each combination of field capacity with watering interval treatments compared individually and treatments means with the same letter are not statistically different at $p \leq 0.05$ level of least square means.

Measurement time	Field Capacity %	Watering Interval (day)	Day length (light/ dark) hours					
			DL (14/10)[†]			DL (16/8)		
			Temp.[‡] 24/19°C	Temp. 27/16°C	Temp. 30/24°C	Temp. 24/19°C	Temp. 27/16°C	Temp. 30/24°C
3 weeks from emergence	25	3	6 a[§]	8 a	6 a	10 a	7 ab	7 a
		5	5 a	6 a	6 a	8 a	8 a	9 a
		7	4 a	6 a	6 a	8 a	5 b	9 a
	50	3	6 a	7 a	8 a	8 a	8 a	12 a
		5	6 a	6 a	7 a	10 a	7 a	12 a
		7	5 a	6 a	6 a	10 a	3 b	8 b
	75	3	5 a	5 b	8 a	17 a	6 ab	11 a
		5	6 a	6 a	9 a	9 b	8 a	11 a
		7	6 a	8 a	7 a	11 b	5 b	10 a
	100	3	5 a	6 a	7 a	12 ab	6 a	3 b
		5	7 a	5 a	8 a	11 b	6 a	10 a
		7	5 a	4 a	7 a	15 a	5 a	8 a
6 weeks from emergence	25	3	8 a	7 a	4 a	7 a	7 a	5 a
		5	6 ab	7 a	6 a	7 a	7 a	7 a
		7	5 b	6 a	4 a	6 a	6 a	7 a
	50	3	7 a	7 a	5 b	6 a	7 a	7 a
		5	7 a	7 a	7 ab	7 a	6 a	7 a
		7	6 a	6 a	8 a	7 a	5 a	7 a
	75	3	7 a	7 a	7 a	7 a	7 a	7 a
		5	8 a	8 a	7 a	7 a	7 a	7 a
		7	7 a	7 a	7 a	6 a	6 a	7 a
	100	3	8 a	7 a	7 a	6 a	7 a	7 a
		5	8 a	6 a	8 a	7 a	7 a	7 a
		7	7 a	7 a	6 a	7 a	7 a	8 a
9-10 weeks from emergence	25	3	9 a	9 a	9 a	11 a	10 a	-[¶]
		5	8 a	9 a	10 a	10 a	10 a	-
		7	7 a	9 a	8 a	7 b	7 b	-
	50	3	8 a	9 a	9 a	11 a	10 a	-
		5	9 a	8 a	10 a	11 a	11 a	-
		7	8 a	8 a	9 a	11 a	6 b	-
	75	3	9 a	9a	9 a	11 a	11 a	-
		5	9 a	9 a	8 a	11 a	10 a	-
		7	9 a	8 a	9 a	11 a	11 a	-
	100	3	9 a	10 a	9 a	11 a	11 a	-
		5	9 a	9 a	8 a	11 a	10 a	-
		7	9 a	9 a	9 a	11 a	10 a	-

†DL= day length (14/10 and 16/8 hours light/dark).

‡ Temp. = Temperature treatments.

§ Combination of each field capacity (%) with water interval (day) individually followed by the same letter are not statistically different at $p \leq 0.05$ level of least square means.

¶ Data was not available (early reached the physiological maturity because of high temperature).

Table 1.7. Statistical analysis (PROC MIXED with repeated measurement) of Leaf number per teff plant as affected by the combination of each field capacity (%) with watering intervals (day) treatments under the effect of combination of temperature with day length in growth chamber studies in 2011 and 2012.

Day Length (14/10 hours) light/dark

Effect	Num DF	Temperature (24/19°C)		Temperature (27/16°C)		Temperature (30/24°C)	
		F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
Date[†]	2	59	<.0001	25.36	<.0001	8.1	0.003
FC[‡]	3	5.0	0.004	0.7	0.6	8.2	0.001
+Date	6	0.6	0.8	1.5	0.2	1.0	0.5
Widays[§]	2	4.7	0.01	1.2	0.3	1.9	0.2
+Date	4	1.0	0.4	0.4	0.8	0.3	0.9
FC*WIdays[¶]	6	1.2	0.3	0.7	0.7	1.2	0.3
Date*FC*WIdays[#]	12	0.3	1.0	0.5	0.9	0.7	0.7

Day Length (16/8 hours) light/dark

Effect	Num DF	Temperature (24/19°C)		Temperature (27/16°C)		Temperature (30/24°C)	
		F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
Date	2	37	<.0001	56.85	<.0001	121.46	<.0001
FC	3	6.2	0.0009	2.00	0.12	1.9	0.14
+Date	6	4.2	0.001	2.02	0.08	1.85	0.10
Widays	2	1.4	0.25	11.96	<.0001	1.16	0.32
+Date	4	3.4	0.01	2.10	0.09	0.69	0.60
FC*WIdays	6	2.5	0.03	1.83	0.11	0.87	0.52
Date*FC*WIdays	12	2.6	0.007	0.98	0.48	0.75	0.70

†Date Time to measure the Tiller Number per plant (teller and harvesting stages).
‡ FC%= Field capacity (%).
§ WIdays= Watering intervals (day).
¶ FC*WIdays= Interaction of field capacity and watering interval.
# Date*FC*WIdays= Interaction of date, field capacity and watering interval.

The statistical Results of the combination of water quantity with watering interval ($P \leq 0.05$) showed that there was a significant effect on leaf area per plant (Tables 1.8 and 1.9). At 4 weeks, all of water quantity (field capacity) by watering interval combinations treatments affected leaf area at both day lengths. The greatest leaf area was (16 cm^2) at the combination of FC_{100} + I3 treatment at temperature (24/19°C) under the effect of (14/10 hours) day length and it was also (16 cm^2) but at different combination of FC_{75} and FC_{100} with watering interval at day length (16/8 hours). The same results of the effect of the combination of water quantity (field capacity) with watering interval was obtained at 8 and 10 weeks measurements at both day length as well as the effect of day length and temperatures. The lowest leaf area (1 cm^2) was obtained at different combinations treatments of FC_{25} and FC_{50} with watering interval at either day lengths at 10 weeks measurement. Likewise, the greatest leaf area was (47 cm^2) at the combination of FC_{75} + I3 days of watering interval treatment at the effect of day length (14/10 hours) and temperature (24/19°C) at 10 weeks of measurement. However, leaf area per plant was highly related to soil moisture, and it increased at high level of soil moisture (FC_{100} and FC_{75}) and decreasing at low level of soil moisture (FC_{25}). Leaf area decreased with increased temperature at day length (14/10 hours), but slightly increased with increasing temperature at day length (16/8 hours).

Table 1.8. Leaf area (cm^2) per teff plant at 4, 8 and 10 weeks after emergence as affected by the interaction of field capacity (%) with watering intervals treatments. Each combination of field capacity with watering interval treatments compared individually and treatments means with the same letter are not statistically different at $p \leq 0.05$ level of least square means.

Measurements time	Field Capacity %	Watering Interval (day)	Day length (light/ dark) hours					
			DL (14/10)[†]			DL (16/8)		
			Temp.[‡] 24/19°C	Temp. 27/16°C	Temp. 30/24°C	Temp. 24/19°C	Temp. 27/16°C	Temp. 30/24°C
			----------------cm^2---------------			----------------cm^2---------------		
4 weeks from emergence	25	3	4 a[§]	4 a	2 a	4 b	6 a	8 a
		5	5 a	4 a	3 a	12 a	5 a	9 a
		7	7 a	3 a	3 a	8 a	2 a	5 a
	50	3	5 b	11 a	3 a	5 a	10 a	11 a
		5	7 ab	4 b	4 a	8 a	12 a	8 a
		7	11 a	4 b	8 a	7 a	6 a	6 a
	75	3	10 a	8 a	5 b	8 a	10 a	16 a
		5	4 b	5 a	4 b	11 a	7 a	12 a
		7	12 a	4 a	10 a	8 a	10 a	8 a
	100	3	16 a	10 a	6a	11 a	15 a	16 a
		5	5 c	6 a	4 a	16 a	11 a	13 a
		7	11 b	5 a	5 a	12 a	10 a	11 a
8 weeks from emergence	25	3	9 a	25 a	-[¶]	25 a	24 a	-
		5	9 a	21 a	13	22 ab	27 a	12 a
		7	10 a	24 a	-	17 b	26 a	12 a
	50	3	19 a	24 a	-	23 a	25 a	7 ab
		5	9 b	21 a	12 a	22 a	23 a	4 b
		7	12 b	22 a	15 a	18 a	22 a	12 a
	75	3	27 a	30 a	6 b	27 a	28 a	17 a
		5	13 c	26 a	8 ab	20 b	26 ab	15 a
		7	19 b	27 a	12a	20 b	21 b	13 a
	100	3	16 a	33 a	22 a	26 a	30 a	16 a
		5	9 b	21 b	16 b	25 a	26 a	20 a
		7	16 a	20 b	3 c	25 a	27 a	14 a
10 weeks from emergence	25	3	14 a	20 a	-	13 a	12 a	-
		5	13 a	26 a	1	8 a	11 a	-
		7	15 a	20 a	-	7 a	12 a	-
	50	3	30 a	32 a	2 a	14 a	16 a	-
		5	14 b	29 a	4 a	12a	13 a	-
		7	19 b	29 a	2 a	13 a	12 a	-
	75	3	47 a	45 a	5 a	23 a	22 a	-
		5	19 c	43 a	7 a	18 ab	19 a	-
		7	28 b	33 b	3 a	15 b	17 a	-
	100	3	39 a	43 a	6 ab	21 a	27 a	-
		5	20 b	45 a	8 a	18 a	22 ab	-
		7	25 b	39 a	3 b	17 a	19 b	-

†DL= day length (14/10 and 16/8 hours light/dark).

‡ Temp.= Temperature treatments.

§ Combination of each field capacity (%) with water interval (day) individually followed by the same letter are not statistically different at $p \leq 0.05$ level of least square means.

¶ Data was not available (early reached the physiological maturity because of high temperature).

Table 1.9. Statistical analysis (PROC MIXED with repeated measurement) of leaf area (cm^2) per teff plant as affected by the combination of each field capacity (%) with watering intervals (day) treatments under the effect of combination of temperature with day length in growth chamber studies in 2011 and 2012.

Day Length (14/10 hours) light/dark

Effect	Num DF	Temperature (24/19°C)		Temperature (27/16°C)		Temperature (30/24°C)	
		F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
Date[†]	2	144	<.0001	165.1	<.0001	13.46	0.0007
FC[‡]	3	22	<.0001	7.84	0.001	8.73	0.0008
+Date	6	7.4	<.0001	5.27	0.0005	1.2	0.33
Widays[§]	2	32	<.0001	3.27	0.06	2.35	0.12
+Date	4	10	<.0001	1.19	0.33	3.45	0.02
FC*WIdays[¶]	6	4.4	0.004	0.4	0.87	5.07	0.003
Date*FC*WIdays[#]	12	2.3	0.02	0.51	0.90	2.23	0.04

Day Length (16/8 hours) light/dark

Effect	Num DF	Temperature (24/19°C)		Temperature (27/16°C)		Temperature (30/24°C)	
		F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
Date	2	71	<.0001	193.8	<.0001	61.29	<.0001
FC	3	24	<.0001	13.1	<.0001	6.68	0.002
+Date	6	1.8	0.16	3.71	0.005	0.66	0.68
Widays	2	9.8	0.01	5.49	0.01	1.09	0.35
+Date	4	3.5	0.03	0.23	0.92	1.60	0.20
FC*WIdays	6	1	0.49	0.68	0.67	1.20	0.34
Date*FC*WIdays	12	0.3	0.97	0.88	0.57	0.43	0.94

†Date Time to measure the Tiller Number per plant (teller and harvesting stages).
‡ FC%= Field capacity (%).
§ WIdays= Watering intervals (day).
¶ FC*WIdays= Interaction of field capacity and watering interval.
# Date*FC*WIdays= Interaction of date, field capacity and watering interval.

Biomass and grain yield

Biomass production (g pot^{-1}) was significantly affected by the combination of water quantity (field capacity) and watering interval under the effect of the combination of temperature with day length treatments (Figure 1.2 and Table 1.10).

At temperature 24/19°C, biomass yield increased as field capacity increased and watering interval decreased at both day lengths. Thus, I3 and I5 days of watering interval yielded the greatest biomass production compared to I7 days watering interval. Likewise, biomass yield was greater at FC_{100} and FC_{75} than biomass yield at FC_{50} and FC_{25}. Biomass production was significantly affected by the combination of field capacity with watering interval at day length 16/8 hours compared with day length 14/10 hours. Thus, the greatest biomass yield was (18 and 17 g/pot) at the combination of FC_{75} and FC_{100} with I3 and I5 days of watering interval treatment, respectively. At temperature 27/16°C, opposite effect of 24/19°C, biomass yield at day length 16/8 hours was lower than for day length 14/10 hours. Furthermore, biomass yield increased with increasing water quantity (field capacity) and with decreasing watering interval time, thus, the combination of FC_{100} and FC_{75} + I3 days produced the greatest yield (27 & 23 g/pot at 14/10 hours and 13 & 11 g/pot at 16/8 hours respectively).

The same result of 24/19°C was obtained at 30/24°C, and biomass yield at day length 16/8 hours was greater than biomass yield at day length 14/10 hours. Likewise, biomass yield increased at the combination of FC_{100} + I3 days of watering interval treatment at 16/8 and 14/10 hours (17 and 14 g/pot). Thus, biomass production typically increased with increasing field capacity (FC_{100} and FC_{75}) at I3 and I5 treatments at either day lengths.

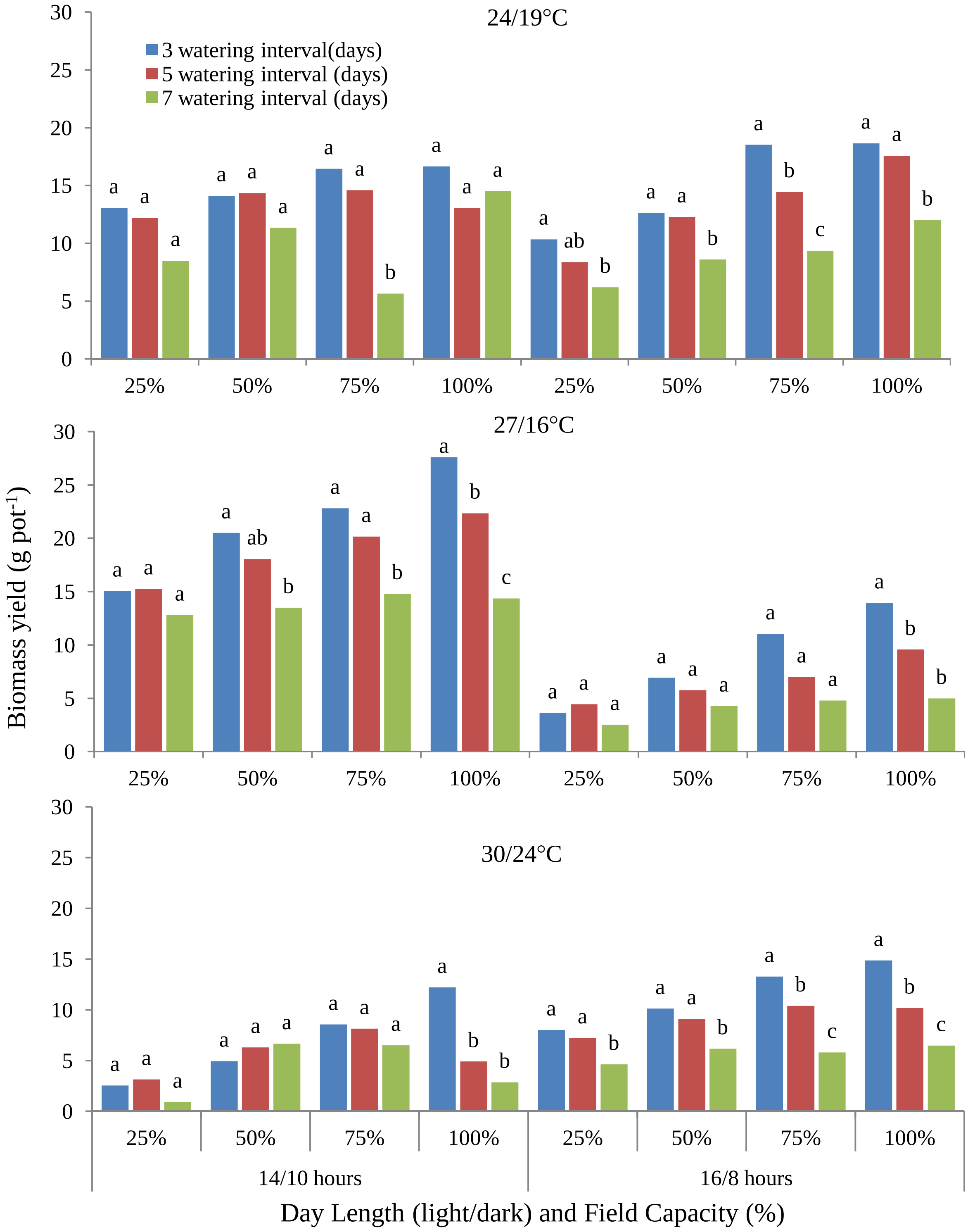

Figure 1.2. Biomass yield (g pot^{-1}) of teff plant as affected by the combination of each field capacity treatments (%) with watering intervals (day) treatments. Each combination of field capacity with watering interval treatments compared individually and bars with the same letter are not statistically different at $p \leq 0.05$ level of least square means.

Table 1.10. Statistical analysis (PROC MIXED with repeated measurement) of Biomass yield (g pot^{-1}) of teff plant as affected by the combination of each field capacity (%) with watering intervals (day) treatments under the effect of combination of temperature with day length in growth chamber studies in 2011 and 2012.

Day Length (14/10 hours) light/dark							
		Temperature (24/19°C)		Temperature (27/16°C)		Temperature (30/24°C)	
Effect	Num DF	F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
FC†	3	1.20	0.351	9.87	0.002	6.85	0.007
+25	2	1.06	0.378	0.68	0.528	0.54	0.600
+50	2	0.50	0.619	4.62	0.035	0.32	0.734
+75	2	6.02	0.015	6.08	0.017	0.47	0.639
+100	2	0.59	0.568	16.31	0.001	9.54	0.004
WIdays‡	2	4.88	0.028	22.09	0.000	3.18	0.081
+3	3	0.57	0.647	9.95	0.002	7.03	0.007
+5	3	0.23	0.874	3.36	0.059	1.77	0.210
+7	3	2.60	0.100	0.29	0.832	3.16	0.068
FC*WIdays§	6	1.10	0.417	1.87	0.175	2.56	0.084

Day Length (16/8 hours) light/dark							
		Temperature (24/19°C)		Temperature (27/16°C)		Temperature (30/24°C)	
Effect	Num DF	F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
FC	3	34.1	<.0001	15.15	<.0001	11.0	<.0001
+25	2	4.24	0.023	0.72	0.496	4.0	0.029
+50	2	4.89	0.0138	1.35	0.272	5.3	0.0105
+75	2	20.8	<.0001	7.65	0.002	17.7	<.0001
+100	2	12.5	<.0001	15.29	<.0001	22.1	<.0001
WIdays	2	37.1	<.0001	17.17	<.0001	42.6	<.0001
+3	3	17.4	<.0001	15.73	<.0001	11.9	<.0001
+5	3	14.7	<.0001	3.66	0.022	2.6	0.069
+7	3	5.61	0.0032	0.97	0.417	0.8	0.491
FC*WIdays	6	1.79	0.1326	2.61	0.035	2.2	0.073

† FC%= Field capacity (%).

‡ WIdays= Watering intervals (day).

§ FC*WIdays= Interaction of field capacity and watering interval.

The results of grain yield (g pot^{-1}) showed that the combinations of water quantity with watering interval significantly were affected the grain yield at either day length at all temperatures (Figure 1.3 and Table 1.11). In general, grain yield at 24/19°C was constant under both day lengths, and it increased with increasing soil moisture (field capacity) and decreased watering interval necessary to sustain production. Thus the highest yield was obtained at the combination of FC_{100} + I3 days water interval compared to FC_{25}, which had the lowest grain yield at both day lengths (≈ 1.1 g pot^{-1}). On the other hand, grain yield was more affected by the combinations of water treatments at 27/16°C compared with 24/19°C. However, grain yield decreased dramatically with changing photoperiod to 16/8 hours and increased as water quantity exceeded FC_{50}. I3 days of watering interval treatment was more efficient in grain yield, and the greatest yield was (≈3.8 and 3.5 g pot^{-1}) at the combination of FC_{75} and FC_{100} + I3 treatments, respectively. At 30/24°C, grain yield highly decreased and the greatest yield was (≈0.5 g pot^{-1}).

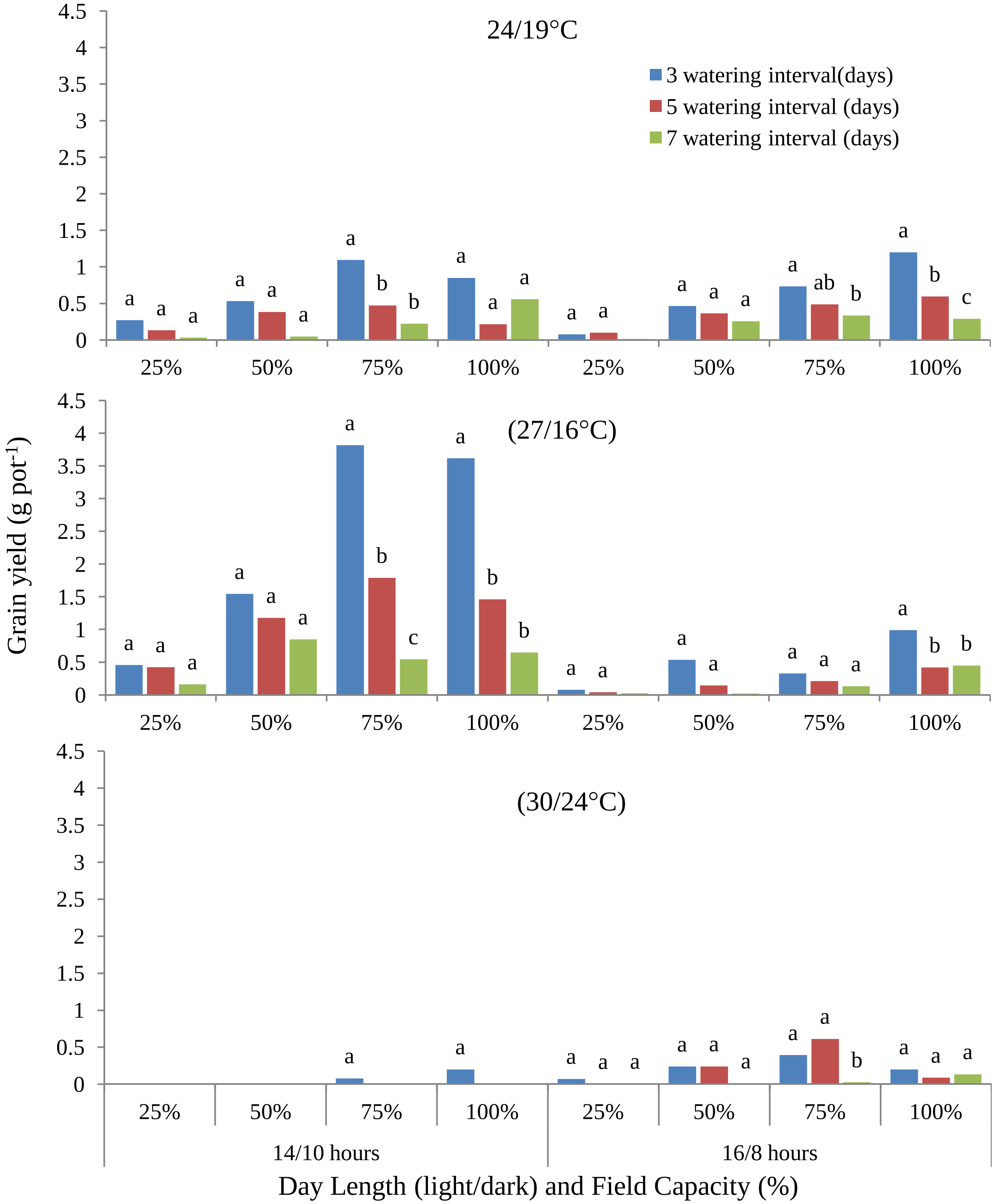

Figure 1.3. Grain yield (g pot^{-1}) of teff plant as affected by the combination of each field capacity (%) with watering intervals (day) treatments. Each combination of field capacity with watering interval treatments compared individually and bars with the same letter are not statistically different at $p \leq 0.05$ level of least square means.

Table 1.11. Statistical analysis (PROC MIXED with repeated measurement) of grain yield (g pot^{-1}) of teff plant as affected by the combination of each field capacity (%) with watering intervals (day) treatments under the effect of combination of temperature with day length in growth chamber studies in 2011 and 2012.

Day Length (14/10 hours) light/dark							
	Num	Temperature (24/19°C)		Temperature (27/16°C)		Temperature (30/24°C)	
Effect	DF	F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
FC[†]	3	3.28	0.059	17.79	0.0002	0.82	0.51
+25	2	0.36	0.708	0.26	0.778	-[¶]	-
+50	2	1.55	0.252	1.18	0.344	-	-
+75	2	5.09	0.025	26.54	<.0001	0.57	0.58
+100	2	2.54	0.12	22.9	0.0001	3.69	0.06
WIdays[‡]	2	6.35	0.013	32.57	<.0001	1.79	0.21
+3	3	3.29	0.058	25.89	<.0001	2.47	0.12
+5	3	0.6	0.624	3.29	0.062	-	-
+7	3	1.5	0.264	0.81	0.517	-	-
FC*WIdays[§]	6	1.06	0.435	6.10	0.005	0.82	0.57

Day Length (16/8 hours) light/dark							
	Num	Temperature (24/19°C)		Temperature (27/16°C)		Temperature (30/24°C)	
Effect	DF	F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
FC	3	24.38	<.0001	6.08	0.002	4.11	0.01
+25	2	0.23	0.7927	0.02	0.976	0.12	0.89
+50	2	1.21	0.3122	2.52	0.096	1.43	0.25
+75	2	4.57	0.0178	0.34	0.717	-	-
+100	2	24.41	<.0001	3.58	0.039	0.26	0.77
WIdays	2	17.87	<.0001	4.31	0.022	3.75	0.03
+3	3	25.25	<.0001	5.2	0.005	1.41	0.26
+5	3	5.15	0.005	0.89	0.457	-	-
+7	3	2.34	0.091	1.43	0.253	0.3	0.82
FC*WIdays	6	4.18	0.003	0.72	0.639	1.69	0.15

† FC%= Field capacity (%).
‡ WIdays= Watering intervals (day).
§ FC*WIdays= Interaction of field capacity and watering interval.
¶ - = Data not available.

The results of linear contrasts of biomass and grain yields to treatments support the previous finding of this study (Tables 1.12 and 1.13).

Biomass yield and showed that there was a significant trend with treatments. At temperature 24/19°C, a significant ($P \leq 0.05$) linear contrast of biomass yield to water interval was reported at FC_{25}, FC_{50}, FC_{75} and FC_{100} at LD day length, and a linear contrasts to field capacity was also significant at I3, I5 and I7 at either day lengths. The results of linear contrast of watering interval and field capacity at 27/16°C showed a significant effect of treatments in biomass yield at both day lengths, but only the linear contrast of watering interval at FC25 at day length (LD) hours was not significant. At temperature 30/24°C, all the linear contrast of treatments watering interval and field capacity had a significant effect in biomass production at either day lengths. Also, biomass yield decreased by the combinations of field capacity with watering interval at LD compared with other day length (Figure 1.4).

Linear contrasts of grain yield of water interval and water quantity (Tables 1.12 and 1.13) showed a negative significant response of grain yield to treatment combinations. Most of the linear contrasts of water interval were significant at 24/19°C and 27/16°C at both day lengths as well as linear contrasts of field capacity. Likewise, none of treatments of watering interval and field capacity at 30/24°C showed a significant linear contrast in grain yield at either day lengths. Furthermore, results (Figure 1.4) showed that the response of grain yield to the combinations of water quantity with watering interval at LD was significant (R^2= 0.58) under all temperatures and was highly significant (R^2= 0.87) at SD. Day length 16/8 hours had a negative effect on increasing in grain production compared with day length 14/10 hours.

Table 1.12.Linear contrast of biomass and grain yield (g pot^{-1}) of teff plant as affected by watering interval of the treatments of the combination of day lengths with temperatures.

Yield factor (g/pot)	Temperature Treatments	Linear Contrast	Day Length 14/10 hours (light/dark)				Day Length 16/8 hours (light/dark)			
			Field Capacity (%)				Field Capacity (%)			
			25	50	75	100	25	50	75	100
Biomass Yield	24/19°C	Watering Interval	*[†]	NS	NS	NS	*	*	**	*
	27/16°C	Watering Interval	*	*	*	*	NS	*	*	*
	30/24°C	Watering Interval	NS	*	*	*	*	*	*	*
Grain Yield	24/19°C	Watering Interval	*	*	NS	*	NS	*	*	**
	27/16°C	Watering Interval	*	NS	*	**	NS	NS	*	NS
	30/24°C	Watering Interval	-[‡]	-	NS	NS	NS	NS	NS	NS

†NS, *, and ** = Nonsignificant or significant at the 0.05, 0.01probability level respectively.
‡ -= Data was not available.

Table 1.13. Linear contrast of biomass and grain yield (g pot^{-1}) of teff plant as affected by field capacity of the treatments of the combination of day lengths with temperatures.

Yield factor (g/pot)	Temperature Treatments	Linear Contrast	Day Length 14/10 hours (light/dark)			Day Length 16/8 hours (light/dark)		
			Watering Interval (day)			Watering Interval (days)		
			3	5	7	3	5	7
Biomass Yield	24/19°C	Field capacity	*[†]	*	*	*	***	**
	27/16°C	Field capacity	*	*	*	**	*	**
	30/24°C	Field capacity	*	*	**	**	*	*
Grain Yield	24/19°C	Field capacity	NS	NS	*	***	*	NS
	27/16°C	Field capacity	*	*	NS	*	*	*
	30/24°C	Field capacity	NS	-[‡]	-	NS	NS	*

†NS, *, and ** = Nonsignificant or significant at the 0.05, 0.01probability level respectively.
‡- = Data was not available.

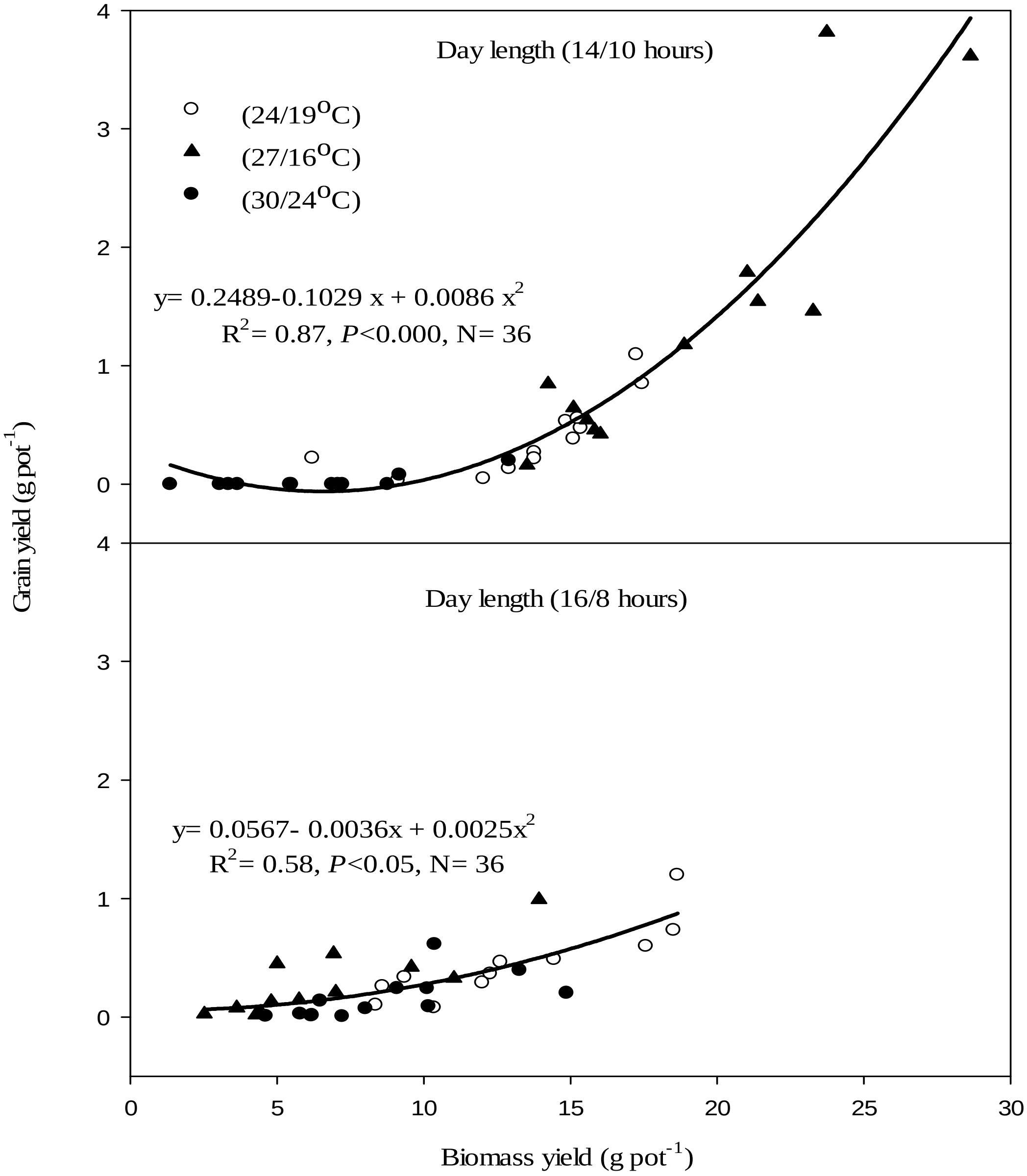

Figure 1.4. Relation of grain yield (g pot^{-1}) to biomass yield (g pot^{-1}) of teff plant as affected by the combination of watering quantity (field capacity) with watering interval under the effect of the combination of day lengths with temperatures. Each value is presented the mean of three replicates of each interaction between field capacity and watering interval at either day lengths and temperatures.

Teff Photosynthetic traits

Photosynthetic CO_2 assimilation yield A (μmol CO_2 m^{-2} s^{-1}) and stomatal conductance to water vapor g_{sw} (mol H_2O m-2s^{-1}) were affected by the combination of field capacity with watering interval at both day lengths and all temperatures (Figure 1.5). The trend of g_{sw} to A rate showed that g_{sw} decreased with decreasing A, especially with increasing time of watering interval. Also, both were decreased with increasing temperature and with changing day length from 14/10 hours to 16/8 hours. Maximum g_{sw} and A was (≈ 0.4 and 16 mol m^{-2} s^{-1} respectively) of the combination FC_{25} + I3 treatment of day length 14/10 hours and 24/19°C. The response at 14/10 hours to the treatments was quadratic (R^2= 0.76, 0.45, 0.40) at 24/19, 27/16 and 30/24°C respectively and at 16/8 hours was (R^2= 0.90, 0.47 and 0.67) at the temperatures respectively.

Combinations of water quantity with watering interval, and combinations of temperature and day length treatments were not clearly affected the intercellular CO_2 concentration Ci (μmol CO_2 mol air^{-1}), and the range of C_i was (100 to 300 μmol mol air^{-1}). Response A to intercellular [CO_2] C_i was related to the influence of treatments in C_i and A, especially at high temperatures and low water treated (Figure 1.6). The response was not significant at (P<0.4 and P<0.0001) and single linear regression (R^2= 0.18 and 0.28) at 24/19 and 27/16°C respectively at day length 14/10 hours. On the other hand, it was significant at (P<0.0001) with individual single regression (R^2= 0.7, 0.76 and 0.55) at 30/24, 27/16 and 30/24°C respectively at both day lengths.

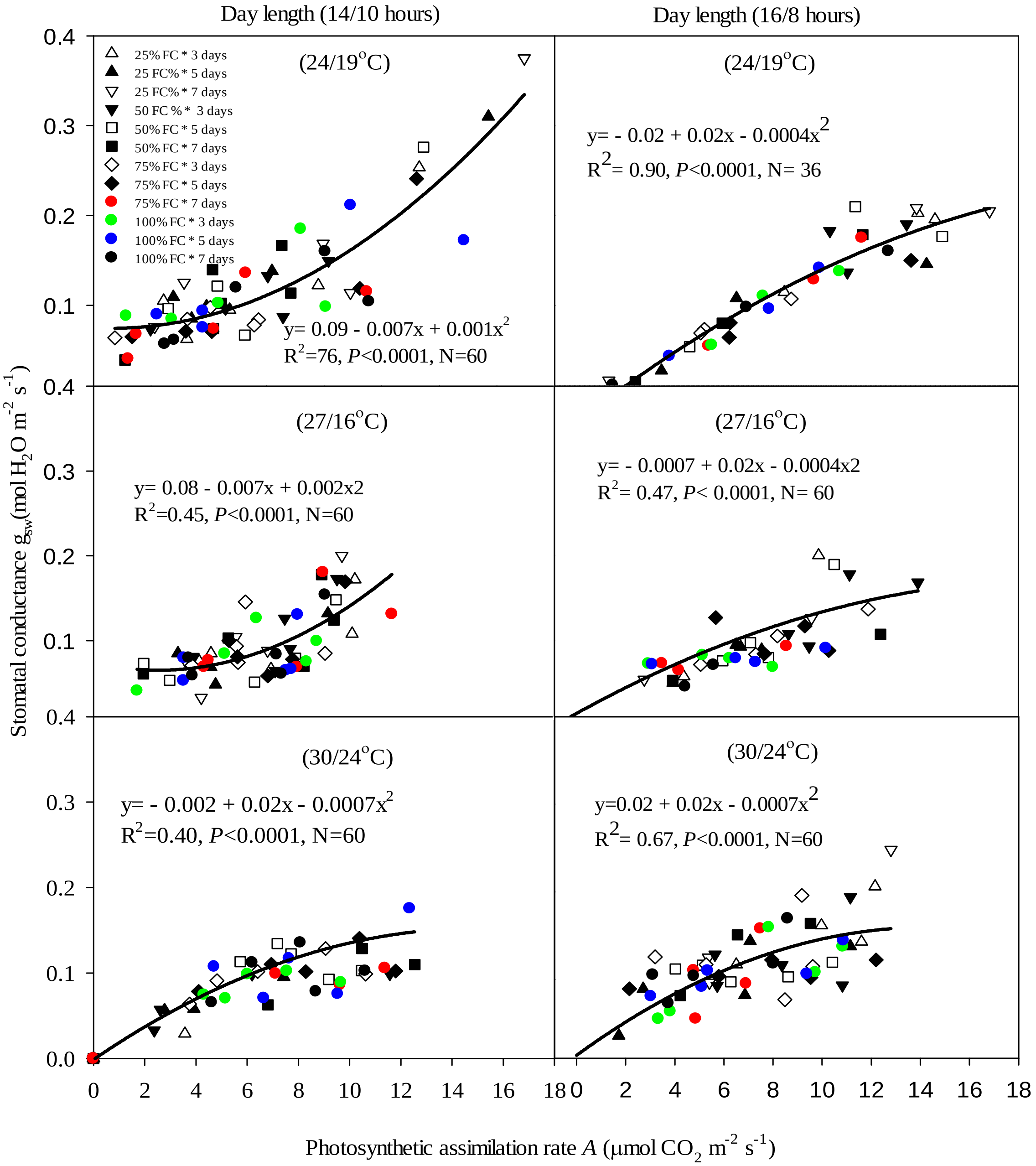

Figure 1.5. Photosynthetic assimilation rate A and stomatal conductance g_{sw} of teff plant as affected by the combinations of watering quantity (field capacity) with watering interval under the effect of the combination of day lengths and temperatures. Each value is presented five time readings over crop growth season of each combination between field capacity and watering interval at both day lengths and temperatures.

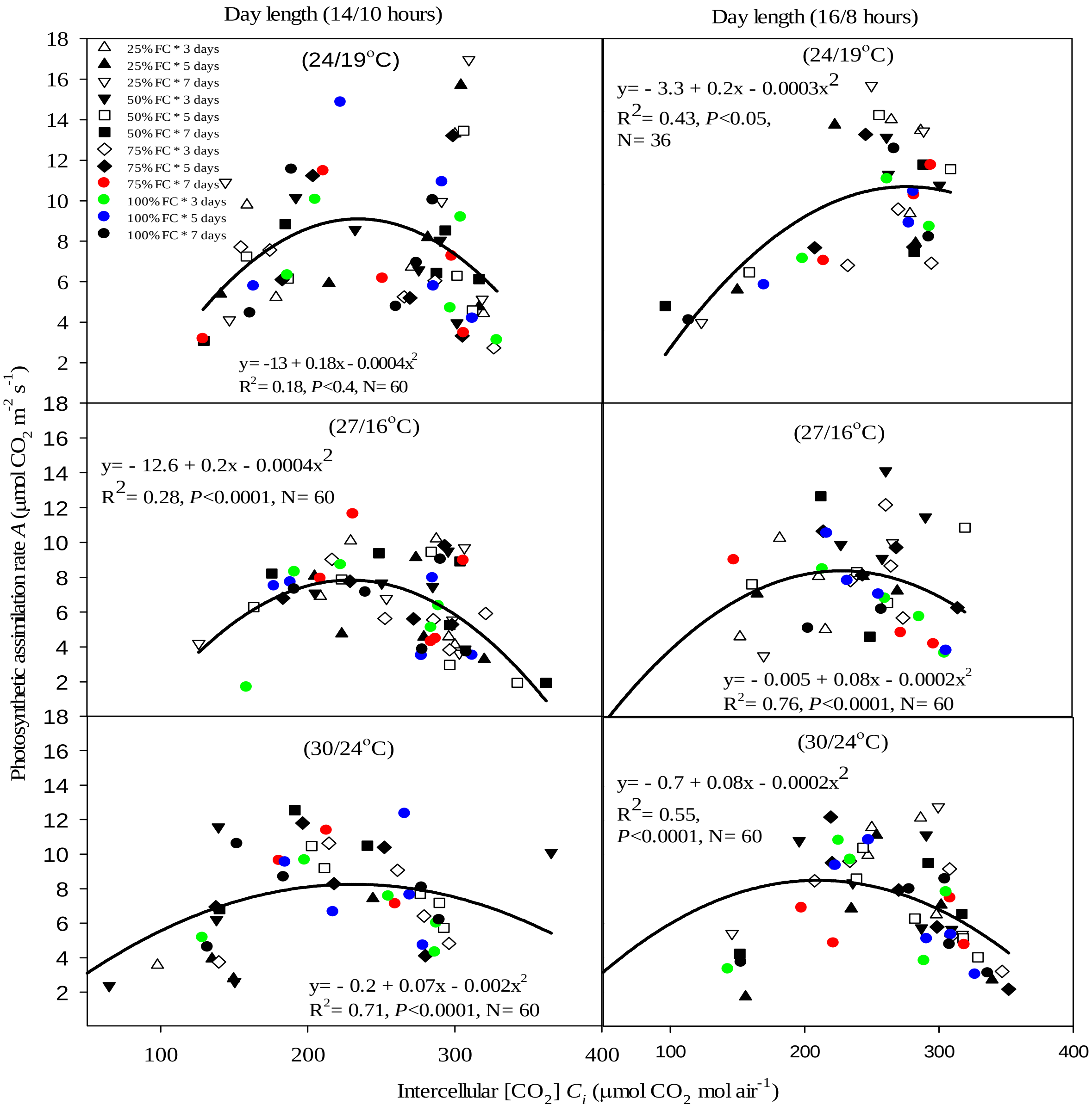

Figure 1.6. Response teff photosynthetic assimilation rate *A* to intercellular [CO_2] C_i of teff plant as affected by the combinations of watering quantity (field capacity) with watering interval under the effect of the combination of day lengths and temperatures. Each value is presented five time readings over crop growth season of each combination between field capacity and watering interval at both day lengths and temperatures.

DISCUSSION

The combination of field capacity with watering interval under the combination of temperature with day length showed that there was significantly increased tiller number, plant height, leaf number and leaf area. However, the impact of the combination treatments was not consistent. The reason for this effect in tiller number, plant height and leaf number might be due to the effect of temperature and water availability. Water stress decreased the growth and development of plant because of decreasing the level plant photosynthesis in addition to physical causes especially stomates closer, and leaf rolling that will be decreased the water-gas exchange between plant and atmosphere. Plant growth especially leaf growth and elongation is highly related to temperature and leaf elongation rate of C4 plant is correlated to temperature (13° and 36°C) (Ben-Haj-Salah and Tardieu, 1995). However, plant vegetative growth is affected by the time of the moisture and temperature stress effect in early growth stages and/or late growth stages. The results of the current study agreed with previous studies. Dejene (2009) mentioned that later moisture deficit negatively affected teff development, especially initiation of flag leaf and flowering. Escalada and Plucknett (1975) found less sorghum tillering under of 23.9/15.5°C day/night temperature and ten hours or less day length, but also found it increased at the same temperature by increasing the day length to 14 hours light. Shiferaw et al. (2012) reported that there was highly significant effect of environmental conditions (non water stress, water stress, and temperature stress) and highly correlated with teff plant height in Ethiopia. These results might due to the effect of increasing the effect of temperature by increasing day length of photoperiod as well as decreasing in amount of soil moisture. Teff is sensitive to day length and to moisture stress and high temperature (Admas and Belay, 2011; Ketema, 1997; Miller, 2010; Roseberg et al., 2005). Fahej (2012) reported that switchgrass plant height and tiller number decreased with increasing moisture stress under green house conditions.

Crop growth is sensitive to environmental conditions such as temperature, light and moisture. Water is important and essential for cell division and expansion. Both very low and high temperature caused physiological injuries to plant. Combination of temperature with short and long photoperiod can be effect the metabolism and growth of plants (Went, 1953, Escalada and Plucknett, 1975). Biomass and grain yield was affected by the combination of treatments. Day length might affect the flowering stage then negatively affect grain yield. Teff in this study responded to photoperiod more than 12 hours and that might be due to the genotype that used in this study (*Quick-E*), but in general teff is sensitive to photoperiod and that decreased the grain yield. The results of this study concur with previous studies, that teff showed flowered very well at 12 hours photoperiod in Ethiopia (Ketema, 1997; Miller, 2010; Roseberg et al., 2005) and teff's flowers failed to produce pollen grain at short daylength (8 hours light). The response of biomass and grain due to drought stress of this study agree with Teferra et al., (2000) who found decreasing in biomass and grain yield of teff under early and terminal moisture stress as compared with well watered. Water stress from anthesis to maturity is critical and affects the translocation of photosynthetic assimilation. This causes grain yield decreases, especially with increase temperature (Shpiler and Blum, 1991). Late moisture stress affected teff flowering, panicle initiation and early grain filling (Dejene, 2009). However, biomass yield was more efficient than grain yield at the highest temperature, long photoperiod, and lowest level of moisture due to these environmental conditions might affect the flowering stage more than the vegetative sages. Thus teff produced lowest grain yield than biomass yield.

Photosynthetic CO_2 assimilation A (µmol CO_2 m^{-2} s^{-1}) was highly related to water treatments and affected by temperature and photoperiod. Thus photosynthetic CO_2 assimilation decreased at high water and temperature stress. Temperature and moisture stress decreased the net assimilation of teff, bahiagrass and switchgrass (Dejene, 2009; Kakani et al, 2008; Fahej, 2012). Likewise stomatal conductance to water vapor was slightly decreased with increasing water and temperature stress. Kebede et al. (1989) reported that stoamtal conductance to water vapor and [CO_2] was slowly affected by temperature and g_{ws} increased with increasing temperature from 18 to 48°C but C_i increased at very low and very high temperature. Stomatal conductance was highly affected by water stress at the time of teff growth and switchgrass (Dejene, 2009; Fahej, 2012). C_i level was constant at all the treatments levels might due to bundle sheath increased CO_2 concentration inside plant cell in turn to phase the effect of water and temperature stress.

CONCLUSIONS

Even though the influence was not constant among the treatment combinations, this study showed that environmental conditions had a significant effect in teff growth and yield. Environment had a slight influence on tiller number per plant, and the greatest tiller number was reported at the high level of soil moisture and less time to water as well as at optimal temperature 27/16°C especially at day length 16 light/8 dark hours. Likewise, the same effect was reported for plant height, and it increased with changing day length from 14/10 hours to 16/8 hours as well increased with increasing soil moisture and time to water. Furthermore, leaf number per plant was significantly affected by the treatments. Also, Leaf area per plant was decreased with increasing temperature at the lowest soil moisture FC_{25} and least time of I7 days watering interval. Effect of day lengths on leaf area was not constant and it increased slightly at long day 16/8 hours. The economic yield (biomass and grain g pot^{-1}) was highly affected by the treatments, and biomass yield greater than grain yield. Biomass yield was significantly increased with increasing water quantity FC_{100} and FC_{75} + I3 treatments and decreased with increasing temperature and day length. In general, non orthogonal linear contrasts showed a significant response of biomass yield to treatments combinations at either day lengths. The same results were also reported for grain yield, and the low grain yield was reported at high temperature at both day lengths. In addition, soil moisture treatments were also impacted grain yield and there was almost zero at low moisture. Photosynthetic CO_2 assimilation A, stomatal conductance to water vapor g_{ws} were highly related to the combination of water treatments and slightly to temperatures and day lengths. Intercellular CO_2 concentration Ci was somewhat not affected significantly by the interaction of treatment, especially at the temperature with day length. Teff growth and yield was affected by the high temperature and long day length with very sever moisture deficit. Thus, its response to these environmental conditions can be used to improve and estimate teff grain and biomass yield in simulation model.

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CHAPTER III

RESPONSE OF TEFF BIOMASS AND GRAIN YIELDS TO SOIL WATER AVAILABILITY AND WATERING INTERVALS.

Abstract

Teff [*Eragrostis tef* (Zucc.) Trotter] is a cereal crop grown in some states in the US as a forage crop and in some parts of State of Oklahoma. Field trials were established at the Stillwater Agronomy Research Station to understand teff response to water deficit stress and to typical Oklahoma summer temperatures. Treatments were three genotypes (*DZ-Cr-387*, *Quick-E* and *Tiffany*), four soil moisture regimes (rainfed, water at field capacity (FC), 75% FC, and 50% FC), and two watering intervals (7 and 14 days). Plots were arranged in a split plot arrangement of a randomized complete block with two replications in 2011 and three replications in 2012. Whole plot were teff genotypes, and sub-plots were water treatments. Tiller number, plant height, and leaf area were highly responsive to water treatments R^2= 0.94, R^2=0.78, and R^2=0.79 respectively. Tiller number ranged 4.7, 3.4 and 2.5 tillers/ plant for *DZ-Cr-387*, *Quick-E* and *Tiffany*, respectively. Leaf area was 677, 478 and 301 cm^2 for *DZ-Cr-387*, *Quick-E* and *Tiffany*, respectively. Biomass and grain yield increased within creasing water amount and ranged

from 0.707 to 0.372 kg biomass m^{-2} and from 0.309 to 0.062 kg grain m^{-2} for 100% FC* weekly water and rainfed respectively. *Quick-E* produced the highest grain yield 0.234 kg m^{-2}. Water use efficiency (WUE) of biomass and grain significantly responded to water treatments R^2=0.58 and R^2=0.92, respectively. *Quick-E* was highly tolerant to drought and produced grain and biomass in the presence of drought. Teff might be adopted by producers as forage under high water deficit and used to produce grain with acceptable amount of rain in Oklahoma.

INTRODUCTION AND LITERATURE REVIEW

Teff [*Eragrostis tef* (Zucc.) Trotter] is a major cereal crop in Ethiopia and represents approximately 25-30% of cereal production in Ethiopia. It can be grown under 300 mm to 1000 mm of rainfall (Debelo, 1992; Admas and Belay, 2011). Temperature, light, soil type, and soil moisture affecte teff growth and yield, as any other crop. Teff is grown in many countries around the world such as India, Australia, New Zealand, Argentina, Zimbabwe, Kenya, and Zaire. It was introduced by Ethiopian immigrants to California in 1962 (Tadesse, 1975). Approximately 250,000 acres in the US in 2008-2009 were planted to teff as a summer forage crop, with acres mostly concentrated in the Midwestern and Southeastern United States (Millar, 2010). The crop grows well in wide ranges of ecologies and soil types but Veritsols such as *Heiden clay* located in the SE corner of Oklahoma and *Osage clays* in the NE corner have greatest potential for teff (Keith Boevers and Jerry Chandler, personal communication).

Diversification of crop enterprises is an effective strategy for achieving agricultural sustainability. Crop diversification can increase crop production, helps to build soil health, and minimize weed and pest populations by interfering with their life cycle (Katema, 1997; Ghebrehiwot et al., 2008). Above all, crop diversification increases income per unit area and enhances the economy of local communities.

Teff gives reasonable yield when other cereals yield is depressed under low or excess moisture conditions (Hunter et al., 2007). According to Belayneh (1986), teff in Ethiopia produced 106% more yield than wheat in waterlogged and unfertilized conditions and 70% greater in fertilized and waterlogged conditions. Teff makes excellent quality hay and can be grown for grain and forage for horses, cattle and sheep (Hunter et al., 2007; Nsahlai et al., 1998; Twidwell et al., 2002). In fact, sheep and horse preferentially feed on teff hay (Keith Boevers and Jerry Chandler, personal communication).

Several preliminary experiments have been conducted prior to the current experiment in Central Oklahoma to evaluate suitability of teff as an alternative crop. Six and ten varieties were evaluated in 2009 and 2010, respectively, for forage and grain production by Girma (2009), who determined the spring temperature determines the establishment and growth of early-planted teff for forage/hay and grain. Some varieties (*Quick-E* and *DZ-01-99*) performed well during the hot summer (Girma, et al., 2012; Reinert, 2012), and all varieties performed well after the heat index dropped below 90. Evertt et al. (2009) reported that temperature did not influence final plant population or biomass production of teff. Optimal temperature for teff was 26.7- 32.3°C, and teff growth was very slow at 15.5- 23.4°C (Roseberg et al., 2005). Teff germinated very well at 15.5°C soil temperature with a frequent irrigation for 2-3 weeks from planting until the establishment of the root system (Davison et al., 2011).

Acceptable teff grain yield was obtained with a minimum 432 mm of rain per season in Ethiopia, and in general teff needs at least 610 mm of rain per season to achieve the highest grain and forage yield (Hunter et al., 2007; Millar, 2010). In Ethiopia, teff grain yield of different genotypes was decreased under stress. Yield of *Denkeye* and *DZ-Cr-387* genotypes ranged from 55 to 100 g m^{-2} under stress and yield of *Rubicunda* and *DZ-01-974* genotypes ranged from 108 to 203 g m^{-2} under non-stress condition (Shiferaw et al., 2012). Eckhoff et al., (1993) and Stallknecht et al., (1993) reported that teff grain yield in Montana was (700 and 1400 kg ha^{-1}) under drought and irrigation conditions respectively. Shiferaw et al., (2012) reported that total biomass yield of *Addisie* and *DZ-01-974* genotypes was 537 to 866 g m^{-2} respectively under stress compared with 737 to 1056 g m^{-2} for *Rubicunda* and *DZ-01-974* genotypes under non-stress conditions. In Oregon State, forage yield of teff required at least 102-254 mm of irrigation water for each cutting, and in Nevada and California the minimum amount of water was 610 mm per season (Davison et al., 2011). Teff forage yield in Montana was increased by 13.8 tons ha^{-1} by irrigation compared with drought land, and the grain yield ranged from 0.2 to 1.5 ton ha^{-1} under drought land conditions (Stallknecht et al., 1993). Approximately 69 to 77% of teff grain yield is lost under drought conditions in Ethiopia (Takele, 1997, 2001). Other studies have shown tiller number, shoot biomass, root number and weight and grain yield to be significantly decreased at low soil moisture (Admas and Belay, 2011). Shiferaw and Baker (1996a) reported that in Ethiopia about 14% of teff grain yield was lost to drought conditions. Effect of stress, especially water stress in leaf stomata and photosynthetic assimilation of teff was observed in some studies in Ethiopia. Water stress had more effect on stomatal conductance than on photosynthetic rate (Shiferaw and Baker, 1996b; Abuhay et al., 2001). Abuhay et al., (2001) reported that teff germination increased with increasing soil moisture from 25% to 85% of field capacity. A study in Japan showed that there were a significant effect of soil water potential (-2.0 MPa) and severe soil water stress in relative growth rate, leaf water potential, and leaf rolling in all teff genotypes (Degu et al., 2008).

Producers are interested in growing teff for grain and hay in some parts of Oklahoma and preliminary studies in Kingfisher, Hennessey, Morrison, and Perry clarified some of the challenges for teff production in Oklahoma. High temperature, lack of rainfall, and high humidity of Oklahoma weather in summer make it important to study teff in this area to understand if teff will produce acceptable biomass and grain yield. The objectives of this study were:

1- Evaluate the impact of soil moisture at different level of soil field capacity at watering intervals on the growth of teff as compared to a non-irrigated treatment (rainfall).
2- Determine the best time to estimate teff biomass and grain yields by using NDVI measurements.
3- Evaluate drought susceptibility index (DSI) and cumulative stress relative index (CSRI) of teff varieties.

MATERIALS AND METHODS

The field experiment was initiated at the Stillwater Agronomy Research Station in 2011 and repeated in 2012. Treatments included three genotypes (*DZ-Cr-387*, *Quick-E* and *Tiffany*), four soil moisture regimes {rainfed, water at field capacity (FC_{100}), 75% of FC (FC_{75}), and 50% of FC (FC_{50})} treatments and two watering intervals 7 days (1W) and 14 days (2W) treatments. Experimental design was split plot arranged in a randomized complete block design with two replications in 2011 and three replications in

2012. Whole plots were teff genotypes and sub-plots were the interaction of field capacity treatments with watering intervals. Plot size was 1.53 m by 3.05 m within a 1.53 m alley between plots. Each plot was surrounded by soil berms to keep irrigation water inside the plot (Figure 2.1.A). For the soil moisture treatments, a 0.61 m by 0.31 m micro plot with depth 0.304 m was set up to contain lateral water movement using custom designed (13 mm thickness) iron sheet (Figure 2.1.B).

Field capacity was determined using methods similar to Anderson and Ingram (1993). Micro plots were covered by a plastic sheet (0.4 cm thickness) to protect the area from rainfall (Figure 2.1.C). Teff was manually planted as broadcast in 1 May 2011 and 26 May in 2012. Two teff varieties '*Quick-E* and *DZ-Cr-387*' were used in 2011. In 2012 '*Quick-E* and *Tiffany*' were used due to unavailability of *DZ-Cr-387*. *Quick-E* and *DZ-Cr-387* were harvested in 15 August and 2 September in 2011. *Quick-E* and *Tiffany* were harvested in 15 September and 1 October in 2012. Harvesting was performed by using sickle and electric clipper (AccuPower 100, Gardena model 8805, 4-Inch). Crop and weather related data were collected throughout the study period from the weather station 150 m away from the field (Table 2.1).

Each plot received 65 kg N $h^{-1}$and 50 kg P h^{-1} in the form of urea and triple superphosphate. One-third of N was applied as pre-plant and the two third was applied after the tillering stage and P was applied as pre-plant.

Crop related measurements included number of tillers per plant at tillering stages (4-5 weeks from planting date), plant height (cm) at harvesting, leaf area (cm^2) before flowering stage by using LI-3000 leaf area meter (LI-COR, Lincoln, Nebraska USA), and total biomass and grain yields kg per m^2. Biomass and grain yield per micro plot was measured and included with whole final plot results. The plot area was 4.7 m^2. After harvesting teff was dried at 42°C for 7-10 days in a forced-air dryer and then weighted to determine biomass yield. Dried teff was threshed using a custom made belt thresher, and teff seeds were cleaned to determine the grain yield. Normalized difference vegetative index (NDVI) was measured 7 times throughout the growing season by using green seeker (Ukiah, CA, USA) fitted with hp iPAQ (pocket PC 2003 prem).

Polynomial linear (equation 1) and quadratic (equation 2) models were used to determine the relationship of grain and biomass yields and treatment.

$$(Y = a + ax) \qquad 1$$

$$(Y = y0 + ax + bx^2) \qquad 2$$

A soil moisture tensiometer (2725 ARL12 JET FILL, CA, USA) was used to measure soil water tension (water potential KPa) at a 0.30 m depth in each plot (Figure 2-1-D) every week starting at watering interval initiation (10 days from planting). The amount of irrigation water (Table 2.2) was calculated by using a portable soil moisture meter (TDR 300, IL USA) fitted with a 20 cm probe to determine volumetric water content (VWC) in soil.

Drought susceptibility index (DSI) (Fischer and Maurer, 1978) of teff varieties was calculated using the following formula:

$$\mathrm{DSI} = \left(\left\{ \frac{1 - \mathrm{Ys}}{\mathrm{Yc}} \right\} \Big/ \left\{ \frac{1 - \mathrm{Yas}}{\mathrm{Yac}} \right\} \right)$$

where, Ys and Yc = biomass or grain yields of stress plot (rainfed plot) and non-stress plot (watering plot) of given variety respectively, and Yas and Yac= average biomass or grain yields of all varieties of stress plot and non-stress plot respectively.

A cumulative stress response index (CSRI) was also calculated using the following formula as described by (Dai et al., 1994; Koti et al., 2004):

$$\mathrm{CSRI} = \left(\begin{array}{l} \frac{\mathrm{TNs} - \mathrm{TNc}}{\mathrm{TNc}} + \frac{\mathrm{PHs} - \mathrm{PHc}}{\mathrm{PHc}} + \frac{\mathrm{LAs} - \mathrm{LAc}}{\mathrm{LAc}} + \frac{\mathrm{YBs} - \mathrm{YBc}}{\mathrm{YBc}} + \\ \\ \frac{\mathrm{YGs} - \mathrm{YGc}}{\mathrm{YGc}} + \frac{\mathrm{EPSIIs} - \mathrm{EPSIIc}}{\mathrm{EPIIc}} + \frac{\mathrm{EYQs} - \mathrm{EYQc}}{\mathrm{EYQc}} \end{array} \right) \times 100$$

where, TN= tillers number, PH= plant height, LA= leaf area, YB= biomass yield, YG= grain yield, EPSII= efficiency of PSII, EYQ= yield of quantum efficiency, $_{C}$= control treatment (water quantity treatments plot), and $_{S}$= stress treatment (rainfed plot).

Water use efficiency (WUE) of the teff crop was also established as describe by the equation of Viest (1962),

$$\mathrm{WUE} = \frac{\text{grain or biomass yield (kg)}}{\text{water amount (mm)}}$$

A chlorophyll fluorometer (OS1-FL, NH USA) was used to measure the physiological variables Fo; minimal fluorescence (arbitrary unit), Fm= maximal fluorescence (arbitrary unit), Fv= variable fluorescence, Fv/Fm= photosynthetical efficiency of PSII, F_{VS}= Fluorescence under steady state conditions (arbitrary unit), Fms= maximal fluorescence under steady state conditions (arbitrary unit), and yield= yield of quantum efficiency (Fms/Fvs).

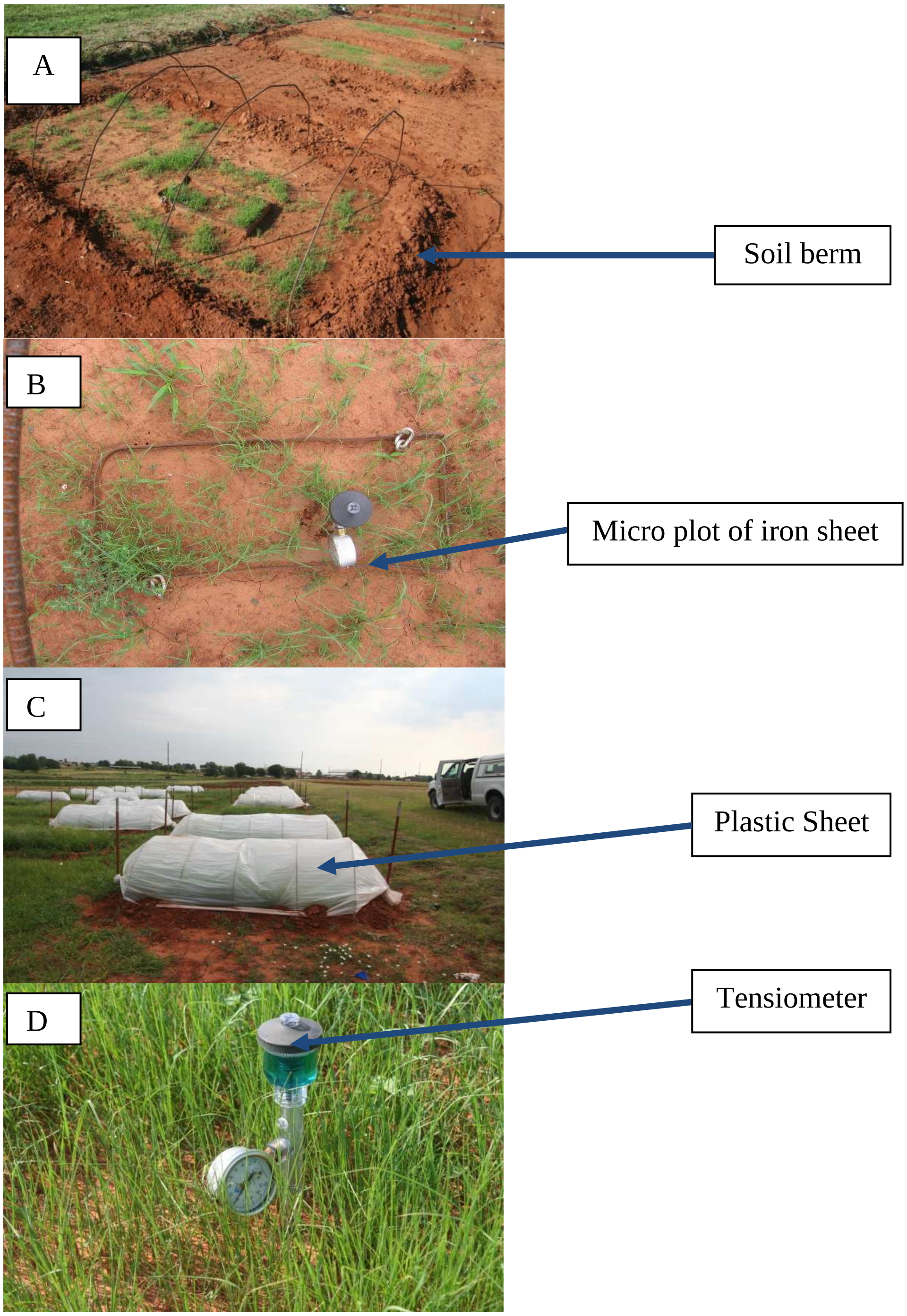

Figure 2.1. Soil berm, iron sheet, plastic sheet, and soil moisture tensiometer.

Table 2.1. Average maximum and minimum (°C) air temperature and relative humidity (%) and total rainfall (mm) from May to September, 2011 and 2012 at Stillwater, Oklahoma.

Year	Month	Temperature (°C)[†]			Relative humidity (%)			Total rainfall (mm)
		Max.[‡]	Min.	Ave.	Max.	Min.	Ave.	
2011	May	26	14	20	87	49	70	99.3
	June	36	22	29	87	49	70	43.4
	July	40	25	32	71	23	45	18.5
	August	39	23	31	79	25	49	38.1
	Average and total rain	35	21	28	81	37	58	199.4
2012	May	29	16	23	87	38	62	28.4
	June	32	19	26	87	40	62	54.9
	July	38	23	31	72	24	46	1.8
	August	35	20	27	79	25	50	67.1
	September	31	17	23	84	34	58	27.9
	Average and total rain	33	19	26	82	32	56	180.1

† Source of data (http://www.mesonet.org; http://www.mesonet.org/index.php/weather/daily_data_retrieval).

‡ Max, Min, and Ave.= maximum, minimum and average respectively.

Table 2.2. Total amount of water (Liter) added to each plot of teff plant based on the combination of field capacity and watering interval at Stillwater, OK at growing seasons 2011 and 2012.

Treatment	Growing season	
	2011	2012
	-------------------Liter plot^{-1}------------------	
1 weeks (1W)†		
FC_{100}‡	5878	6964
FC_{75}	3654	4109
FC_{50}	1999	2523
2 weeks (2W)		
FC_{100}	7489	8234
FC_{75}	4013	5823
FC_{50}	2370	3846

† 1W and 2W= Watering interval every 1 and 2 weeks.
‡ FC= Field capacity at 100%, 75%, and 50%.

RESULTS

Morphological Variables

Analysis of variance (Table 2.3) showed that years and treatment had highly significant effect ($P< 0.001$) on tiller number per plant, plant height (cm), and leaf area (cm^2). Tiller number and leaf area were significantly different ($P<0.01$, and $P<0.05$ respectively) among varieties.

Tillers per plant increased with increasing water quantity as well as with increased frequency of watering, thus the greatest tiller number was (3.4 tillers $plant^{-1}$) at treatment of the combination of FC_{100} + 1W. The lowest number of tillers was (2.4 tillers $plant^{-1}$) at the non-irrigated treatment. Tiller number decreased with decreased soil moisture thus tiller number at FC_{100} (4 tiller $plant^{-1}$) was higher than tiller number at FC_{75} and FC_{50} (3.5 and 3 tiller $plant^{-1}$, respectively). *DZ-Cr-387* had the highest number of tillers (4.7 tillers $plant^{-1}$) compared to *Tiffany* (2.5 tillers $plant^{-1}$). A highly significant linear contrast of variety and treatment was obtained on tillers per plant with high response of tillers to treatments and variety $R^2=0.94$; N=70; at $P<0.001$ respectively (Table 2.4).

Plant height was reduced by some treatments ($P<0.001$), and ranged from 62.9 to 81.5 cm for non-irrigated and the combination FC_{100} + 1W treatment. Over all, the highest soil moisture (FC_{100}) had the greatest plant height 79 cm compared to the lowest soil moisture FC_{75} and FC_{50} (76 and 71 cm, respectively). Also, plant height decreased from (77 to 74 cm) with decreased the watering frequency from 1W to 2W. Although, the analysis of variance showed no significant effect of variety on plant height, a linear correlation response ($R^2 = 0.78$; N=70; at $P<0.01$) of plant height to variety was observed (Table 2.4).

The greatest leaf area was 618.6 cm^2 for the treatment of the combination of FC_{100} + 1W compared with 248.4 cm^2 for the non-irrigated treatment. Leaf area decreased from 577 to 478 and 449 cm^2 with decreasing field capacity from FC_{100} to FC_{75} and FC_{50}, respectively. Also, the largest leaf area was 524 cm^2 at 1W compared to 479 cm^2 at 2W. The lowest leaf area was (198.7 and 376.2 cm^2) of *Quick-E* and *Tiffany* variety, respectively, compared with *DZ-Cr-387* (677.6 cm^2). There was a significant linear relation contrast of leaf area to treatments and variety ($R^2=0.79$; N=70; at $P<0.001$ and $P>0.05$), which means that leaf area was significantly affected by treatments and varieties.

Table 2.3. Analysis of variance (PROC GLM) and means separation for tillers per teff plant at tillering stage (4-5 weeks from planting date), teff plant height (cm) at harvesting stags, and leaf area (cm^2) of teff before flowering stage as affected by year, variety and the combination of water quantity (field capacity) with watering interval treatments at Stillwater, OK, 2011-2012.

Source of Variation	DF[†]	Tiller number/ plant	Plant height (cm)	Leaf area (cm^2)
Replication (Year)	3	NS[‡]	NS	*
Year	1	***	***	***
Variety	2	**	NS	*
Treatment	6	***	***	***
Variety X Treatment	12	NS	NS	NS

Treatment	Treatment Means		
	Tiller number	Plant height	Leaf area
		-----cm-----	----cm^2----
1 week (1W)[§]			
FC_{100}[¶]	4.3 a[††]	81.5 a	618.6 a
FC_{75}	3.7 b	77.1 ab	462.7 bc
FC_{50}	3.1 c	71.4 c	489.7 bc
2 weeks (2W)			
FC_{100}	3.8 b	76.0 bc	535.3 ab
FC_{75}	3.4 c	74.2 bc	493.9 bc
FC_{50}	3.0 c	71.3 c	409.2 c
Non-irrigated[#]	2.4 d	62.9 d	248.4 d
Duncan's multiple range	0.36	5.3	122.7
DZ-Cr-387	4.7 a	81.5 a	677.6 a
Quick-E	3.4 b	72.6 b	478.9 b
Tiffany	2.5 c	69.7 b	301.4 c
Duncan's multiple range	0.25	NS	83.4

[†] DF= degree of freedom.

[‡] *, **, ***, and NS= nonsegnificant and significant at 0.5, 0.01, and 0.001 respectively.

[§] WI= watering interval every one and two weeks.

[¶] FC= field capacity at 100, 75, and 50%.

[#] Non-irrigated= rain treatment.

[††] Means followed by a common letter in a column are not statistically different alpha = 0.05 using Duncan’s multiple range test.

Table 2.4. Linear and quadratic contrast and response of NDVI, tillers number per plant at tillering stage of teff plant, teff plant height (cm) at harvesting stage, and leaf area (cm^2) of teff plant (before flowering stage) to variety and the combination of water quantity (field capacity) with watering interval treatments, at Stillwater, Ok, 2011-2012.

Contrast	Variable Factors					
	NDVI-1[†]	NDVI-4	NDVI-7	Tiller number	Plant height	Leaf area
Linear						
Variety	***[‡]	**	**	***	**	*
Treatment	***	***	***	***	***	***
Quadratic						
Variety	NS	NS	*	NS	NS	NS
Treatment	*	NS	NS	NS	NS	NS
R-Square	0.69	0.72	0.70	0.94	0.78	0.79
C.V. (%)[§]	14.97	17.15	16.55	10.8	7.4	26.95
Number of Observations	70	70	70	70	70	70

† NDVI= normalized difference vegetative index at three weeks after planting (NDVI-1), four weeks from emergence (NDVI-4), and flowering stage (NDVI-7).

‡ NS, *, **, and ***= nonsegnificant and significant at 0.5, 0.01, and 0.001 respectively.

§ C.V.= coefficient variance.

Biomass and Grain Yield

Biomass yield was not affected by year, and there was no difference among varieties in biomass production. Treatments had a significant effect ($P<0.01$) on biomass yield (Table 2.5). Biomass productivity increased with increasing the soil moisture, thus the maximum and minimum yields were 0.707 and 0.372 kg m^{-2} at FC_{100} + 1W and at non-irrigated respectively. In general, the trend biomass yield increased with increasing field capacity 0.501, 0.512 and 0.629 kg m^{-2} for FC_{50}, FC_{75} and FC_{100}, respectively, and increased with increasing frequency for watering interval 0.604 and 0.490 kg m^{-2} for watering weekly and every two weeks, respectively. A significant linear relation of biomass yield with treatments ($P<0.001$) and with varieties ($P<0.05$) was observed with a significant correlation response (R^2= 49; N=70) (Table 2.5).

NDVI readings were analyzed statistically using stepwise regression procedure in SAS to choose the NDVI measurement timing to estimate biomass yield. The early reading of NDVI at four weeks from emergence (NDVI-4) was the best time to estimate biomass yield (Table 2.4). There was a significant linear correlation of variety and treatment to NDVI-4 ($P>0.01$ and $P>0.001$ respectively) with a significant single response (R^2= 0.72; N= 70). A significant linear and quadratic response of biomass yield to treatments was reported, and water use efficiency of biomass (kg biomass m^{-2} mm^{-1}) was highly significant ($P<0.001$) with a significant single regression response (R^2= 0.92, N= 70) (Table 2.6).

Grain yield was significantly affected by year, variety, treatment and combination of variety with treatment (Table 2.5). Grain yield decreased with decreasing field capacity, and the maximum and minimum grain yield was 0.309 and 0.062 kg m^{-2} at the combination of FC_{100} + 1W and rainfed treatments, respectively. Trend of grain production increased with increasing field capacity by 31% and 50% at FC_{100} compared to FC_{75} and FC_{50}, respectively. Also, grain yield increased by 26% at 1W watering compared to 2W watering. *Quick-E* variety produced the highest yield (0.234 kg m^{-2}) compared with *DZ-Cr-387* (0.129 kg m^{-2}) and *Tiffany* (0.081 kg m^{-2}). In general, average grain yield of varieties was (0.148 kg m^{-2}) compared with biomass yield (0.531 kg m^{-2}).

The best NDVI readings to estimate grain yield was NDVI-1 (three weeks after planting) and NDVI-7 (flowering stage). NDVI-1 highly linear related to grain yield of variety and treatment ($P<0.001$ and $P<0.01$ respectively) with a significant single regression response (R^2= 0.69, N= 70). Likewise, grain yield response to NDVI-7 was a significant linear and quadratic contrast at variety and was linear at treatments (R^2= 0.70, N= 70; at $P>0.01$, $P>0.001$, and $P>0.05$, respectively) (Table 2.4). Grain yield responded linearly to variety and treatment with a significant single contrast (R^2= 92; N= 70; at $P<0.01$), and WUE of grain yield was significant response to water quantity (field capacity) with watering interval treatments (R^2=58; N=70; at $P<0.01$) (Table 2.6).

Table 2.5. Analysis of variance (PROC GLM) and separation means of biomass and grain yields (kg m^{-2}) of teff plant as affected by year, variety and the combination of water quantity (field capacity) with watering interval treatments at Stillwater, Ok, 2011-2012.

Source of Variation	DF[†]	Biomass yield kg m^{-2}	Grain yield kg m^{-2}
Replication (Year)	3	NS[‡]	**
Year	1	NS	*
Variety	2	NS	***
Treatment	6	**	***
Variety X Treatment	12	NS	NS

Treatment	Treatment Means	
	Biomass yield	Grain yield
	------------------------kg m^{-2}---------------------	
1 week (1W)[§]		
FC_{100}[¶]	0.707 a[††]	0.309 a
FC_{75}	0.564 b	0.211 b
FC_{50}	0.540 b	0.146 c
2 weeks (2W)		
FC_{100}	0.550 b	0.222 b
FC_{75}	0.459 bc	0.153 c
FC_{50}	0.462 bc	0.117 c
Non-irrigated[#]	0.372 c	0.062 d
Duncan's multiple range	0.144	0.039
DZ-Cr-387	0.534 a	0.129 b
Quick-E	0.491 a	0.234 a
Tiffany	0.567 a	0.081 c
Duncan's multiple range	NS	0.027

[†] DF= degree of freedom.

[‡] *, **, ***, and NS= nonsegnificant and significant at 0.5, 0.01, and 0.001 respectively.

[§] WI= watering interval every one and two weeks.

[¶] FC= field capacity at 100, 75, and 50%.

[#] Non-irrigated= rain treatment.

[††] Means followed by a common letter in a column are not statistically different at alpha = 0.05 using Duncan’s multiple range test.

Table 2.6. Linear and quadratic contrast and response of biomass and grain yields (kg m^{-2}) of teff plant, and water use efficiency (kg $plot^{-1}$ mm^{-1}) of teff plant to variety and the combination of water quantity (field capacity) with watering interval treatments at Stillwater, Ok, 2011-2012.

Contrast	Variable Factors			
	Biomass Yield	Grain Yield	WUE of Grain[‡]	WUE of biomass
Linear				
Variety	*[†]	**	NS	NS
Treatment	***	**	**	***
Quadratic				
Variety	NS	NS	NS	NS
Treatment	NS	*	**	***
R-Square	0.49	0.92	0.58	0.92
C.V. (%)[§]	29.2	22.1	331.1	92.4
Number of Observations	70	70	70	70

† NS, *, **, and ***= nonsegnificant and significant at 0.5, 0.01, and 0.001 respectively.
‡ WUE= water use efficiency of grain and biomass yields.
§ C.V= coefficient variance.

Soil water potential (KPa) had a significant effect on biomass and grain yield, but grain yield was more affected by the water amount in soil than biomass yield (Figure 2.2). Response of biomass and grain yield to water potential was polynomial (linear) and there were significantly correlated (R^2= 0.95 and R^2= 0.92, respectively). In general, soil water potential more than -75 KPa had significant effect to decreased the biomass and grain yield of teff, thus, teff grew well with acceptable biomass yield (≈ 450 kg m^{-2}) and grain (≈ 150 kg m^{-2}) under soil water potential -75 KPa. With decreasing soil water potential less than (-75 KPa), biomass and grain yield increased significantly. However, teff grew well under soil water potential ranged from -25 Kpa to about -100 KPa (Figure 2.3) and produced acceptable biomass and grain yield.

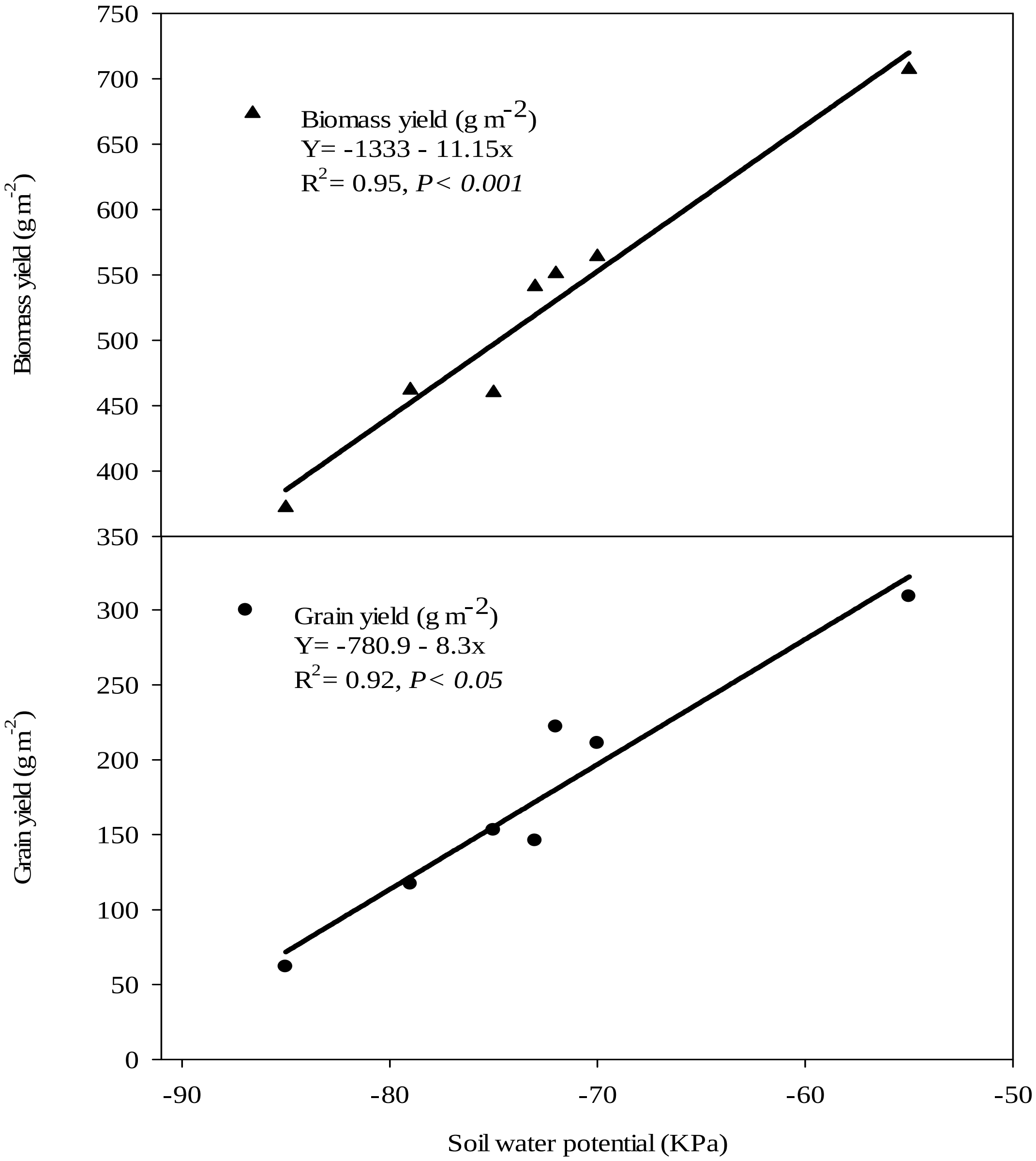

Figure 2.2. Trend of biomass and grain yields (g m^{-2}) of teff plant as affected by water potential (KPa). Each point is the average of eleven readings of each combination of water quantity (field capacity) with watering interval during growth seasons at Stillwater, Ok, 2011-2012.

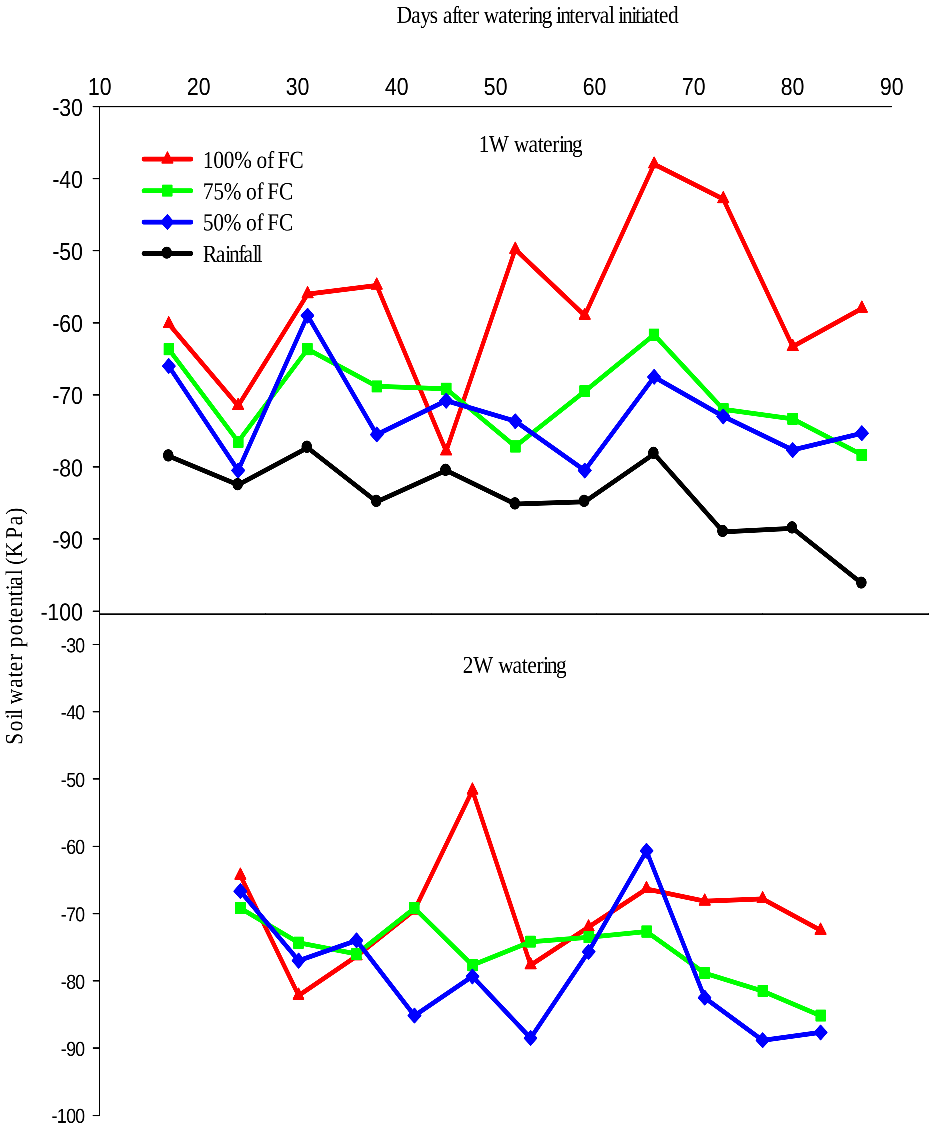

Figure 2.3. Soil water potential of water quantity (field capacity) at every one week and two weeks watering interval over teff plant growing seasons at Stillwater, Ok, 2011-2012.

Photosynthesis and physiological resistance related traits

The analysis of variance showed that there was no significant difference among varieties or between years on yield of quantum efficiency (Fms/F_{VS}), but water treatments had a significant effect ($P< 0.05$) on Fms/F_{VS} (Table 2.7).

Yield of quantum efficiency decreased with increasing the intervals between irrigations and ranged from 0.513 to 0.498 for weekly and every two weeks watering, respectively. Likewise, the greatest yield of quantum efficiency was 0.522 at the combination of FC_{100} + 1W treatment compared with the non-irrigated treatment 0.480 with a significant correlation (R^2= 0.36 at $P<0.05$). The same trend was observed in photosynthetic efficiency of PSII, and it increased with increasing water quantity (field capacity) and ranged from 0.519 at the combination of FC_{100} + 1W and the combination of FC_{75} + 1W treatments compared to 0.482 at non-irrigated treatment with positive correlation response (R^2= 0.35 at $P<0.05$).

Results of cumulative stress response index (CSRI) showed that CSRI ranged -269.3 to -146.6 at the combination of FC_{100} + 1W and at the combination of FC_{50} + 2W treatments. CSRI of teff varieties ranged from -186.8, -231.7 to -249.1 for *Quick-E, DZ-Cr-387* and *Tiffany*, respectively. However, CSRI increased with increasing water quantity and watering interval (Table 2.8). Thus *Quick-E* was considered as tolerant variety to water stress compared to other varieties, and in general, teff is water stress tolerant depending upon the results of current study.

Drought stress among varieties was evaluated using drought stress index (DSI) to estimate performance of varieties under stress (Table 2.9). DSI of biomass production was 0.6 to 0.9 for all varieties, and *Quick-E* had the greatest DSI which ranged from 0.6 to 0.9 compared to other varieties. Likewise, *Quick-E* showed the best DSI of grain which ranged from 0.3 to 0.6 compared with *DZ-Cr-387* ranged from 2.0 to 2.8 and *Tiffany* ranged from 2.1 to 4.6.

Table 2.7. Analysis of variance (PROC GLM) and separation means of yield of quantum efficiency and photosynthetical efficiency of PSII of teff plant as affected by year, variety and the combination of water quantity (field capacity) with watering interval treatments at Stillwater, Ok, 2011-2012.

Source of Variation	DF[†]	Yield of quantum efficiency	Photosynthetical efficiency of PSII[§]
Replication(Year)	3	***[‡]	***
Year	1	NS	*
Variety	2	NS	NS
Treatment	6	*	*
Variety X Treatment	12	NS	NS
Treatment		Treatment Means	
		Yield of quantum efficiency	Photosynthetical efficiency of PSII
1 week (1W)[¶]			
	FC_{100}[#]	0.522 a[‡‡]	0.519 a
	FC_{75}	0.513 ab	0.519 a
	FC_{50}	0.506 ab	0.512 ab
2 weeks (2W)			
	FC_{100}	0.510 ab	0.492 bc
	FC_{75}	0.496 bc	0.508 ab
	FC_{50}	0.489 bc	0.488 bc
Non-irrigated[††]		0.480 c	0.482 c
Duncan's multiple range		0.023	0.024
DZ-Cr-387		0.500 a	0.502 a
Quick-E		0.502 a	0.500 a
Tiffany		0.506 a	0.507 a
Duncan's multiple range		NS	NS
R square		0.36	0.35
C.V.(%)		14.5	14.7

† DF= degree of freedom.

‡ *, **, ***, and NS= nonsegnificant and significant at 0.5, 0.01, and 0.001 respectively.

§ PSII= photosystem 2.

¶ WI= watering interval every one and two weeks.

FC= field capacity at 100, 75, and 50%.

†† Non-irrigated= rain treatment.

‡‡ Means followed by a common letter in a column are not statistically significant at alpha = 0.05 using Duncan's multiple range test.

Table 2.8. Cumulative stress response index (CSRI) of tillers number at tillering stage (4-5 weeks from planting date), plant height at harvesting stage, leaf area before the flowering stage, biomass and grain yield, yield of quantum efficiency, and photosynthetical efficiency of PSII of teff plant under the effect of the combination of water quantity (field capacity) with watering interval treatments and the effect of varieties at Stillwater, Ok, 2011-2012.

Treatment	Stress response index (SRI)							CSRI[‡]
	Tiller number	Plant height	Leaf area	Biomass yield	Grain yield	Yield of quantum efficiency	Photosynthetical efficiency of PSII	
1 week WI								
FC_{100}[†]	-44.2	-22.8	-59.8	-47.4	-79.9	-8.0	-7.1	-269.3
FC_{75}	-35.1	-18.4	-46.3	-34.0	-70.7	-6.4	-7.1	-218.2
FC_{50}	-22.6	-11.9	-49.3	-31.1	-57.5	-5.1	-5.9	-183.4
2 weeks WI								
FC_{100}	-36.8	-17.2	-53.6	-32.4	-72.1	-5.9	-2.0	-220.1
FC_{75}	-29.4	-15.2	-49.7	-19.0	-59.5	-3.2	-5.1	-181.1
FC_{50}	-20.0	-11.8	-39.3	-19.5	-47.0	-1.8	-1.2	-140.6
DZ-Cr-387	-32.1	-27.8	-39.1	-42.5	-82.1	-4.4	-3.7	-231.7
Quick-E	-32.6	-15.6	-58.4	-39.2	-34.9	-3.2	-2.9	-186.8
Tiffany	-37.0	-9.1	-45.9	-81.1	-69.9	-3.6	-2.5	-249.1

† FC_{100}, FC_{75} and FC_{50} = treatment at 100, 75 and 50% of field capacity.

‡ CSRI= Cumulative stress response index.

Table 2.9. Drought susceptibility index (DSI) of biomass and grain yields of teff varieties under the effect of the combination of water quantity (field capacity) with watering interval at Stillwater, Ok, 2011-2012.

Treatment	Quick-E		DZ-Cr-387		Tiffany	
	DSI[†] of biomass	DSI of Grain	DSI of biomass	DSI of Grain	DSI of biomass	DSI of Grain
1 week (1W)						
FC_{100}[‡]	0.7	0.5	0.6	2.1	0.7	4.2
FC_{75}	0.7	0.5	0.7	2.1	0.6	2.1
FC_{50}	0.8	0.4	0.7	2.5	0.7	2.3
2 weeks (2W)						
FC_{100}	0.9	0.4	0.7	2.4	0.7	4.6
FC_{75}	0.6	0.3	0.6	2.0	0.6	2.2
FC_{50}	0.8	0.6	0.7	2.8	0.6	2.6

[†] DSI = Drought susceptibility index

[‡] FC_{100}, FC_{75} and FC_{50} = treatment at 100, 75 and 50% of field capacity.

DISCUSSION

The observation of effect of high temperature coupled with low soil moisture might affect seedling establishment at adequate moisture (Girma and Ali, personal observation). A preliminary study we conducted in 2010 suggested that teff can thrive if soil moisture is over 15% of water content (weight of water/weight of soil) at relative humidity of 65% or lower. The effect of weather conditions might have a major role in the results of this study. A dramatic increase in temperature and relative humidity from May to August in both seasons combined with decrease in total amount of rainfall (Table 2.1) might be affected teff growth and its response to the combination of field capacity with watering interval treatments. Thus, teff tillers number, plant height and leaf area decreased with decreasing soil water availability to plant. In general, teff varieties grew well and resulted in a good stand under low soil moisture level. The results of morphological variables of the current study agreed with some previous observation and studies about teff. *Quick-E* and *DZ-01-99* varieties grew well during the hot summer, and growth of all varieties decreased with increasing heat index above 90 (Girma, et al., 2012; Reinert, 2012). Adams and Belay (2011) reported that tillers number per plant of teff decreased at low soil moisture, and Roseberg et al., (2005) reported that the optimal temperature for teff growth was 26.7- 32.3°C. Plant height of soybean was increased at the adequate soil water by about 5-21 cm compared with the low or limiting soil water (Doss et al., 1974). Teff can grow under drought conditions, especially after establishing very good root system, therefore; in this trial, teff had a good growing season. Davision et al., (2011) reported that teff root system was established very well after 2-3 weeks from planting with frequent water during this period.

The results of biomass and grain yields of this trial showed that both yields were affected by the combination of field capacity with watering interval treatment, and biomass yield was higher under the low soil moisture than grain yield. Both biomass and grain yields linearly related to the water treatments combinations. The reason of the difference response of biomass and grain yields to water treatments might due to the effect of weather conditions (Table 2.1). At low level of soil moisture, grain yield was more negatively affected than biomass yield and that might due to the effect of stress on the flowering stages and failed to pollinate. Teff at the flowering stage responded negatively to day length, temperature, and water amount. This has affected final grain yield. Similar result was reported in the past (Ketema, 1997; Miller, 2010; Roseberg et al., 2005, Shpiler and Blum, 1991). The response of biomass and grain to drought stress in this study agreed with previous studies of teff. In Ethiopia, Teferra et al., (2000) found in Ethiopia that teff biomass and grain yields decreased under the early and terminal moisture stress compared with well watered. The results of this study showed that there was an effect of moisture on grain and biomass yields as well as varieties. In contrast, Shiferaw et al.(2012) found in Ethiopia that the yield increased of both genotypes *DZ-01- 974* and *DZ- Cr- 387* under moisture stress and non- stress conditions. In Montana, teff grain yield increased from 700 to 1700 kg ha^{-1} under drought and irrigation treatment, respectively (Eckhoff et al., 1993; Stallknecht et al., 1993). Biomass production under the rainfed treatment was somewhat acceptable because teff can grow and yield under drought conditions (Katema, 1997; Miller, 2010; Davison et al., 2011). In contrast, vegetative growth is more sensitive to water stress than grain filling, especially if the stress happened at vegetative stages (Teffera et al., 2000). In the current study, grain yield decreased at high level of stress compared to biomass yield. The reasons for the contrasting results between these two studies might be due to the effect of temperature and photoperiod besides the effect of water stress on the flowering and pollination.

Teff grain yield was highly related to NDVI for measurements taken three weeks after planting and at flowering stage, but biomass yield was more closely related to NDVI measurements taken four weeks after emergence. Likewise, water use efficiency was also highly related to water treatment combinations, and WUE was low for both biomass and grain yield, especially in the well watered treatment. In addition, the high temperature might be increasing the transpiration of water (Table 2.1). Teff, especially after establishing a good root system, is considered tolerant to water stress (Katema, 1997; Miller, 2010; Davison et al., 2011). The crop grew well under high soil water potential -2.0 MPa (Degu et al., 2008).

Teff varieties in this study are considered tolerant to water stress because they had high level of PSII photochemical efficiency (F_v/ F_m) and yield of quantum efficiency. Munné- Bosch and Alegre (1999) reported that a plant is considered tolerant to particular stress if it has high level of F_v/ F_m. These results showed that there was no clear effect of water stress treatments on photosynthetic traits because teff net photosynthesis was tolerant to water stress (Shiferaw and Baker, 1996b; Abuhay et al., 2001). However, high water deficit or high water stress affected photosynthetic assimilation rate (Dejene, 2009) as shown in the rainfed treatment in this study. In addition, teff is considered resistance to water stress if the DSI is less than 1 unit and is considered sensitive or susceptible to water deficits (Clarke et al., 1987). Consequently, all varieties in this study were resistant to water stress for producing biomass yield. *Quick-E* was highly resistant to drought to produce grain yield compared with *DZ-Cr-387* and *Tiffany* which were susceptible to drought. The results of current study agreed with Admas and Belay (2011) who reported that of 25 genotypes the studied, 17 were resistance to water stress because DSI ranged from 0.5 to 1, and 8.

CONCLUSIONS

In this study, teff growth was highly responsive to different levels of combination of water quantity and watering intervals under field conditions. Tiller number, plant height, and leaf area significantly increased with increasing soil moisture or water availability (R^2= 0.94, R^2= 0.78 and R^2= 0.79 respectively). Biomass and grain yield were affected by water stress treatments and were highly related to soil water potential. In general, teff resulted acceptable biomass under non-irrigated treatment of 0.372 kg m^{-2} compared to grain yield (0.257 kg m^{-2}); especially under very low amount of rainfall in both growing seasons. Teff varieties were identified to be drought tolerant; especially to produce biomass, but only *Quick-E* and somewhat *DZ-Cr-387* were considered tolerant to water deficit to produce grain yield. More agronomic studies are needed to get enough information about teff response and grow under Oklahoma weather condition to adopt it as summer alternative crop.

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CHAPTER IV

RESPONSE OF WINTER WHEAT GROWTH, GRAIN YIELD, AND PHOSPHORUS AND NITROGEN UPTAKE TO FOLIAR PHOSPHITE FERTILIZATION

ABSTRACT

One of the major problems that potentially hinders the use of foliar application as a tool to improve nutrient use efficiency is the lack of formulations that can be easily absorbed by cereal leaves. A phosphite based product, Nutri-phite was evaluated as an alternative formulation for foliar application in hard red winter wheat in this study. Hard red winter wheat field trials were established in the fall of 2009 and 2010 at Perkins, Perry, and Morrison, OK. Treatments encompassed the application of nitrogen (N) at 100 and 75% of crop need, and phosphorus at 100 and 80% sufficiency with and without Nutri-phite. Nutri-phite was applied at two stages of winter wheat (GS 13 to 14) and (GS 49 to 53) at the rate of 4 L ha^{-1}. Non-treated and standard practice treatments were treated as control treatments, and seed treated was studied in 2009. Application of Nutri-phite at both growth stages (2 app Nutr) with P100% sufficiency and N100% of crop need improved plant height (50 and 56 cm) at Perkins and Perry field 2 respectively. Grain

yield was slightly increased by Nutri-phite treatments, especially using Nutri-phite (2 app Nutr) with N100% (1563, 1220, and 1718 kg ha^{-1}) at Perkins, Perry field 2, and Morrison respectively. Grain yield was negatively affected by the combination of Nutri-phite with P100% and was the same as non-treated effect. Total phosphorus of grain was significantly increased at Nutri-phite (2 app Nutr) (4565, 3625, and 2830 mg kg^{-1}) at Perkins 2009 & 2011 and Perry field 2 respectively. P uptake was increased by using Nutri-phite (5.79 and 4 kg ha^{-1}) at Perkins in both seasons. The application of Nutri-phite with adequate N and P did , somewhat, slightly result in yield increases and quality when compared with only Nutri-phite application.

INTRODUCTION AND LITERATURE REVIEW

Since nutrient use efficiency of crops remains low for major cereals (33% for N (Raun and Johnson, 1999), 15% for P (Sander et al., 1990; 991), it is necessary to investigate methods for improving nutrient use efficiency of cereal crops. The cost associated with traditionally-applied P fertilizers has also become an issue for many producers, especially as phosphorus use efficiency (PUE) is considered very poor because of P behavior in soil. Millions of tons of soil P fertilizer are lost, thus Tillman et al., (2001) predicted that P fertilizer use will increase by 1.4 xs in 2020 and by 2.4 xs in 2050 as compared to current P use. Finding methods to reduce the cost and loss of P fertilizer are critical for wheat (*Triticum aestivum* L.) producers in Oklahoma.

Foliar fertilization of nutrients, especially P, in major cereal crops has been evaluated to improve nutrient use efficiency (Girma et al., 2007; Mosali et al., 2006). Applying foliar P fertilizer to coincide with crop need to complete its metabolism is important to complete the crop life cycle. One of the potential hindrances for the use of foliar application as a tool to improve nutrient use efficiency is the lack of a good formulation that can be easily absorbed by cereal leaves (Girma et al., 2007). Several products including powdered forms of diammonium phosphate (DAP), triple superphosphate (TSP), monoammonium phosphate (MAP), and potassium phosphate monobasic salt have been evaluated with limited success (Walsh, unpublished data; Torres, Unpublished data). Some of these products were not small enough for entry through the leaf while others, like potassium phosphate monobasic, dried quickly resulting in poor entry into the leaf.

Nutri-phite® is a fertilizer formulation designed to overcome problems associated with absorption of P through leaf tissue and to thereby improve nutrient use efficiency, boost crop yield, and increase grain quality (Biagro Western, 2006). Nutri-phite® contains phosphite (PO_3) and a blend of organic acids (Biagro Western Inc., 2006) that stabilize and safens the phosphite molecule that is taken up by leaves of plants. The compound is designed to improve nutrient use efficiency by plants including major nutrients such as N and P. The Nutri-phite compositions are 3-20-7 and 0.5 Mn-0.5 Zn. This product has been used in many horticultural crops; however, it has not been tested in major cereals like corn (*Zea mays* L.) and wheat. Nutri-phite is proposed as an alternative formulation for foliar application in wheat in this study.

The goal of most agricultural producers is to obtain optimal crop yields with minimum input from fertilizers and to minimize negative environmental impacts of agricultural operations (Morel and Fardeau, 1990). Applying fertilizer directly to the soil surface is a popular method for supplying crop nutrients that are lacking, but surface applied nutrients can be lost from the soil. In Oklahoma, winter wheat is a primary agricultural crop and requires many tons of nitrogen and phosphorus.

Phosphorus is second only to nitrogen in importance as an essential crop nutrient It is critical for plant growth, especially in the early jointing stages (between 6 and 9 Feekes), and for enhancing grain yield and yield components (Römer and Schilling, 1986). Phosphorus has an important role throughout the plant growth cycle. It increases and improves the development of roots and flowers, strengthens stalk and stem, increases seed yield, and ensures timely crop maturity (Griffith, unpublished). Phosphorus is important in building energy for metabolism of plant growth through cellular productions such as ATP and ADP from the early stages to the end of the plant's life. Phosphorus is necessary for building coenzymes, phospholipids, nucleic acid, and nucleotide components structures. Further, phosphorus is important in building the phosphorus bond that helps link DNA and RNA. In addition, P can be stored as polyphosphate and phytate forms in plant vacuole tissue (Marschner, 1995). Phosphorus also enhances plant disease resistance, crop quality, and legume N-fixation capacity, (Griffith, unpublished.; Marschner, 1995). The amount of P in plant tissues is very small and the total phosphorus is approximately 0.05% to 0.30% of the total dry weight of plant tissues (Vance, 2001). The inorganic form of P is absorbed by plant roots from soil solutions; therefore, soil should be fertilized continuously after each crop harvesting and before planting to recover P again (Holford, 1997).

Several researchers have reported that there are many issues that affect P availability to the plant when it is applied directly in soil (Sander et al., 1990; 991, Batten, 1992; Mosali et al., 2006, and Schachtman et al., 1998). In acidic soil, phosphorus is fixed by Al^{3+}, Fe^{3+}, and Mg^{2+} at soil pH 6 to 6.5. But, in alkaline soil, P is adsorbed by calcium carbonate and becomes unavailable to plants (Lindasy et al., 1989). Moreover, the recycling of P in soil is considered very slow because it gets fixed and adsorbed in soil particles. More than 80% of soil P is unavailable for plant use (Batten, 1992; Mosali et al., 2006). Movement of P through soil is very low because it moves only via diffusion (Schachtman et al., 1998). Mosali et al. (2006) found that application of broadcast-incorporated pre-plant fertilizer at 11 to 22 kg P ha^{-1} was required for cereal production in

Oklahoma. Römer and Schilling (1986) reported that yield of winter and spring wheat was affected by the time application of foliar P (1 ppm, especially at 6 to 9 Feekes).

In phosphorus-deficient soils, surface-applied P needs to be applied in large quantities which can increase PUE. Foliar phosphorus may assist in increasing PUE while still correcting P deficiency. The time and method of foliar P fertilizer application are critical factors for increasing wheat grain yield. McBeath et al., (2011) reported that foliar P fertilizer increased grain yield, grain P uptake, and the transfer of P to grain. Sherchand and Paulsen (1985) examined four sources of foliar P fertilizer applied at the flowering stage of winter wheat and found that the grain yield was increased by foliar P fertilizer with the exception of phytic acid. Shoot growth, leaf area, and chlorophyll of maize were increased by the foliar application of P fertilizer (Ling and Silberbush, 2002). Mosali et al., (2006) reported a linear relationship between P grain concentration and foliar treatments of P at Lahoma and a slight effect on P uptake, especially at Feekes 7. Phosphorus absorption and metabolism in the plant was very fast when P was applied as a foliar fertilizer when compared to traditional P soil fertilizer application (Bayton, 1954).

Mosali et al., (2006) found that delaying foliar P application to a Feekes 10.5 increased PUE by 8% as compared to the same application at Feekes 7. Girma et al. (2007) reported a greater PUE at 2 kg P ha^{-1} of foliar P in applied to corn at growth stage V8 compared to 4 and 8 kg P ha^{-1} applied at the same time. Foliar P increased wheat PUE by 28% compared with pre-plant P fertilizer in soil (Torres, 2011). There is a need to improve PUE as well as P concentration in grain and plant tissues to increase grain yield.

In addition, using foliar P application methods is considered the best way to reduce the amount of phosphorus fertilizer required as a soil fertilizer.

Foliar inorganic fertilizers have been studied for the last 200 years (Kannan, 1986 a). There are many factors that affect the absorption or uptake of foliar fertilizer. The first factor is the cuticle layers on the plant leaves. Foliar applied nutrients of inorganic foliar fertilizer is absorbed through leaves in a two-step process in which they penetrate the cuticle (passive percolation or surface adsorption) and then pass through (active absorption) the cells below the cuticle layers (Kannan, 1986 a; Tyree et al., 1990). Foliar applied nutrients can be absorbed by leaves through the cuticle, stomata, leaf hairs, and epidermal cells (Noack et al., 2010). Movement of nutrient within and from leaves is achieved by two pathways, passive (apoplastic) and active (symplastic), through the plasmadesmate (Erwee et al., 1985; and Kannan, 1986 b). Light, temperature, and relative humidity affect the opening stomata which will, in turn, affect absorption of nutrition (Kannan, 1986 a; Noack et al., 2010). The uptake of foliar fertilizer was affected by temperature and relative humidity when a thin layer of moisture is made on the leaves by transpiration (Thorne, 1958). At high temperatures, cuticle adhesiveness increases, surface tension increases and nutrition is increasingly diffused through the cuticle and stomata (Kirkwood, 1999). Phosphorus absorption is also affected by leaf age (upper and lower leaf), wetting of leaf surface, and solution droplet angle (Koontz and Biddulph, 1957; Wittwer and Teubner, 1959; Reed and Tukey, 1987). Phosphorus was rapidly absorbed at low solution PH compared to high solution PH; in addition, solution pH (3 to 5.5) was the best for uptake of minerals (Fisher and Walker, 1955; Kannan, 1980). Fritz (1978) reported that the plant benefited from P fertilizer by 10% of the total P amount when the fertilizer was applied at the plant root compared with 50% of the total P amount when the P fertilizer was sprayed on the canopy. Supplying phosphorus fertilizer in the early growth stage impacts the grain yield of the wheat crop. Römer and Schilling (1986) reported that applied phosphorus at Feekes 6 to 9 at a (1ppm) rate increased grain yield compared with Feeks 11 to 17 at the same application rate.

There are several papers that reported the impact of P foliar fertilizer on the grain yield of wheat, PUE, and P grain concentration. KH_2PO_4 sprayed on the wheat canopy at rates of 1 to 4 kg P ha^{-1} increased grain yield in low temperature conditions in China (Sherchand and Paulsen, 1985). KH_2PO_4 sprayed at late wheat flowering at rates 0, 2.2, 4.4, and 6.6 kg P ha^{-1} and increased grain yield especially at the higher rate (Benbella and Paulsen, 1998).

The hypothesis of this study was the application of Nutri-phite with and without the addition of N at 100 and 75 % of crop need and P at 100 and 80 % sufficiency would increase and/or improve growth, grain yield and grain quality of hard red winter wheat. Thus, the objective of this study was to determine whether Nutri-phite application with and without pre-plant P (100 and 80% sufficiency) fertilizer at two growth stages (GS 13 to 14 and GS 49 to 53 growth stages) at the rate of 4L ha^{-1} would increase hard red winter wheat grain yield and improve grain quality.

MATERIALS AND METHODS

Five winter wheat field experiments were established over the fall of 2009/2010 and 2010/2011. Two fields were chosen in 2009/2010 one at Perkins (Kirkland silt loam-fine, mixed, thermic Udertic Paleustoll) and one at Perry field 1 (Kirkland fine, mixed, superactive, thermic Udertic Paleustolls). Three fields were chosen in 2010/2011 at Perkins, Perry field 2 (Norge fine-silty, mixed, active, thermic Udic Paleustolls), and Morrison (Grainola fine, mixed, active, thermic Udertic Haplustalfs) as described in (Table 3.1). A total of 18 and 12 treatments were arranged in a randomized complete block design with three replications 2009/2010 and 2010/2011 respectively. Plot size was 6 m by 3 m with a 3 m alley between replicates.

Table 3.1. Study fields at location over two production years of hard red winter wheat at State of Oklahoma.

Location	Year of study	
	2009	2010
Perkins	+†	+
Perry field 1	+	-
Perry field 2	-	+
Morrison	-	+

† +, - = field studied within a production year

Treatments and treatments structure

Nutri-phite was applied at two stages of hard red winter wheat: 2-4 leaf stage (GS 13 to 14) and at 61 cm high (GS 49 to 53) at the rate of 4L ha^{-1}. There were two control treatments consisting of no fertilizer add (non-treated) and standard practice (full fertilizer). Fertilizer treatments were applied with and without Nutri-phite at one stage (1 app Nutr) in the 2009/2010 season and at two stages (2 app Nutr) of wheat growth in both seasons. Additionally, the treatments encompassed the application of N at 100 and 75% of crop need, and P at 100 and 80% sufficiency, both with and without Nutri-phite at one and two stages of hard red winter wheat, in the 2009/2010 season. A combination of both nutrients, each at 75% of crop need and 80% P sufficiency, was evaluated with and without Nutri-phite. Also, seed treated with Nutri-phite was evaluated in the 2009/2010 season (Table 3.2).

Table 3.2. Structure and abbreviations of treatments of Nutri-phite and soil fertilizer with and without Nutri-phite of hard red winter wheat at 2009/ 2010 and 2010/ 2011 seasons at State of Oklahoma.

Treatment Structure	Abbreviations	2009	2010
No Fertilizer control	Non-treated	+†	+
Treated seed by Nutri-phite	Treated Seed	+	-
No Fertilizer + Nutri-phite @ 2-4 leaf stage	1 app Nutr	-	+
No Fertilizer + Nutri-phite @ 2-4 leaf stage & 61 cm height	2 app Nutr	+	+
100% Sufficiency N and P (standard practice)	NP 100%	+	+
N applied at 75% of crop need	N 75%	+	-
N applied at 75% of crop need+ Nutri-phite @ 2-4 leaf stage	N 75% & 1 app Nutr	+	-
N applied at 75% of crop need+ Nutri-phite @ 2-4 leaf stage & 61 cm height	N 75% & 2 app Nutr	+	-
N applied at 100% of crop need	N 100%	+	+
N applied at 100% of crop need+ Nutri-phite @ 2-4 leaf stage	N 100% & 1 app Nutr	+	+
N applied at 100% of crop need + Nutri-phite @ 2-4 leaf stage & 61 cm height	N 100% & 2 app Nutr	+	+
P applied at 80% sufficiency	P 80%	+	-
P applied at 80% sufficiency + Nutri-phite @ 2-4 leaf stage	P 80% & 1 app Nutr	+	-
P applied at 80% sufficiency + Nutri-phite 2-4 leaf stage & 61 cm height	P 80% & 2 app Nutr	+	-
P applied at 100% sufficiency	P 100%	+	+
P applied at 100% sufficiency + Nutri-phite @ 2-4 leaf stage	P 100% & 1 app Nutr	+	+
P applied at 100% sufficiency + Nutri-phite @ 2-4 leaf stage & 61 cm height	P 100% & 2 app Nutr	+	+
N applied at 75% of crop need and P applied at 80% sufficiency	N 75% & P 80%	+	+
N applied at 75% of crop need and P applied at 80% sufficiency + Nutri-phite @ 2-4 leaf stage & 61 cm height	N 75% &P 80% & 2 app Nutr	+	+

† +, - = Treatments applied or not applied within a production year.

Soil samples and fertilizer application

Soil samples (0-15 cm depth) were collected and analyzed for available N and P in the soil prior to initiation of the experiment. This information was used to calculate additional fertilizer needed for 100% and 75% of crop N need and 100% and 80% P sufficiency Based on soil analysis results, K was applied uniformly to all plots if analysis warranted application (Table 3.3). Nitrogen (urea) was split (1/3 and 2/3) between pre-planted and Feekes 5, and all P (TSP) was applied pre-plate. In addition, Nutri-phite was sprayed by using a backpack sprayer over the wheat canopy at the rate of 4L ha^{-1} in both growth stages.

Table 3.3. Initial surface (0-15 cm) soil test characteristics of hard red winter wheat field at Perkins, Perry, and Morrison, OK, 2009/2010 and 2010/2011.

Location	2009/2010			2010/2011		
	NO_3-N	P	K	NO_3-N	P	K
	---------------kg ha^{-1}-------------			--------------------kg ha^{-1}--------------		
Perkins	28	45	300	27	43	297
Perry field 1	37	39	295	-	-	-
Perry field 2	-†	-	-	25	42	302
Morrison	-	-	-	45	17	284

† - = field was not planted within a year production.

Sowing date and field practices

Duster winter wheat was no-till planted November 6, 2009 at Perry field 1 and November 18, 2009 at Perkins. Endurance winter wheat was no-till planted October 8, 2010 at Perry field 2 and Morrison and on October 11, 2010 at Perkins with 19.5 cm row spacing at the rate of 101 kg ha^{-1} at all sites. Weeds were controlled following Oklahoma Cooperative Extension Service recommendations.

Data collection and analyzing

Primary data included tillers per plant at harvesting stage, plant height (cm) at harvesting stage, grain yield (kg ha^{-1}), and grain phosphorus concentration (mg kg^{-1}). Grain was harvested at maturity by harvesting the center 2 m using a Massey Ferguson 8XP experimental combine. This combine was equipped with a Harvest Master automated weighing system (Harvest Master Inc, Logan, Utah). Grain subsamples of some treatments in 2009 and all treatments in 2010 were collected for P quantification in SWAFL lab. Also P uptake was calculated by multiplying P percentage in grain by grain yield. All data were analyzed using the GLM procedure of SAS 9.3 (Sas institute, Cary, NC).

RESULTS

Perry field 1, 2009

The analysis of variance showed that none of the treatments affected morphological characteristics or grain yield at Perry field 1 in 2009/2010 (Table 3.4). Also, grain phosphorus concentration in mg kg^{-1} and P uptake in kg ha^{-1}were not significantly affected by treatments (Table 3.6).

Table 3.4. Analysis of variance and mean separation for tiller number per wheat plant, plant height (cm), and grain yield (kg ha^{-1}) in hard red winter wheat as affected by treatments at Perry field 1, OK, 2009.

Source of Variation	df	Tiller Number/ plant	Plant Height (cm)	Grain Yield (kg ha^{-1})
Treatment	17	NS[†]	NS	NS
Replication	2	NS	NS	NS
		Treatment Means		
Treatment		Tiller Number/ plant	Plant Height	Grain Yield
			cm	kg ha^{-1}
Non-treated		3	50	1629
Treated seed		3	48	1806
2 app Nutr[‡]		3	42	1077
NP 100%		3	48	1622
N 75%		3	43	1356
+ 1 app Nutr[§]		2	41	1636
+ 2 app Nutr		2	43	1123
N 100%		2	42	1183
+ 1 app Nutr		2	42	1334
+ 2 app Nutr		3	46	1454
P 80%		3	47	1756
+ 1 app Nutr		2	44	1021
+ 2 app Nutr		3	48	1350
P 100%		3	46	1602
+ 1 app Nutr		2	47	1114
+ 2 app Nutr		2	48	1123
N 75% & P80%		2	46	1275
+ 2 app Nutr		2	44	1407
C.V. (%)		35	12	29

†NS= Nonsignificant.

‡Nutri-phite at two growth stages.

§Nutri-phite at one growth stage.

df= Degree of freedom; CV= Coefficient of variation.

Perkins 2009

There were no significant differences found between the treatments in number of tillers per plant in Perkins (Table 3.5). Significant differences were found among the treatments in plant height (cm) and ranged from 51 to 43 cm (Table 3.5). Nutri-phite increased plant height gradually from 45, 47, to 50 cm in the P100%, P100% & 1 app Nutr, and P100% & 2 app Nutr treatments respectively. The effect of Nutri-Phite with P80% was not as consistent. Plant height increased from 47 to 49 cm by using 2 app Nutr with N75% & P80% treatment compared to N75% & P80% without Nutri-Phite. 2 app Nutr treatments had less impact in plant height compared with non-treated and NP 100%, and plant height increased by 3 cm at non-treated and NP 100%. However, using only Nutri-phite without N and P did not significantly affect plant height compared with using the combination of Nutri-phite with P pre-plant treatments.

Grain yield was significantly affected by treatments, and treated seed treatment resulted in greater grain yield (1779 kg ha^{-1}) compared P80% & 1 app Nutr treatment (1106 kg ha^{-1}). There was no significant difference in grain yield among 2 app Nutr, non-treated, and NP 100% treatments (1236, 1401 and 1217 kg ha^{-1} respectively). Nutri-phite at 1 and 2 app Nutr did not increase grain yield when used in conjunction with P100% and P80% compared to P100% and P80% without Nutri-phite. The same result was found at N100% and N75% with and without Nutri-phite. There was a slight increase in grain yield (243 kg ha^{-1}) by using 2 app Nutr with N75% & P80% compared to combination of N75% & P80% without Nutri-phite.

Table 3.5. Analysis of variance and mean separation for tiller number per wheat plant, plant height (cm), and grain yield kg ha^{-1} in hard red winter wheat as affected by treatments at Perkins, OK, 2009/2010.

Source of Variation	Df	Tiller Number/plant	Plant Height (cm)	Grain Yield (kg ha^{-1})
Treatment	17	NS[†]	**	*
Replication	2	NS	**	NS

Treatment	Treatment Means		
	Tiller Number/plant	Plant Height	Grain Yield
		cm	kg ha^{-1}
Non-treated	2	49 abc[¶]	1401 bc
Treated seed	3	51 a	1779 a
2 app Nutr[‡]	2	46 cde	1236 bc
NP 100%	2	49 abc	1217 bc
N 75%	2	49 abc	1330 bc
+ 1 app Nutr[§]	2	45 de	1167 c
+ 2 app Nutr	2	49 abc	1115 c
N 100%	2	47 bcd	1246 bc
+ 1 app Nutr	2	43 e	1146 c
+ 2 app Nutr	3	46 cde	1563 ab
P 80%	2	45 de	1120 c
+ 1 app Nutr	2	47 bcd	1106 c
+ 2 app Nutr	2	46 cde	1314 c
P 100%	2	45 de	1167 c
+ 1 app Nutr	2	47 bcd	1113 c
+ 2 app Nutr	2	50 ab	1260 bc
N75% & P80%	2	47 bcd	1176 c
+ 2 app Nutr	2	49 abc	1420 abc
LSD	0.7	3	367
C.V. (%)	20.2	4.3	17.4

† NS,*, **non significant or significant at the $P \leq 0.05$ or 0.01 respectively.

‡ Nutri-phite at two growth stages.

§ Nutri-phite at one growth stage.

¶ a, b, c, d, e= Test of treatments means (LSD at $P \leq 0.05$ and 0.01)

df= Degree of freedom; CV= Coefficient of variation; LSD= Least significant difference.

Grain phosphorus concentration (mg kg^{-1}) was significantly affected by treatments (Table 3.6), and the results showed that 2 app Nutr significantly increased the grain phosphorus concentration compared to non-treated and NP 100% (4565, 3335, and 3155 mg kg^{-1} respectively). The 2 app Nutr of Nutri-phite had greater impact on grain phosphorus concentration compared to P 100%, and it was increased by the combination of Nutri-phite (1 and 2 app Nutr) with P 100% from 3655 to 3735 and 3725 mg kg^{-1} at P100%, P100% & 1 app Nutr and P100% & 2 app Nutr respectively. A slight increase in grain phosphorus concentration was recorded when using Nutri-phite (1 and 2 app Nutr) with N100% compared to N 100% alone (1146, 1563 and 1246 kg ha^{-1} respectively). In general, the greatest grain phosphorus concentration was recorded at 2 app Nutr of Nutri-phite (4565 mg kg^{-1}) when compared with other treatments.

Phosphorus uptake was significantly affected by treatments (Table 3.6). Nutri-phite (2 app Nutr) was effective for increasing P uptake (5.79 kg ha^{-1}) than control treatments (4.67, and 3.99 kg ha^{-1}) at non-treated and NP% respectively. Likewise, the trend of increased P uptake was more efficient when using Nutri-phite (2 app Nutr) in contrast to P100% (3.96 kg ha^{-1}). Also the combination of P100% with 2 app Nutr significantly increased P uptake compared to the combination of P100% with 1 app Nutr (4.74 and 3.93 kg ha^{-1} respectively). However, the greatest P uptake was recorded at treated seed, Nutri-phite (2 app Nutr), and N100% & 2 app Nutr treatments (5.87, 5.79, and 5.73 kg ha^{-1} respectively).

Table 3.6. Analysis of variance and mean separation for total phosphorus mg kg^{-1} and P uptake kg ha^{-1} in hard red winter wheat as affected by treatment at Perkins, and Perry Field 1, OK, 2009/2010.

Location	Source of Variation	DF	Grain P concentration(mg kg^{-1})	P uptake (kg ha^{-1})
Perkins	Treatment	11	*[†]	*
Perry field 1	Treatment	11	NS	NS

Treatment	Perkins		Perry field 1	
	Grain P concentration	P uptake	Grain P concentration	P uptake
	mg kg-1	kg ha-1	mg kg-1	kg ha-1
Non-treated	3335 b[¶]	4.6 abcd	4450	7.3
Treated seed	3440 b	5.8 a	3435	6.7
2 app Nutr[‡]	4565 a	5.7 ab	4355	4.7
NP 100%	3155 b	3.9 cd	3675	6.2
N 75% & 2 app Nutr	3050 b	3.1 d	3615	4.5
N 100%	3045 b	3.4 d	3680	3.0
+ 1 app Nutr[§]	3215 b	4.0 bcd	2975	4.3
+ 2 app Nutr	3240 b	5.7 abc	3345	4.8
P 80% & 2 app Nutr	3460 b	4.1 abcd	4315	6.3
P 100%	3655 b	3.9 cd	3055	6.1
+ 1 app Nutr	3735 ab	3.9 d	3825	4.1
+ 2 app Nutr	3725 ab	4.7 abcd	4245	5.2
LSD	368	1.8	NS	NS
C.V%	11.9	18	17.3	33.7

† NS,* Nonsignificant or significant at $P \le 0.05$, respectively.

‡ Nutri-phite at two growth stages.

§ Nutri-phite at one growth stage.

¶ a, b, c, d, e= Test of treatments means (LSD $P \le 0.05$)

df= Degree of freedom; CV= Coefficient of variation; LSD= Least significant difference.

Perkins 2010

The results of variance analysis of morphological characteristics and grain yield at this site revealed no significant differences among the treatments (Table 3.7).

There was a significant effect of treatments in grain phosphorus concentration mg kg^{-1}. (Table 3.10). There was no significant difference between Nutri-phite treatments (1and 2 app Nutr) compared to control treatments (non-treated and NP 100%). There was a significant influence when using Nutri-phite with N100%, P100% and N75% & P80% to increase grain phosphorus concentration. The greatest total grain phosphorus was 3770, 3710, 3645 and 3625 mg kg^{-1} from treatments N100% & 1 app Nutr, N 75% & P 80% & 2 app Nutr, N100% & 2 app Nutr and 2 app Nutr respectively.

Nutri-phite treatments (1and 2 app Nutr) significantly affected P uptake compared to non-treated treatment (Table 3.10) and the P uptake of those treatments was (3, 4 and 2 kg ha^{-1} respectively). NP% treatment was more significant to increase P uptake (5 kg ha^{-1}) compared to Nutri-phite treatments (1and 2 app Nutr) 3 and 4 mg kg^{-1} respectively. The combination of Nutri-phite treatments (1and 2 app Nutr) with P100 had a negative effect compared with the combination of Nutri-phite (1and 2 app Nutr) with N100%. P uptake was decreased from (4 kg ha^{-1}) at P100% to (1 kg ha^{-1}) at P100% &1 and 2 app Nutr. Nutri-phite (2 app Nutr) was more efficient than Nutri-phite (1app Nutr) in P uptake, especially at the combination with N100% and N75% & P80%.

Table 3.7. Analysis of variance and mean separation for tiller number per wheat plant, plant height (cm), and grain yield kg ha^{-1} in hard red winter wheat as affected by treatment at Perkins, Ok, 2010/2011.

Source of Variation	df	Tiller Number/plant	Plant Height (cm)	Grain Yield (kg ha^{-1})
Treatment	11	NS[†]	NS	NS
Replication	2	NS	NS	*

Treatment	Treatment Means		
	Tiller Number/plant	Plant Height	Grain Yield
		cm	kg ha^{-1}
Non-treated	3	51	698
1 app Nutr[‡]	3	51	1058
2 app Nutr[§]	3	52	1305
NP 100%	3	55	1413
N 100%	3	48	782
+ 1 app Nutr	3	51	1015
+ 2 app Nutr	3	57	1410
P 100%	3	55	1191
+ 1 app Nutr	3	58	1727
+ 2 app Nutr	3	58	1321
N75% & P80%	4	57	1286
+ 2 app Nutr	3	53	867
C.V. (%)	16.9	10.9	45

† NS, * Nonsignificant or significant at $P \leq 0.05$.
‡ Nutri-phite at one growth stage.
§ Nutri-phite at two growth stages.
df= Degree of freedom; CV= Coefficient of variation.

Perry field 2, 2010

The analysis of variance showed significant effects among treatments on tillers number per plant, plant height (cm), and grain yield (kg ha^{-1}) (Table 3.8). Nutri-phite treatments (1 and 2 app Nutr) did not show a significant increase in tiller number compared to non-treated wheat. Plant height was significantly increased at the combination of N100% with Nutri-phite (2 app Nutr treatment) (3 tiller per plant) compared to N100% without Nutri-phite (2 tiller per plant). The same effect was also recorded at N75% & P80% with and without Nutri-phite. The treatments with P100% with and without Nutri-phite treatments resulted in no significant effect on tiller number (2 tillers per plant).

There was no difference between Nutri-phite treatments and non-treated wheat, especially between 2 app Nutr and non-treated in plant height (39 and 40 cm respectively). In addition, plant height increased significantly by (5 and 21 cm) at N100% with 1 and 2 app Nutr respectively compared to N100%. Also, plant height increased at N75% & N80% & 2 app Nutr by 11 cm compared with N75% & P80%. Nutri-phite treatments did not significantly affect plant height when Nutri-phite use with P100%.

The grain yield (kg ha^{-1}) result showed that there was no significant differences among Nutri-phite treatments (1 and 2 app Nutr) and non-treated wheat. Grain yield was significantly affected by NP100% compared to Nutri-phite (1 and 2 app Nutr) treatments (1138, 345, and 434 kg ha^{-1} respectively). Application of Nutri-phite treatments (1 and 2 app Nutr) with P100% did not show any impact on grain yield but grain yield was slightly decreased from (650 kg ha^{-1}) at P100% to (481 and 525 kg ha^{-1}) at Nutri-phite (1 and 2 app Nutr) respectively. Otherwise, slight increase in grain yield was recorded at N75% & P80% with 2 app Nutr compared to N75% & P80% without 2 app Nutr (1223 and 969 kg ha^{-1} respectively). Also, the effect of Nutri-phite treatments with N100% in grain yield was not consistent and slightly increased at N100% & 2 app Nutr (1220 kg ha^{-1}) but decreased at N100% & 1 app Nutr (977 kg ha^{-1}) compared to N100% (1106 kg ha^{-1}).

The analysis of variance showed that the treatments had a significant effect in grain phosphorus concentration (Table 3.10). The effect of Nutri-phite treatments was not consistent, and there was similar effect of Nutri-phite treatments (1 and 2 app Nutr) on grain phosphorus concentration (3320 and 2830 mg kg^{-1} respectively) and non-treated, and NP100% treatments (3485 and 2545 mg kg^{-1} respectively). Nutri-phite with pre-plant N100% did not show any effect on grain phosphorus concentration. In contrast, grain phosphorus concentration was increased by using Nutri-phite (1 and 2 app Nutr) with P100% (3650 and 3950 mg kg^{-1} respectively) compared to P100% (3470 mg kg-1). Furthermore, there was a negative effect of the combination of Nutri-phite (2 app Nutr) with N75% & P80% compared to N75% & P80%, and grain phosphorus concentration decreased from (3180 mg kg^{-1}) at N75% & P80% to (2765 mg kg^{-1}) at N75% & P80% & 2 app Nutr. None of the treatments significantly affected the P uptake kg ha^{-1} (Table 3.10).

Table 3.8. Analysis of variance and mean separation for tiller number per wheat plant, plant height (cm), and grain yield kg ha^{-1} in hard red winter wheat as affected by treatments at Perry Field 2, Ok, 2010/2011.

Source of Variation	df	Tiller Number/plant	Plant Height (cm)	Grain Yield (kg ha^{-1})
Treatment	11	*†	*	**
Replication	2	*	NS	*

Treatment	Treatment Means		
	Tiller Number/plant	Plant Height	Grain Yield
		cm	kg ha-1
Non-treated	2 cde¶	40 bcd	471 c
1 app Nutr‡	1 e	31 d	345 c
2 app Nutr§	2 cde	39 bcd	434 c
NP 100%	3 abc	51 abc	1138 a
N100%	2 de	35 d	1106 a
+ 1 app Nutr	2 cde	40 bcd	977 ab
+ 2 app Nutr	3 ab	56 a	1220 a
P100%	2 cde	42 abcd	650 bc
+ 1 app Nutr	2 bcde	43 abcd	481 c
+ 2 app Nutr	2 cde	38 cd	525 c
N75% & P80%	2 abcd	43 abcd	969 ab
+ 2 app Nutr	3a	53 ab	1223 a
LSD	0.9	15	419
C.V. (%)	24	20	31

† NS, *, ** Nonsignificant or significant at $P \leq 0.05$ or 0.01.
‡ Nutri-phite at one growth stage.
§ Nutri-phite at two growth stages.
¶ a, b, c, d, e= Test of treatments means (LSD $P \leq 0.05$ or 0.01)
df= Degree of freedom; CV= Coefficient of variation; LSD= Least significant difference.

Morrison 2010

None of the treatments affected tiller number per plant or plant height (cm) at Morrison (Table 3.9). In contrast, the treatments significantly affected grain yield (kg ha^{-1}) and the greatest and lowest grain yield were (1830 and 874 kg ha^{-1}) at the combination of N75% & P80% with 2 app Nutr and non-treated respectively. The results showed that there was a significant increase in grain yield (1416 and 1498 kg ha^{-1}) at 1 app Nutr and 2 app Nutr compared to the control (non-trated) treatment (874 kg ha^{-1}). On the other hand, a negative influence of Nutri-phite (1 and 2 app Nutr) treatments in grain yield was observed when combined with P100% (1497, 1025 and 1744 kg ha^{-1}). Grain yield was significantly increased at N75% & P80% & 2 app Nutr (1809 kg ha^{-1}) compared with the combination of N75% & P80% (1289 kg ha^{-1}). The combination of N100% with and without Nutri-phite treatments (1 app Nutr and 2 app Nutr) did not show significant differences in grain yield and there was only slight difference among the treatments. The results of variance analysis showed that none of the treatments was significantly affected grain phosphorus concentration (mg kg^{-1}) or P uptake (kg ha^{-1}) (Table 3.10).

Table 3.9. Analysis of variance and mean separation for tiller number per wheat plant, plant height (cm), and grain yield kg ha^{-1} in hard red winter wheat as affected by treatments at Morrison, Ok, 2010/2011.

Source of Variation	df	Tiller Number/plant	Plant Height (cm)	Grain Yield (kg ha^{-1})
Treatment	11	NS[†]	NS	**
Replication	2	NS	NS	***
Treatment		Treatment Means		
		Tiller Number/plant	Plant Height	Grain Yield
			cm	kg ha^{-1}
Non-treated		3	55	874 d[¶]
1 app Nutr[‡]		2	50	1416 abc
2 app Nutr[§]		3	55	1498 abc
NP 100%		3	49	1355 abcd
N 100%		3	54	1419 abc
+ 1 app Nutr		3	55	1830 a
+ 2 app Nutr		3	58	1718 ab
P 100%		3	56	1744 ab
+ 1 app Nutr		4	60	1497 abc
+ 2 app Nutr		3	53	1025 dc
N75% & P80%		3	54	1289 bcd
+ 2 app Nutr		4	64	1809 a
LSD		NS	NS	486.2
C.V. (%)		19	12	20

† NS, *, ** Nonsignificant or significant at $P \leq 0.05$ or 0.01or 0.001.

‡ Nutri-phite at one growth stage.

§ Nutri-phite at two growth stages.

¶ a, b, c, d, e= Test of treatments means (LSD $P \leq 0.05$ or 0.01 or 0.001)

df= Degree of freedom; CV= Coefficient of variation; LSD= Least significant difference.

Table 3.10. Analysis of variance and mean separation for total phosphorus (mg kg^{-1}) and P uptake (kg ha^{-1}) in hard red winter wheat as affected by treatments at Perkins, Perry Field 2, and Morrison, OK, 2010/2011.

Location	Source of Variation	DF	Grain P concentration (mg kg-1)	P uptake (kg ha-1)
Perkins	Trt	11	*[†]	*
Perry field 2	Trt	11	*	NS
Morrison	Trt	11	NS	NS

Treatment	Perkins		Perry Field 2		Morrison	
	Grain P concentration	P uptake	Grain P concentration	P uptake	Grain P concentration	P uptake
	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}
Non-treated	3365 ab[¶]	2 d	3485 ab	1	2605	2
1 app Nutr[‡]	2815 b	3 abcd	3320 abc	1	2705	3
2 app Nutr[§]	3625 a	4 abcd	2830 bcd	1	2915	3
NP 100%	3405 ab	5 a	2545 cd	3	2770	3
N 100%	3525 ab	2 dc	2490 d	3	2695	3
+ 1 app Nutr	3770 a	3 abcd	2460 d	2	2540	4
+ 2 app Nutr	3645 a	5 ab	2455 d	2	2525	4
P 100%	3090 ab	4 abcd	3470 ab	2	2585	4
+ 1 app Nutr	3520 ab	4 abc	3650 a	1	2405	3
+ 2 app Nutr	2740 b	1 d	3950 a	2	2735	2
N75% & P80%	3475 ab	1 d	3180 abcd	2	2785	3
+ 2app Nutr	3710 a	2 bcd	2765 bcd	3	2935	4
LSD	807	2.3	819	NS	NS	NS
C.V%	10.8	30.8	12.2	31.5	16.1	30.1

[†] NS, * Nonsignificant or significant at *P* ≤ 0.05.

[‡] Nutri-phite at one growth stage

[§] Nutri-phite at two growth stages.

[¶] a, b, c, d= Test of treatments means (LSD at *P* ≤ 0.05).

df= Degree of freedom; CV= Coefficient of variation; LSD= Least significant difference.

DISCUSSION

Among all the trials and years, the results of analysis of variance showed inconsistence results of Nutri-phite on tillers number, plant high, grain yield, grain quality and phosphorus uptake compared to non-treated standard practice treatments. Nutri-phite alone applied once or twice slightly increased tillers, plant height, grain yield, and grain phosphorus concentration compared to P100 & 80% sufficiency with and without Nutri-phite (1 and 2 app Nutr) treatments. The reason for this response may be because the high levels of P concentration in the soils of this study (Table 3.3) making the effect of additional P fertilizer minimal. In addition, the effect of the environmental conditions, especially less rainfall and high temperature during these two years, might have influenced results, because of their negative impact on Nutri-phite absorption through stomata (Thorne, 1958; Kannan, 1986 a; Tyree et al., 1990; Kirkwood, 1999).

In contrast to tiller per plant, plant height was more affected by Nutri-phite treatments and the combination of Nutri-phite with P100% and N100% compared to P100% and N100% without Nutri-phite as well as using 2 app Nutr of Nutri-phite with N75% & P80% compared to N75% & P80% at Perkins, 2009 and at Perry field 2, 2010 seasons. Number of tillers was increased significantly by using Nutri-phite with treatments (N100% and N75% & P80%) at Perry field 2, 2010. Ling and Silberbush (2002) reported that there was a significant effect of P foliar fertilizer on corn shoot growth. In addition, fertile tillers of winter wheat were increased by using P foliar fertilizer at early stages (Batten et al., 1986; McBeath et al., 2011; Grant et al., 2001). This effect of Nutri-phite especially at two growth stages (2 app Nutr) might improve the uptake of nitrogen fertilizer by wheat which then increases the plant growth. Phosphorus is essential to root growth and development that then might help to increase root uptake of nutrients (Marschner, 1995).

The influence of Nutri-phite (1 and 2 app Nutr), especially with other treatments, was shown to have somewhat limited impact on grain yield (kg ha^{-1}) The increase of grain yield was not consistent among locations and between years; the treatments significantly affected grain yield at Perkins in 2009, Perry field 2 and Morrison in 2010. The combination of Nutri-phite (1 and 2 app Nutr) with N100% significantly increased grain yield compared to the combination of Nutri-phite with P100% as well as the combination of Nutri-phite (2 app Nutr) with N75% & P80% compared to N75% & P80% without Nutri-phite. The influence of Nutri-phite (1 and 2 app Nutr) in grain yield was same essentially as the influence of non-treated and standard practice treatments.

These results disagree with Mosali et al., (2006) and Torres (2011) who found a slight effect of foliar P on the P uptake and grain yield of wheat especially at Feekes 7 as foliar P was applied with a pre-plant fertilizer. In addition, the use foliar P at the V8 corn growth stage at 2 kg P ha^{-1} affected yield and PUE (Girma et al., 2007). The reasons for the effect were not consistent among locations and years and could be influenced by the condition of the soil and the weather, especially the moisture and temperature. These last two reasons maybe affect the opening of the stomata which may affect absorption and the movement of Nutri-phite throughout leaf tissues. Light, temperature, and relative humidity are the most powerful environmental conditions influencing the opening of the stomata, which, then affect absorption, and evaporation of foliar nutrition (Thorne, 1958;

Kannan, 1986a; Kirkwood, 1999; Noack et al., 2010). In addition, the time or growth stage of the crop and the application rate of Nutri-phite might affect uptake of P. Mosali et al., (2006) mentioned that high rate of application of P as a foliar fertilizer at the earliest growth stages (6 to 9 Feekes) was more efficient, but Sherchand and Paulsen (1985) reported that grain yield of winter wheat increased at the lower rate of foliar P at flowering stages. Contrarily, wheat grain yield was affected positively at high rate of foliar P at the flowering stage (Benbella and Paulsen, 1998). Similarly, using 120 L ha^{-1} (1.65 P ha^{-1}) increased grain yield of winter wheat (McBeath et al., 2011).

Grain phosphorus concentration was also affected by treatments, especially Nutri-phite treatments and the significant effect was reported in three of five fields at two years of this study. Nutri-phite treatments, especially 2 app Nutr increased grain phosphorus concentration at Perkins in two years compared with control treatments, N treatments, and P treatments. Also the results showed that there was a significant increase in grain phosphorus concentration when Nutri-phite was combined with P treatments at Perkins in 2009 and Perry field 2 in 2010. However, Nutri-phite treatments with and without other treatments somewhat increased grain phosphorus concentration. Grain phosphorus concentration of wheat might be increased when foliar phosphorus was sprayed at anthesis (Sherchand and Paulsen, 1985).

Application of Nutri-phite (2 app Nutr) was more efficient at affecting crop growth development and slightly increased grain yield than the Nutri-phite (1 app Nutr). Also, application of Nutri-phite (2 app Nutr) with the other treatments was more effective than the combination of Nutri-phite (1 app Nutr) with the other treatments. The reason for this effect might be the increased amount of Nutri-phite (2 app Nutr) compared with Nutri-Phite (1 app Nutr). Using foliar P fertilizer at high rate (1 ppm) gave greater grain yield in wheat (Römer and Schilling, 1986); also, Benbella and Paulsen (1998) reported that the grain yield of wheat was increased at high level of foliar KH_2PO_4. P uptake kg ha^{-1} was significantly affected by the treatments, and the stronger effect was reported by Nutri-Phite treatments (1and 2 app Nutr) compared to check treatment (non-treated). Likewise, the impact of P100% and Nutri-Phite treatments (1and 2 app Nutr) in P uptake was not consistent but was essentially the same. There was a slight increase in P uptake in wheat grain by using P foliar fertilizer (Mosali et al., 2006; Torres, 2011).

CONCLUSIONS

Nutri-phite (1 and 2 app Nutr) with and without other treatments at all locations and years did slightly affect growth and grain yield of wheat, and there was a significant effect in grain phosphorus concentration and P uptake. The results of this study showed that Nutri-phite (1 and 2 app Nutr) treatments increased the number of tillers at Perry field 2 in 2010. The same effect was also noted in plant height at Perkins in 2009 and at Perry field 2 in 2010. Thus, Nutri-phite treatments with and without P and N had a greater impact on plant height than on tillers number per plant.

Grain yield determined by ANOVA was slightly increased by the combination of Nutri-phite (1 and 2 app Nutr) with N 100 and 75% treatments as well as with N75% & P80%, but the combination with P treatments decreased grain yield. There was no significant different effect between Nutri-phite (1 and 2 app Nutr) and check treatment (non-treated) in grain yield compared with standard practice treatment. Nutri-phite (1 and 2 app Nutr) was more efficient in increasing grain phosphorus concentration compared to control treatment (non-treated) and NP% treatment. Likewise, combining Nutri-phite (1 and 2 app Nutr) with P and N treatments resulted in slight increase in grain phosphorus concentration.

In general, two application of Nutri-Phite was more effective at improving growth, grain yield and grain phosphorus concentration compared to one application. When pre-plant P fertilizer was supplied at 100 and 80% sufficiency, the influence of Nutri-phite at (1 and 2 app Nutr) on plant height and grain phosphorus concentration was slight, but the effect on grain yield it was not significant. Even so, there was a slightly significant effect of Nutri-phite treatments on grain yield, especially compared to the control treatment (non-treated). Likewise, P uptake was increased by Nutri-phite application, especially at 2 app Nutr, compared to check treatments (non-treated). Nutri-phite treatments were more efficient than P treatments in P uptake, and Nutri-phite (2 app Nutr) was more efficient than Nutri-Phite (1 app Nutr) in P uptake.

This study demonstrated that the application of Nutri-phite treatments as a P foliar fertilizer might enhance and/or improve the wheat growth, grain yield and grain quality, especially under good environmental conditions. Thus, this study showed that foliar P fertilization should concentrate on the amount of foliar fertilizer applied at the best time of the crop life cycle to get the benefit of foliar application.

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