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Integrated Agronomic Crop Managements to Improve Tef Productivity Under Terminal Drought

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1. Introduction

1.1 Origin, distribution and botany of tef

Tef (*Eragrostis tef* [Zucc.] Trotter) is an allotetraploid ($2n = 4x = 40$) cereal crop grown primarily in Ethiopia. Ethiopia is the center of origin and diversity of tef. It is entirely cultivated only in Ethiopia as food crop and distributed to several other countries in the 19th century, and it is now cultivated as a forage grass in Australia, India, Kenya and South Africa (Costanza *et al.,* 1979). Intensive studies carried out on tef in USA universities initiated its cultivation for both grain and forage has also begun in USA. Studies so far carried out on morphological, cytological and biochemical characters of wild and cultivated species of tef revealed that Ethiopia is the origin and center of diversity of tef even though the wild relative, *Eragrostis pilosa,* a weedy species, occurs throughout the world in tropical and temperate regions (e.g. Vavilov, 1951). This wild relative is the closest relative of the cultivated tef, *E. tef. E. pilosa* is also an allotetraploid and has a karyotype similar to *E. tef* (Tavassoli, 1986). These two species are similar morphologically. The only known consistent morphological distinction between *E. pilosa* and *E. tef* is spikelet shattering of *E. pilosa*.

The multi-floreted spikelets of *E. pilosa* readily break apart at maturity as a means of natural seed dispersal, whereas the lemmas, paleas, and caryopses of *E. tef* remain attached to the rachis at maturity and thereby facilitate harvesting (Phillips, 1995). It is speculated that the transition from shattering to non-shattering is one of the most common traits altered during the domestication process as it allows farmers to control seed dispersal. The current tef breeding program makes interspecific crosses between *E. pilosa* and *E. tef* with fully fertile resultant progenies. Hence, it is highly likely that Ethiopian farmers domesticated tef from *E. pilosa* and altered key agronomic features such as seed mass and spikelet shattering through generations of selections. Furthermore, Endeshaw *et al.* (1995) reported as there is anthropological evidence that *E. pilosa* is harvested and used as a food source in much the same fashion as *E. tef* during times of food scarcity.

Tef is a C4, self-pollinated annual grass, 40 – 80cm tall. It has a shallow fibrous root system with mostly erect stems, although some cultivars are bending or elbowing types (Plate 1). Its sheaths are smooth, glabrous, open and distinctly shorter than the internodes. It has a panicle type of inflorescence showing different forms – from loose to compact, the latter appearing like a spike. The flowers of tef are hermaphroditic with both the stamens and pistils being found in the same floret (Hailu *et al.*, 1990). Florets in each spikelet consist of three anthers, two stigmas and two lodicules that assist in flower opening. Its grain is tiny with 0.9 – 1.7mm long and 0.7 – 1mm wide and its colour varies from white to dark brown (Tadesse, 1975).

A) B) C)

Plate 1. Morphological structure of tef crop: A) the whole plant; B) root and C) panicle

Plants with C4 pathway have a 'Kranz' type of leaf anatomy referring to the bundle sheath, a vascular tissue containing large and thick cell wall with prominent chloroplasts. Possessing such leaf structure helps C4 plants to increase the concentration of CO_2 available to the Calvin cycle even under stress conditions by inhibiting photorespiration. Previous studies such as Hirut *et al*. (1989) and Etagegnehu (1994) showed that tef possesses typical C4 leaf structure. It has two layers of bundle sheath and a single layer of mesophyll cell. Granal chloroplasts are present in both tissues with higher concentration in the bundle sheath cells.

1.2 Grain chemical composition and use

The grain of tef is used to make a variety of food products, including *injera*, a spongy fermented flatbread that serves as the staple food for the majority of Ethiopians. Chemical composition analysis showed that tef has comparable nutritional content with the major cereal crops: maize, barley, wheat and sorghum, cultivated in Ethiopia. Tables 1 and 2 present nutritional and amino acid contents of tef in comparison of other major Ethiopian cereal crops adopted from Agren and Gibson (1968), Alemayehu (1990) and Jansen *et al.* (1962), respectively with minor modification.

Content item	Tef			Barley (whole	Maize (whole)	Wheat (whole)	Sorg-hum (whole)
	Nech (white)	Key (Brown)	Sergegna (mixed)				
Food energy (cal.)	339	336	336	334	356	339	338
Moisture (%)	10.4	11.1	10.7	11.3	12.4	10.8	12.1
Protein (g)	11.1	10.5	7.2	9.3	8.3	10.3	7.1
Fat (g)	2.4	2.7	2.9	1.9	4.6	1.9	2.8
Carbo-hydrate (g)	73.6	73.1	75.2	75.4	73.4	71.9	76.5
Fibre (g)	3.0	3.1	3.6	3.7	2.2	3.0	2.3
Ash (g)	2.5	3.1	3.0	2.0	1.3	1.6	1.5
Calcium (mg)	156.0	157.0	140.0	47.0	6.0	49.0	30.0
Phosphorus (mg)	366.0	348.0	368.0	325.0	276.0	276.0	282.0
Iron (mg)	18.9	58.9	59.0	10.2	4.2	7.5	7.8

Source: Agren and Gibson (1967)

Table 1. Nutrient content of major Ethiopian Cereals per 100gm

Amino acid	Tef	Barley	Maize	Rice	Sorg-hum	Wheat	Pearl millet	FAO pattern	Whole egg
Lysine	3.68	3.48	2.67	3.79	2.02	2.08	2.89	4.20	6.60
Laoleucine	4.00	3.58	3.68	3.81	3.92	3.68	3.09	4.20	7.50
Leucine	8.53	6.67	12.5	8.22	13.3	7.04	7.29	4.80	9.40
Valine	5.46	5.04	4.45	5.50	5.01	4.13	4.49	4.20	7.20
Phe-alanine	5.69	5.14	4.88	5.15	4.90	4.86	3.46	2.80	5.80
Trysosine	3.84	3.10	3.82	3.49	2.67	2.32	1.41	2.80	4.40
Trypto-phan	1.30	1.54	0.70	1.25	1.22	1.07	1.62	1.40	1.40
Threonine	4.32	3.31	3.60	3.90	3.02	2.69	2.50	2.80	4.20
Histidine	3.21	2.11	2.72	2.50	2.14	2.08	2.08	-	2.10
Arginine	5.15	4.72	4.19	8.26	3.07	3.54	3.48	-	6.90
Methionine	4.06	1.66	1.92	2.32	1.39	1.46	31.35	2.20	3.80
Cystine	2.50						3.19	2.00	2.40

Source: Alemayehu (1990); Jansen et al. (1962)

Table 2. Amino acid contents of tef compared with other cereals, the FAO pattern and whole egg (g per 16 grams of nitrogen)

The three tef types are especially rich in mineral nutrients calcium, phosphorus and iron compared to the other major cereal crops maize, barley, wheat and sorghum. There is also slight difference in nutrient content among the three tef types. The carbohydrate content of tef is comparable with other cereal crops ranging from 73.1% (brown) to 75. 2% (mixed tef) with average value of 73.9%. Since tef is the major component of Ethiopian recipe, it provides the major requirement of energy. *Nech* (white seed color) tef has 11.1% protein content which exceeds its content for other major cereal crops during the time of analysis. All the three tef types contain significantly higher mineral nutrients (Calcium, potassium and iron) compared to maize, sorghum, wheat and barley and also have reasonably high fiber (3.2%) and ash (2.9%) contents averaged over the three tef types. Amino acid composition of the three tef types was reported to be the same (Tadesse, 1975; Endeshaw, 1989) regardless of their seed color.

Tef is used in various forms by Ethiopians. The dominant form of usage is *injera*, unleavened pan cake made of tef flour, which is the mainstay of Ethiopian diet. It is also consumed in the form of porridge and bread. Its straw is a nutritious and highly preferred feed for livestock compared to the straw of other cereals particularly during dry season. Besides its local use, it is the major cash earning crop for the farming community as market price for both its grain and straw is higher compared to other cereal crops. It is also among export commodity at national level.

2. Tef productivity under changing climate

In tropics, the most important climatic factors that influence growth, development and yield of crops are rainfall, temperature and solar radiation even though relative humidity and wind velocity can also influence crop growth to some extent. Yielding potential of any crop is mainly depends on climate and more than 50% of variation in yield of a crop is due to climatic variability (Reddy & Reddi, 1992). Rainfall is the most dominating factor that influences crops productivity in tropical environment. Precipitation is reaching of atmospheric humidity either as rain to the ground in regions characterized by high temperature. In Ethiopia, the entire precipitation occurs as rainfall.

The amount of precipitation above the basic minimum required to enable the crop to achieve maturity determines its yield. This requirement varies for various crops and different developmental stages of the same crop. Intensity and distribution of the rainfall are very crucial for satisfactory growth and development of crops. If the intensity of rainfall much exceeds the rate of infiltration of the soil, the consequences are runoff and development of anaerobic conditions in the root zone of the crop. These conditions affect crop performance through nutrient deprivation and oxygen deficiency. Similarly, if its intensity is less to satisfy infiltration and evaporative demands, the crop is subjected to water deficiency which greatly affects its productivity. The amount of rainfall received at periodic interval also determines the final productivity of crops as crops response to moisture varies from stage to stage. Temporal and spatial distribution of rainfall also greatly varies. In tropics the spatial and temporal variability of rainfall is greater compared to the temperate. Records from meteorological stations show much spatial and temporal variability of rainfall in Ethiopia and as a result the country is characterized by many agro ecologies. More than 70% of the rainfall is received in the months of July and August in most parts of the country despite the fact that the cropping period extends to mid October. There is usually water deficiency during the later developmental stages of crops in arid and semiarid parts of the country, this uneven distribution of rainfall within the same cropping season has been blamed for causing significant yield losses. The variability across years is presented in figure 1, based on rainfall data obtained from satellite.

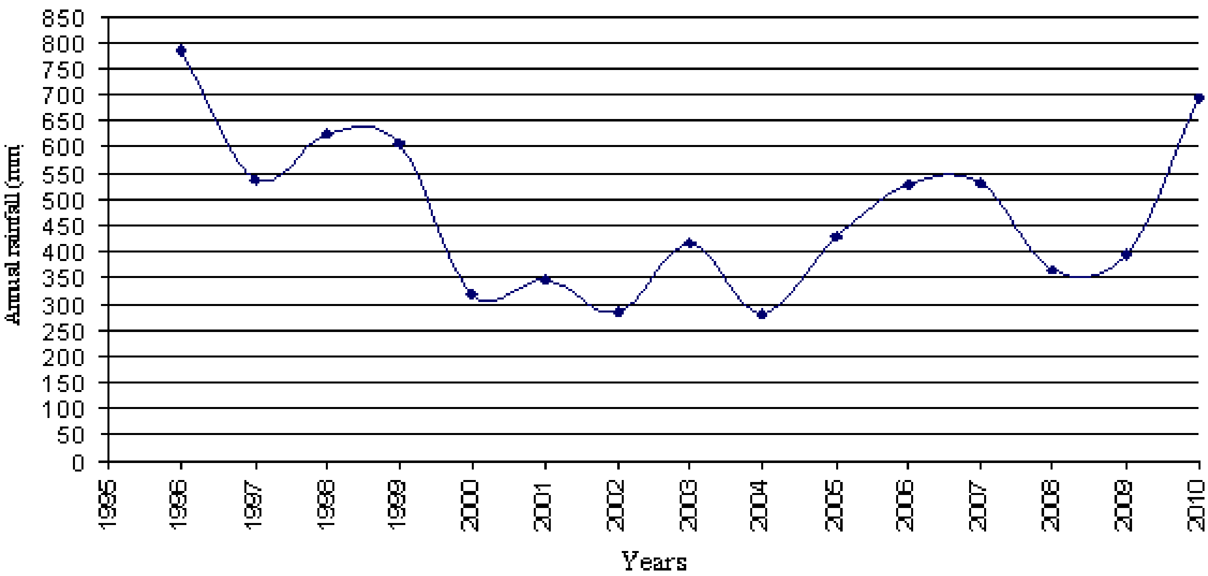


Fig. 1. Trend of annual rainfall distribution of the last 15 years at *Adiha*, northern Ethiopia

More than 50% of the cropping seasons received annual rainfall of less than 500mm which indicates every other year is dry. Early and late season droughts are commonly affecting the agricultural sector in Ethiopia. Early season drought could delay sowing and /or causes poor germination of sown crops as soil moisture content is the major environmental factor affecting crop germination and its establishment. Most of the crop seeds germinate well within the moisture regime of field capacity to 50 percent available soil moisture (Reddy & Reddi, 1992). It is stated that 'drought is an insidious natural hazard characterized by lower than expected or lower than normal precipitation that, when extended over a season or longer period of time, is insufficient to meet the demands of human activities and the environment'. The cropping seasons of 2000, 2001, 2002 and 2004 can be regarded as droughty as the annual rainfall received is by far less than the requirement of most crops. Terminal drought, which usually occurs due to early cessation of rainfall, affects the productivity of crops as it coincides with the most water deficit critical development stages. Water deficit at these critical stages leads to irreversible yield loss. These stages are known as critical period or moisture sensitive stages. In tef, the most important moisture deficit sensitive later developmental stages include flag leaf initiation, flowering, panicle initiation and early grain filling (Dejene, 2009).

Water stress affects various plant growth phases, which starts with activation of the embryo and ends with maturation of the seed, depending on period of its occurrence. Early season stress affects the germination, establishment and crop stands while late season stress affects flowering, fruit or seed setting and fruit or seed quality. Investigations carried out so far on this crop indicated that both its agronomic and physiological traits are affected if the crop is subjected to different levels of water stress.

2.1 Physiological responses

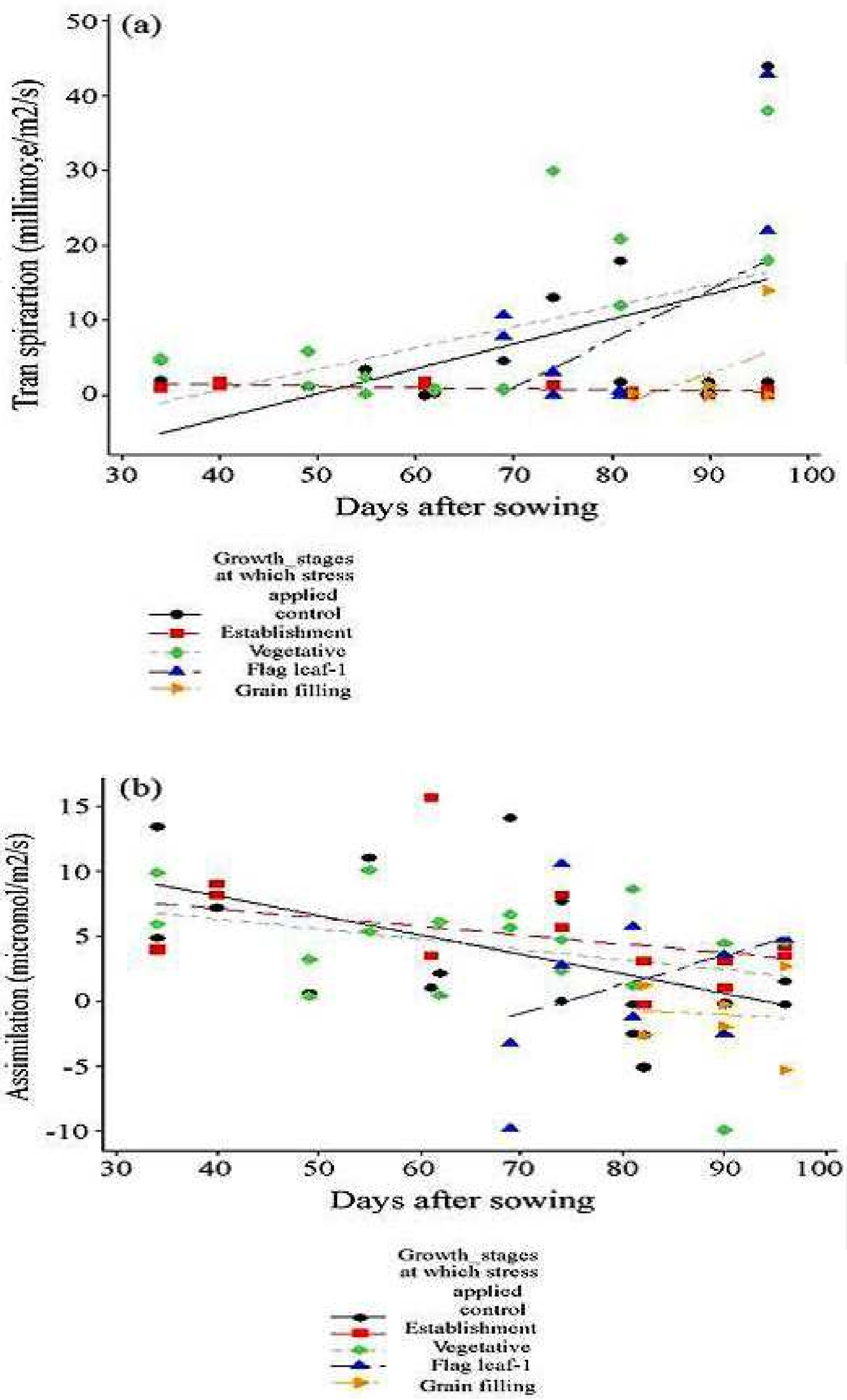
Photosynthesis, which links the inorganic and organic worlds, is an important metabolic process that link water (H_2O) and carbon dioxide (CO_2) in the presence of light to form organic compounds, sugar. So, continuous supply of the raw materials, H_2O and CO_2 and harvesting as much solar energy as possible, is vital for maximum photosynthesis and thereby maximum dry matter accumulation. The main principle in agronomy and physiology is aimed at ensuring appropriate supply of crop with sufficient water and nutrients to keep its health for maximum light interception and carbon dioxide fixation. Hence, the understanding of critical water stress sensitive developmental stages is vital for management of this scarce resource. Water deficit imposed during the reproductive stages of tef can cause reduction in net assimilation rate depending on its severity. For instance, in study conducted to investigate the influence of various soil moisture regimes on physiological processes of tef, it was found that severe water stress (75% of water withhold) has caused 92.8% and 60% reduction in net assimilation and respiration, respectively (Dejene, 2009).

Upon impose of water stress during vegetative developmental stage, tef respiration increased for sometimes and gradually declined below its value obtained under normal growth conditions (Fig. 2a). Similarly the rate of photosynthesis fallen below the control treatment upon exposure to water deficit during vegetative stage and gradually increased to maintain its maximum photosynthesizing potential (Fig. 2b). Stress imposed during flag leaf emergence had significant impact on tef metabolism even though the rate of recovery to normal state is fast after the plant relieved from the stress. Both net assimilation and respiration rates are severely affected by water stress imposed during grain filling stage which shows clearly that the crop possess differential response to water stress during different developmental stages. Reduction of net photosynthesis by moisture stress could be due to reduction in photosynthesis rate, chlorophyll content, leaf area, increase in assimilate saturation in the leaves and closure of stomata.

The stomatal conductance of tef gradually decreased as severity of water deficit increased even though the effect greatly varies for various developmental stages. Highest (97.5%) reduction in stomatal conductance, measured on flag leaf, of tef was reported so far up on exposure of the crop to severe water deficit (75% water withhold), compared to the control treatment, during grain filling stage. The sensitivity of tef physiological processes to water stress imposed during the later developmental stages dictates the need of judicious agronomic crop management in areas where terminal drought is prevalent. Understanding of the physiological processes affected by moisture stress is necessary to ameliorate the stress effects either by management practices or by plant improvement.

2.2 Grain yield

Moisture regimes during flowering and grain development stages determine the number of grains and size of individual grain weight. The effect of water stress depends largely on what proportion of the total dry matter produced is considered as useful material to be harvested (Reddy & Reddi, 1992). For cereals moisture stress during anthesis phase is detrimental. Naturally occurring terminal drought usually coincides with reproductive stages of the crop and consequently the associated yield loss is immense. The magnitude of yield loss actually varies depending on various factors such as crop type, variety, crop developmental stage at which the stress develops and other environmental conditions. Water stress affects yield attributes and final yield. In tef, water stress imposed during reproductive stages significantly affects its yield attributes and the final yield (Tables 3 and 4).



Adopted from Dejene (2009)

Fig. 2. (a) The trend of tef transpiration rate during (start of each line) and after relieved from the stress (b) The trend of net CO_2 assimilation, averaged over stress levels, during (starting point) and after relieving from the stress during different developmental phases compared with the control.

Source of variation	D.f	Mean square values		
		DM	PL	GY
Rep	1	19.636	8.439	0.86970
Variety	10	56.645**	107.218**	1.07495**
Water stress	2	92.924**	64.753**	8.61455**
Variety × water stress	20	24.191**	14.551**	0.14631**
Residual	32	5.574	5.123	0.06765
Total	65			

*** Significant at significance level of 1%*

Table 3. Mean square values of ANOVA results for days to maturity (DM), panicle length (PL) and grain yield (GY) (t ha^{-1}) of tef varieties grown under three water regimes

Stress level	GY	DM	PL
0%	2.30	92.23	31.4
35%	1.49	95.45	29.7
65%	1.09	96.06	28.5
LSD (5%)	**0.16**	**1.45**	**1.07**

Table 4. Effect of water deficit on mean maturity time (DM) mean panicle length (PL) and mean grain yield (GY) (t ha^{-1}) of tef, averaged over varieties under greenhouse conditions

Table 3 shows main effect of both water stress and varieties and their interaction effects on all measured tef attributes is highly significant. The yield loss, due to moderate (35%) and severe (65%) water stresses imposed from booting to grain filling stages, of tef was 35.3% and 52.3% respectively compared with fully irrigated plots (Table 4). For cereals, water deficit at panicle initiation is critical. As the panicle is the organic that growing most rapidly, it is most affected by stress due to reduction in cell expansion (Reddy & Reddi, 1992). The delay in maturity due to water deficit imposed during reproductive stage might imply that tef does not use developmental plasticity as escaping mechanism of the stress period. Even though significant yield reduction recorded under this particular case, the overall performance of the crop under water deficit condition shows that the crop has good level of tolerance to water deficit compared to other cereal crops such as wheat and maize (*data not shown*). The significant variation in response of the imposed water stress among tested tef varieties implied an opportunity of selecting tolerant varieties in drought prone areas (see section 3.2).

This calls for adaptation strategies that ensure minimization of this irreversible yield loss as drought occurrence is inevitable. Drought, because of climate change, is becoming a vital challenge to agricultural sector in the world. Various studies show that without the knowledge of adaptation, climate change is generally detrimental to the agriculture sector; but with adaptation, vulnerability can largely be reduced (e.g. Elizabet *et al.,* 2009; Maddison, 2006). According to Gbetibouo (2009), adaptation is widely recognized as a vital component of any policy response to climate change. The degree to which an agricultural system is affected by climate change depends on its adaptive capacity, which refers to the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damage, to take advantage of opportunities, or to cope with the consequences (IPCC, 2001). Thus, the adaptive capacity of a system or society describes its ability to modify its characteristics or behavior so as to cope better with changes in external conditions. Adaptation to climate change requires that farmers' first notice that the climate has been changing and then identify potential adaptation strategies to be implemented (Maddison 2006).

3. Crop management strategies to avert the effect of terminal drought

There are various agricultural management practices in place for adaptation to water stress including supplementary irrigation, diversification of crop varieties, adjustment of cropping calendar and diversification of different enterprises.

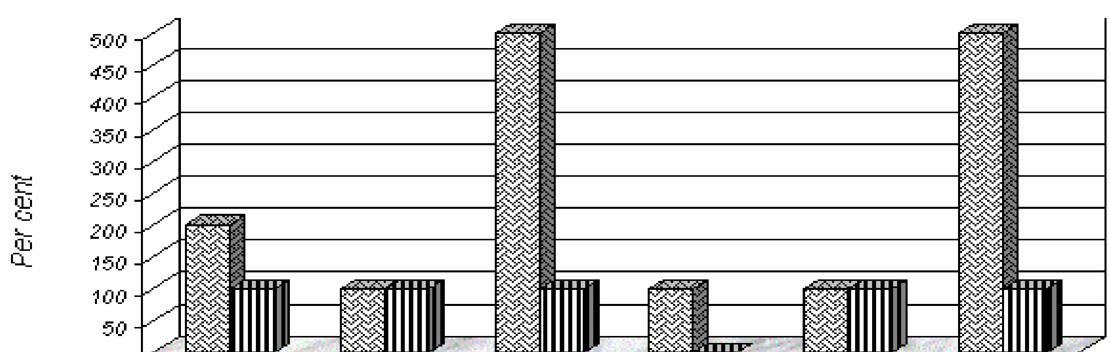
3.1 Spate irrigation

Irrigation is needed to be scheduled whenever soil moisture is depleted to critical soil moisture level to avoid irreversible yield loss. Under limited water supply conditions, irrigation should be scheduled targeting moisture deficit sensitive stages of crops and skipped at non – sensitive stages. In drylands, water is the scarcest natural resource competed for by many sectors. Moreover, many drylands are deprived of running water bodies to use for irrigation. Where the mean annual potential Evapotranspiration exceeds the mean annual rainfall, rainfed crop production is uneconomical, unless supported by irrigation. Runoff flood diversion or spate irrigation, which can be defined as *flood harvesting and management system, involving the diversion of flowing flood using some deflecting technologies (using simple deflectors of bunds constructed from earth, sand, stones, brushwood and recently gabions, masonry or concrete structures) on the beds of normally dry creeks or river channels in to a farmland*, was proved to be an alternative water management system to improve agriculture productivity in drylands. It is believed that spate irrigation was started in the present day Yemen and has been practice there for around five thousand years (Lawrence *et al.,* 2005). This type of traditional irrigation is most commonly practice in arid and semi arid parts of the Middle East, East Africa (e.g. Ethiopia, Eritrea, Somalia and Sudan), North Africa (e.g. Morocco, Algeria and Tunisia) and West Asia (e.g. Pakistan, Iran and Afghanistan). Communities in these areas have developed this irrigation practice to cope with the unpredictable erratic rainfall in the regions (Lawrence *et al.,* 2005).
Spate irrigation is characterized by a great variation in the size and frequency of floods from year to year and season to season, which directly influence the availability of water for agriculture. According to Abraham (2007) spate irrigation is practiced in lowland areas where there is surrounding mountainous with better rainfall pattern that can serve as source of flood and deep soils that are capable of storing ample water to support crops during period of low precipitation. The use of spate irrigation systems varies based on hydro – geological (catchments characteristics, rainfall pattern), geographical and sociological (land tenure, social structure) situations. It is also distinct from other irrigation systems such as river diversions that use water from perennial rivers. In spate irrigation systems there is high uncertainty. Lawrence *et al.* (2005) related this uncertainty to the unpredictability in timing, volume and sequence of floodwater. This system of irrigation is mainly managed by farmers.

Two types of spate irrigation are known in Ethiopia: highland and lowland systems (Wallingford *et al.,* 2007; Catterson *et al.,* 1999). The highland spate system is usually referred as run-off system diverts flashy floods received from the same catchments to the relatively small irrigable land. On the other hand, the lowland spate irrigation system is practiced in the foothills of mountainous water shades and covers larger command areas. Flood that comes from the neighboring mountains becomes steady and lasts for longer time. Spate irrigation in Ethiopia differ form those in the Middle East and South East Asia where farming is more unpredictable and entirely dependent on one or two flood events and rainfall events. In contrast farming in Ethiopia relies more on rainfall and spate irrigation can serve as supplementary to rainfall. More than 140,000 hectare of land in Ethiopia is estimated to be under spate irrigation.

Spate irrigation enriches the moisture content of the soil and assists crops water uptake even after cessation of precipitation. Many crops complete their growth on this residual moisture. The productivity of many cereal and vegetable crops such as sorghum, millets, pepper and cabbage has been increasing in marginal areas due to spate irrigation. For instance, Berhanu (2001) shows a yield increment of 400% and 100% for pepper and sorghum, respectively in Ayub and Jarota lowlands of northern Ethiopia because of spate irrigation (fig.3).

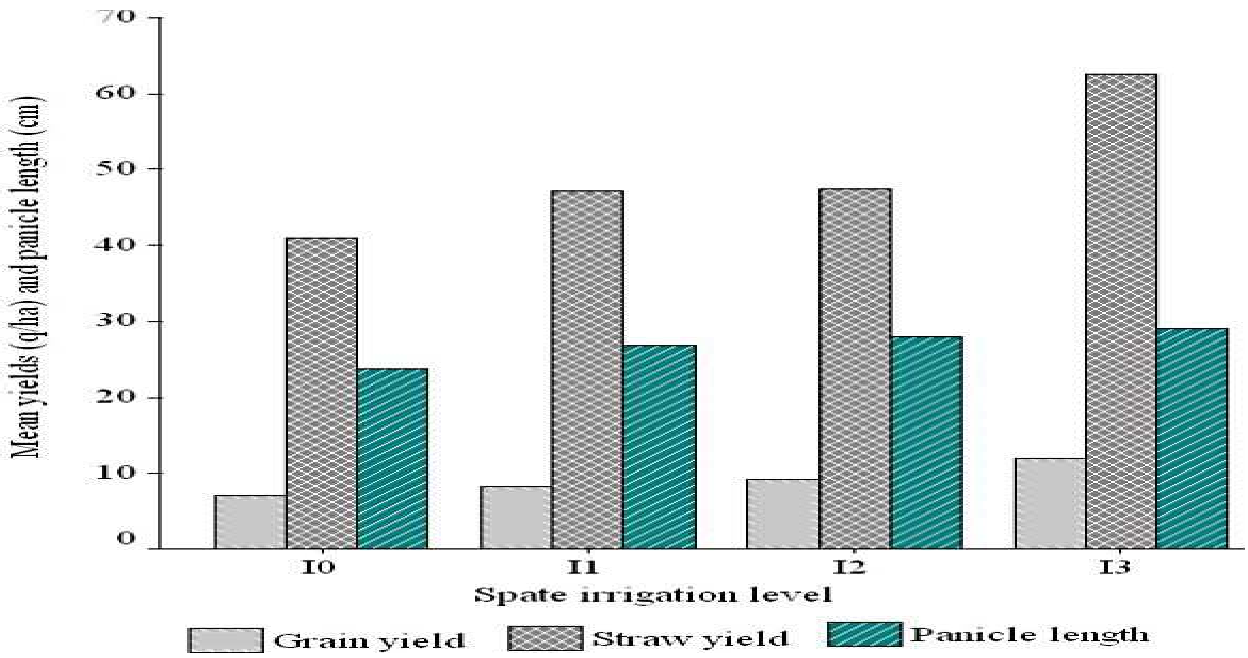
The author reported that there is no any yield advantage for tef due to supplementary spate irrigation despite various studies such as Hailu *et al.* (2000) and Dejene (2009) came up with opposite result. Both studies concluded that tef is susceptible to particularly terminal drought which coincides with its reproductive stages and respond to supplementary irrigation. Strong evidence also came out from 2009 trail conducted to test the effectiveness of spate irrigation for tef based farming system in central Tigray, Ethiopia on fragile soil where the seasonal rainy period last only for two months. Diversion of flood water into tef farm particularly during the later developmental stages significantly increased grain and straw yields over the control plot (Fig. 4).



	Sorghum	Teff	Pepper	Sorghum	Teff	Pepper
			Ayub			Jarota
Yield with flood (%)	200	100	500	100	100	500
Yield without flood (%)	100	100	100	0	100	100

Source: Berhanu, 2001

Fig. 3. Yield differences of various crops due to spate irrigation



I0 = rainfed, no flood irrigation, I1 = supplementary flood irrigation at tillering stage, I2 = supplementary spate irrigation at tillering and flag leaf stages, I3 = supplementary spate irrigation at I2 plus grain filling stages of the crop.
Source Dejene et al. (2010)

Fig. 4. Tef mean grain yield, straw yield and panicle length as affected by spate irrigation at *Adiha*, Tigray, northern Ethiopia

Supplementing tef during reproductive stage with flood irrigation could fetch more than 50% yield advantage over non supplemented plots. The increment for straw yield was also appreciable (Fig. 4). The increment in yield is the result of improvement of soil moisture content in crops root zone. This implies that supplementing tef farm with any form of irrigation could potentially increase its productivity and hence the economical return of involving farmers.

3.2 Varietal selection

There are several varieties of tef cultivated in wider agroecologies of Ethiopia which could not have similar performance elsewhere. These varieties are classified as early, intermediate and late based on their maturity period. Some are engineered for highland areas, others to mid – altitude and still others to lowland areas. Lowland areas are characterized by high temperature and low and erratic rainfall compared to the highlands. Genotype × environment analysis made on common tef varieties by Tiruneh (2000) using bi – plot principal component analysis approach clearly showed differential adaptation of these varieties to different localities. Intermediate maturing varieties are preferred to both early and late maturing varieties in areas characterized by low moisture. Hence, varieties that perform best in highlands might not perform well in low lands and vise versa. Similarly the performance of farmers' landraces and modern improved varieties also differ greatly.
Testing for their performance and selecting best performing ones should be done as varietal selection is suggested as one of the management approaches to adapt to changing climate. Crop varieties have differential response to water deficit developed at various developmental

stages. Because of this, several genotype × environment interaction studies have been conducted on different crops to come up with recommendations that consider the differential response of varieties in various environments to avoid blanket recommendation. The yield of tef varieties under water deficit is presented below (table 5) from experimental finding conducted with the objective of evaluating and screening of tef varieties under three water regimes. Better performance of local varieties (*Abat Key, Abat Nech, Kobo and Wofey*) than improved varieties should be attributed to their adaptation to naturally occurring terminal drought. Even though there is significant reduction of grain yield and other yield components, the level of reduction for local varieties is small as the stress level increases compared to improved varieties. Variability in response among the varieties might be related to difference in their morphological, physiological and biochemical reactions against the stress.

Stress level	Varieties											
	Abat Keyi	Abat Nech	Berkay	DZ- cr-358	DZ-01-1281	DZ-01-1285	DZ-01-1681	DZ-01-99	DZ-Cr-37	Kobo	Wofey	LSD2 (5%)
No stress (0%)	3.19	2.23	1.77	2.68	3.32	2.04	1.96	1.74	2.44	1.96	2.00	**0.15**
Mode-rate stress (35%)	2.15	1.73	0.70	1.39	1.80	1.56	1.18	1.06	1.97	1.62	1.28	
Severe stress (65%)	1.43	1.33	0.32	0.93	1.33	1.32	0.60	0.31	1.48	1.42	1.27	
LSD1 (5%)	**0.53**											

LSD1 (5%) = Least significance difference value for comparing the stress levels effect on particular variety
LSD2 (5%) = Least significance difference value for comparing the differential response of varieties at a particular stress level

Table 5. Mean grain yield (t ha^{-1}) as affected by the interaction of tef varieties (six improved and five local) and three water regimes

Tef adapts drought by using various strategies such as leaf rolling as morphological adaptation (Dejene, 2009); osmotic adjustment by solute accumulation (Mulu, 1999); control of stomatal aperture (Belay & Baker, 1996 and lower excised leaf water loss (ELWL) (Mulu, 1993). These authors, except Dejene (2009), evaluated various tef genotypes for these strategies and their result indicated that there exist different degrees of response to drought among the genotypes. Genotypes with high osmotic adjustment, lower stomatal conductance and gradual water loss (lower ELWL) under drought are high yielder than genotypes having the opposite trait.

3.3 Changing of sowing date

Farm level decision making is vital to adapt to changing climate. Farmers' knowledge and perception of changing climate is vital to adjust their farming practices as response.

Currently, only few farmers adjust their sowing time in response to perceived climate change as they have no access to information based on long term data (Elizabet *et al.,* 2009). Under such situations, the cropping calendar of farmers remains as it is despite change in timing of rainfall. Tef production activity calendar varies from location to location, and its production takes place mainly during the long (Meher) rainy season. Tef sowing starts from end of June and extends to early September (Kenea *et al.,* 2000) depending on growing length of particular location and beginning of rainfall. However, in most places, tef may be sown between mid – July and early August (Yilma & Cajuste, 1980). This cropping calendar was adopted when appreciable amount of rainfall received in the months of September and the first two – weeks of October. And still practiced despite of great departure of rainfall from normal distribution due to global climate change.

In recent days there is change in trend of rainfall across the country where its starts in May and ceases early – to – mid September. This early cease of rainfall matches crop's reproductive stages, stages most sensitive to water deficit, with periods of water shortage. Coincidence of water deficit sensitive developmental stages of crop with soil moisture deficit causes both quantity and quality loss to the final yield as indicated in section 2.2. Date of sowing has a profound influence on crop performance because it determines the kind of environmental conditions to which the various phenological stages of the crop will be exposed. The sensitivity to some diseases and insect pest damage as well as length of growing period is also related to the effect of date of sowing. Table 6 presents the effect of sowing date on performance of tef at *Adiha*, site severely affected by terminal drought.

A trial involved three sowing dates: July 12, July 22 and Aug., 02 was conducted in 2009 to test the effect of sowing date on tef performance at *Adiha*, a site characterized by severe terminal drought due to early cessation of rainfall and sandiness of the soil. Tef is commonly sown starting from the end of July and lasts up to the mid- August in the study area. Late sowing is preferred despite early cessation of rainfall due to the danger of shoot fly (*Delia arambourgi* (Seguy)) infestation on early sown plots. Similarly during the experimental season early sown plots were seriously infested with shoot fly as a result of which the performance of early sown plots was significantly inferior to the other two treatments. Both grain and straw yields of the early sown plots were significantly ($p<0.01$) lower than the other two sowing dates due to infestation by shoot fly (*data not shown*). Had it been no infestation of shoot fly, the early sown plots should have given higher grain and straw yields as the crop takes longer period for maturity which allows it to intercept more light.

Sowing date	Ph	TN	DM	PL	GY	BM
12/7/09	55.0	1.83	88.17	22.4	0.374	2.46
22/7/09	**55.4**	**2.87**	**81.33**	**23.3**	**0.523**	**3.212**
02/8/09	64.4	3.00	75.83	24.3	0.465	3.01
LSD (0.05)	5.5	1.12	5.1	1.74	0.065	0.35
P value	<0.01	0.08	<0.001	0.09	<0.01	<0.01

Table 6. The effect of sowing date on mean plant height (cm), tiller number, days to maturity, panicle length (cm) and grain and straw yields (t ha^{-1}) of tef at Adiha

The second sowing time, 22/7/09, advanced tef sowing calendar of the area by one week and increased grain and straw yields by 12.5% and 6.7% respectively over the third sowing period (Table 6), which is the sowing period of local farmers in the study area. This implies that adjusting cropping calendar is vital to adapt to the changing climate of the area.

3.4 Soil fertility management

Soil factors influencing its water holding capacity are its texture, structure and chemical composition. In dryland areas where the soil is dominantly sandy or sandy loam, the effect of terminal drought on crops performance is reported very significant. Maintenance of soil fertility using various sources of fertilizers has several advantages apart nutrient supply to the plant. The fact on the ground is that soil nutrient status of most farming systems is widely constrained by the limited use of inorganic and organic fertilizers and by nutrient loss mainly due to erosion and leaching (Balesh *et al.,* 2007). Many smallholder farmers do not have access to synthetic fertilizer because of its high price, lack of credit facilities, poor distribution, and other socio-economic factors. Consequently, crop yields are low, in fact decreasing in many areas, and the sustainability of the current farming system is at risk (Stangel, 1995). This declining soil fertility (Fekadu & Skjelvag, 2002) coupled with terminal drought (Edmeades *et al*., 1989; Hailu *et al*., 2000; Dejene, 2009) is posing serious threat to crop production and consequently food security in Ethiopia as elsewhere in Sub – Saharan Africa.

To combat the challenges of climate change, various adaptation strategies have been studied and tried for their effectiveness. Among the different strategies for dryland areas, use of organic fertilizers such as manures and compost applied either in sole or combined with inorganic fertilizers has been attracted special attention. Organic fertilizers have several advantages such as supplying plants with nutrients including micronutrients and improvement of soil structure and water holding capacity (Reddy & Reddi, 1992). Farm generated resources such as crop residues; farmyard manure and compost are regarded as best solutions (CIAT, 2007; Devi *et al.,* 2007) to sustain crop production in dryland areas. Study by Edwards (2007) indicates that organic fertilizers improve crops yield even under arid and semi-arid conditions comparable to chemical fertilizers. Nevertheless sole dependence on organic fertilizers is less feasible due to unavailability of large plant biomass to produce organic fertilizers and competing demands from short-term needs such as for fuel. There should be an alternative approach which reduces heavy reliance on both organic and inorganic fertilizers. Combined application of organic and inorganic fertilizers increase agricultural productivity, improve soil fertility and decrease environmental pollution (Erkossa & Teklewold, 2009; Mugwe *et al*., 2007; Wakene *et al*., 2007; Blaise *et al*., 2003; Corbeels *et al*., 2000). However, this approach has not been yet widely tested in arid and semiarid parts of Ethiopia. Thus, this work presents the effect of combined application of organic [FYM and compost] and inorganic (NP) fertilizers, from two years experiments, on yield and other yield attributes of tef at *Adiha*, a site prone to frequent terminal drought in northern Ethiopia.

3.4.1 Crop improvement

The effects of organic, inorganic and their combined application on yield and yield components of tef were tested on sandy loam soil. Crop response to one factor is influenced by the availability of the other as to the law of the minimum. Yield of crops is the function of many interacting soil and climatic factors. In drylands, water is the most limiting factor of crops productivity even though other factors meet the demand of the crop. Exploring agronomic practices that improve soil water content in the root zones potentially ensures attainment of optimum crop yield. Application of the right type and dose of fertilizer is one of the agronomic practices to improve crops performance. The effect of combined application of organic – inorganic fertilizers, half dose of the recommended rate for both, on crop phenology, grain and straw yields of tef presented in sections 3.4.1.1 and 3.4.1.2.

3.4.1.1 Crop phenology

Organic and inorganic fertilizers affect differently and significantly tef morphological traits such as number of effective tillers per plant, panicle length and plant height (Table 7).

Fertilizer types	Application rate (kg ha^{-1})	Morphological traits of tef		
		Plant height (cm)	Tiller number	Panicle length (cm)
Compost	7000	43.9	4.3	17.2
FYM	7000	44.5	4.9	18.9
NP	23N +30P	68.0	6.6	24.9
½[NPComp]	11.5N+15P+3500Comp	56.7	8.8	22.7
½[NPFYM]	11.5N+15P+3500FYM	64.1	8.0	24.0
Unfertilized	0	40.1	2.5	16.8
LSD (5%)		**5.8**	**1.0**	**2.2**

Values are average of four measurements

Table 7. Effect of organic, inorganic and combined organic – inorganic fertilizers on mean performance of morphological traits of tef at *Adiha*, northern Ethiopia

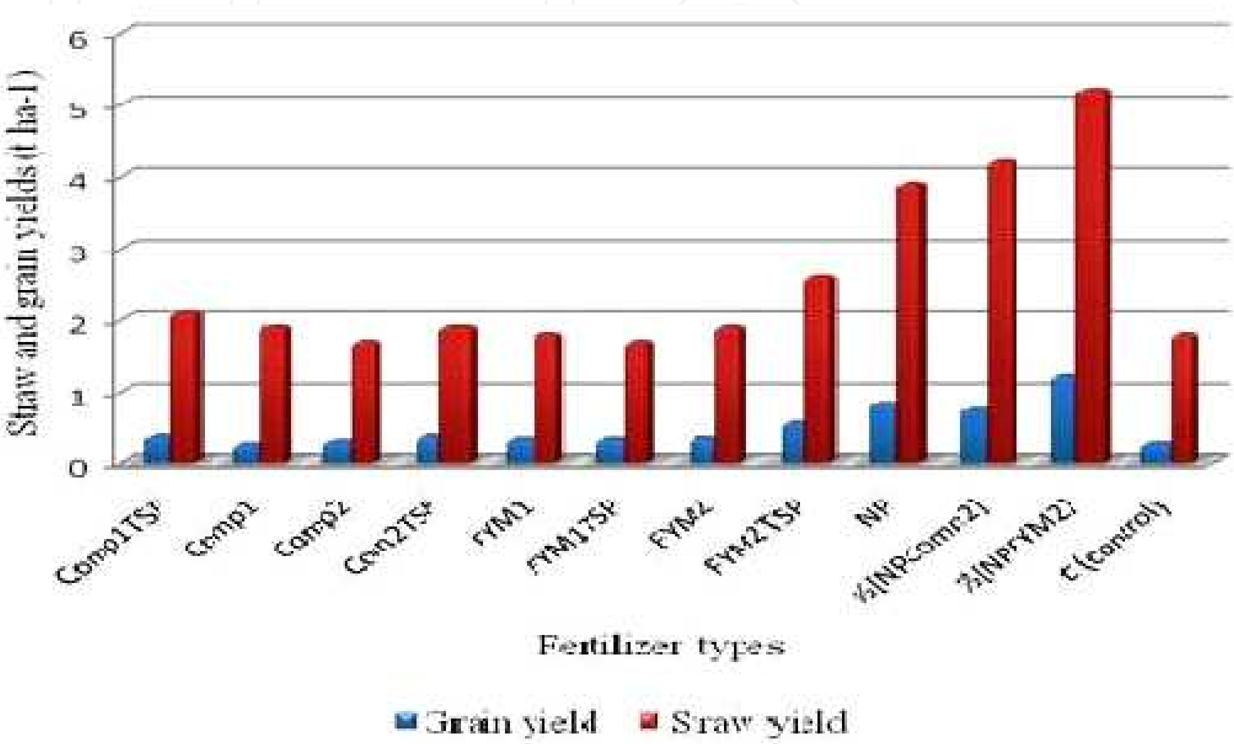
Combined application of, half dose of the sole application, organic – inorganic fertilizers resulted in taller plant height and panicle length and many tillers over sole application of both farmyard manure and compost. The tallest plant and panicle lengths were recorded from inorganically treated plants though the difference is not statistically significant.

3.4.1.2 Straw and grain yields

The importance of tef straw has been becoming as equal as its grain yield as it is preferred as animal feed during dry period and also sold at reasonable price. Farmers prefer varieties having larger biomass and give quite good yield. In dryland areas where soil moisture is deficient for pulverization of and quick release of nutrients from organic fertilizers, mixed application of organic – inorganic fertilizers proved to have more positive effect than sole application of both. Figure 5 presented tef straw (BM) and grain yield (GY) obtained from two years experiment.

Combined application of organic – inorganic fertilizers improves straw yield of tef. The figure shows that the highest (5.2t ha^{-1}) straw yield was obtained from ½[NPFYM2] followed by ½[NPComp2]. ½[NPFYM2] and ½[NPComp2] implies half of the recommended dose for both organic (compost and FYM) and inorganic (NP) fertilizers in the study area. Sole application of both compost and farmyard manure at different rates did not show any improvement over inorganically treated plots for both straw and grain yields. Considering this result as general truth might not be possible as this fact derived from experiment conducted at single location over years. Tef has all cultural, nutritional and economical importance for Ethiopian farmers. The grain is used to make a variety of food products, including *injera*, a spongy fermented flatbread that serves as the staple food for most Ethiopians, and porridge. *Injera* is a cultural food consumed almost by every Ethiopian on daily basis. Ethiopian farmers cultivate tef both for home consumption and for sale. There are three classes of tef based on their seed color: white, red and mixture of both (*sergegna*).

The white seeded tef treated as commercial crop as it fetches them higher market price and not produced for home consumption unless 1) they do not have the red or sergegna tef or 2) if they have surplus white seeded tef. The crop being consumed in Europe and United States of America by Ethiopians and other accustomed nations, its export to these parts of the world has been escalating. On the other hand, as tef is proved to be gluten free, its preference by diabetic people has also been increasing.



Comp1TSP = compost @3.5t ha^{-1} + TSP, Comp1= compost (3.5t ha^{-1}), Comp2= compost (7t ha^{-1}), Comp2TSP = compost (7t ha^{-1}) + TSP, FYM1= FYM (7t ha^{-1}), FYM1TSP = FYM (3.5t ha^{-1}) + TSP, FYM2=FYM@7t ha^{-1}, FYM2TSP = FYM (7t ha^{-1}) +TSP, NP = P@20kg ha^{-1} and N@23kg ha^{-1}, ½[NPComp2) = combined half dose NP and comp2, ½[NPFYM2) = combined half dose NP and FYM2 and C(control) = no fertilizer application
Adopted from Dejene et al. (2011)

Fig. 5. Effect of organic, inorganic and combined organic – inorganic fertilizers, averaged over years, and year on mean Grain yield (GY) and straw yield (DM) of tef

It could be imagined that the productivity of tef is comparable to the productivity of major cereal crops such as wheat and maize having such great cultural, nutritional and economic values. However, due to several production constraints, its yield is far below the average annual yield of other major cereal crops. Although its genetic make – up is to be blamed, suboptimal crop managements contribute the lion share for its low productivity. Recent studies confirm this fact. Recent trials on supplementary application of micronutrients, row planting and transplanting of tef clued that grain yield of tef could increase from 1.2t ha^{-1}, actual current national average productivity, to up to 6t ha^{-1}(*data not presented*).

The response of tef to different fertilizer types significantly vary under various environmental conditions. In drylands, where rainfall both in amount and distribution is erratic, crops response to fertilizers is not the same as when they grow under conducive growing conditions. For instance, result from trial conducted to evaluate the response of tef for compost, farmyard manure, inorganic NP and combination of organic – inorganic fertilizers in area characterized by terminal drought demonstrated that combining FYM with half dose of the recommended rate of NP fertilizers gave the highest grain yield than sole application of either organic or inorganic fertilizers. Grain yield increment of 45% was obtained due to combined application of FYM – inorganic NP over inorganically treated plots. Similarly, application of combined compost and NP fertilizers also increased the grain yield over sole compost and NP even though the increment was not statistically significant for this particular event. Difference in nutrient content (Chong, 2005) could be the reasons for differential impacts of FYM and compost either in sole or combined application. This higher yield from combined application of organic and inorganic fertilizers presumably attributed to continuous supply of nutrient throughout the developmental stages of the crop. Inorganic fertilizers release nutrient during early growth stages and that of organic fertilizers do release during the later developmental stages as they are slow nutrient releasers (Lorry *et al.*, 2006). Furthermore, organic fertilizers potentially increase moisture retention capacity of the soil, which enables the crop to access water even during the dry period. Edwards (2007) indicated that crops treated with organic fertilizers resist wilting for about two weeks longer than inorganically treated plots when encountered terminal drought. Similar reports were came out from Balesh *et al.* (2007) on tef and Mugwe *et al.* (2009) on maize which described the role of organic fertilizers in improving soil water retention capacity which in turn improves water access of the crop.

4. Conclusion

Erraticiness of rainfall and increase of temperature is inevitable due to global climate change. Consensus has been reached among international community that change in climate will have various degrees of negative impacts mainly on agricultural sector. Consequently the vulnerability of agrarian communities to risks related to climate change hazards is very significant. A number of drought mitigation and adaptation strategies were tested in different countries to minimize the effect of climate change on various sectors. The effectiveness of each of the adaptation strategies varies from country to country, region to region and sector to sector. This calls for intensive studies to sort out appropriate and adoptable adaptation strategies. The effectiveness of four agronomic practices: sowing date, varietal test, spate irrigation and fertilizer application was tested for improving tef performance in northern Ethiopia, region characterized by terminal drought. Advancing the sowing day of tef by one week has increased grain yield of tef by 12.5% over sowing date currently practiced by local farmers. Tef varieties have shown significant differential response to water deficit that develop during the later developmental stages.

The significance of interaction effect between tef varieties and stress level shows the possibility of selecting tolerant tef variety to terminal drought prone areas. Local varieties such as *Abat Nech, Abat Keyi* and *Kobo* are more tolerant to terminal drought than improved varieties. This urges the need of paying important attention in tef breeding program to incorporate drought tolerance gene in our improved tef varieties to improve their adaptation to the wider drought prone areas of the country. Tef is highly responsive to water. Supplementing it with any form of irrigation during reproductive developmental stages significantly increase its productivity. On the other hand combined application of organic – inorganic fertilizers revealed to increase both straw and grain yields of tef significantly over inorganic fertilizer. This implies that combining organic - inorganic fertilizers has had positive and synergistic effect on tef productivity in arid and semi-arid areas where terminal drought is acute. Integrating sowing date, selection of tolerant varieties, spate irrigation and maintaining soil fertility will undoubtedly ensures sustainable production of tef even under terminal drought and reduces the vulnerability of communities settled in terminal drought prone areas of Ethiopia.

5. Acknowledgment

We have not written a review of the extensive literature, which records the conclusions of earlier works: references are given mostly to attribute ideas, to back up assertions and to supply elaborations. But we build very largely on other scholars work, and hence take credit which is mostly due to others. We, therefore, are thankful for the contribution of all authors cited in this work.

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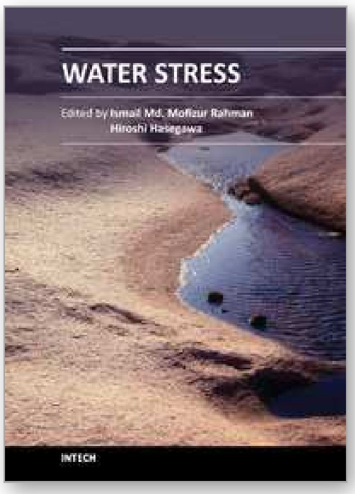

Water Stress

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Plants experience water stress either when the water supply to their roots becomes limiting, or when the transpiration rate becomes intense. Water stress is primarily caused by a water deficit, such as a drought or high soil salinity. Each year, water stress on arable plants in different parts of the world disrupts agriculture and food supply with the final consequence: famine. Hence, the ability to withstand such stress is of immense economic importance. Plants try to adapt to the stress conditions with an array of biochemical and physiological interventions. This multi-authored edited compilation puts forth an all-inclusive picture on the mechanism and adaptation aspects of water stress. The prime objective of the book is to deliver a thoughtful mixture of viewpoints which will be useful to workers in all areas of plant sciences. We trust that the material covered in this book will be valuable in building strategies to counter water stress in plants.