Growth, development and yield responses of sorghum to water deficit stress, nitrogen fertilizer, organic fertilizer and planting density

by

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Abbreviations and Acronyms

AGR	average germination rate
CEC	cation exchange capacity
CGR	crop growth rate
DAE	days after emergence
DAP	diammonium phosphate
EW	epicuticular wax
FC	field capacity
FGP	final germination percentage
FPY	fresh panicle yield
FYM	farmyard manure
GDD	growing degree days
GNC	grain nitrogen concentration
GNU	grain nitrogen uptake
GPC	grain protein concentration
GPY	grain protein yield
GY	grain yield
HI	harvest index
Ie	emergence index
Is	shoot index
LA	leaf area
LAI	leaf area index
LDM	leaf dry matter
LDR	leaf diffusive resistance
m. a. s. l	metres above sea level
MTG	mean time to final germination
NE	northeastern
NHI	nitrogen harvest index
NUE	nitrogen use efficiency
NUE_b	nitrogen use efficiency for biomass production
NUE_g	nitrogen use efficiency for grain production
OC	organic carbon

OM	organic matter
PABM	pre-anthesis biomass mobilization
PADMA	post-anthesis dry matter accumulation
PAR	photosynthetic active radiation
PDM	panicle dry matter
PEG	polyethylene glycol
PL	panicle length
PRI	percent radiation interception
PWP	panicle weight per plant
RDM	root dry matter
RL	root length
RSR	root to shoot ratio
RUE	radiation use efficiency
RWC	relative water content
SDM	stem dry matter
SEM	scanning electron microscope
SHDM	shoot dry matter
SNC	stover nitrogen concentration
SNP	seed number per plant
SNU	stover nitrogen uptake
SWHC	soil water holding capacity
SWP	seed weight per plant
SY	stover yield
TBY	total biomass yield
TDM	total dry matter
TEM	transmission electron microscope
TKW	thousand kernel weight
TNU	total nitrogen uptake
WU	water use
WUE	water use efficiency

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DECLARATION

I, Wondimu Bayu, hereby declare that this thesis for the degree PhD (Agronomy) at the University of Pretoria is my own work and has never been submitted at any other university.

Wondimu Bayu
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GROWTH, DEVELOPMENT AND YIELD RESPONSES OF SORGHUM TO WATER DEFICIT STRESS, NITROGEN FERTILIZER, ORGANIC FERTILIZER AND PLANTING DENSITY

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ABSTRACT

Sorghum (*Sorghum bicolor* L. Moench) is an important crop in the lowland areas of northeastern Ethiopia where its sustainable production is severely hampered by moisture deficits and poor soil fertility. With these problems in mind, experiments were conducted with the goal of quantifying the effect of water deficit stress, rainwater harvesting, organic and inorganic fertilizers, cultivars and planting density on the germination and emergence, growth, yield, grain protein content, grain protein yield and nitrogen use efficiency of sorghum to facilitate the formulation of agronomic practices that can increase the productivity of sorghum under such semi-arid and infertile soil conditions. Soil chemical and physical changes due to farmyard manure (FYM) application were also studied.

Water deficit stress reduced the rate and percentage of germination and seedling emergence, with the greatest effect on the rate of germination and emergence of seedlings. Water deficit stress reduced rates of germination and seedling emergence by as much as 50% and 24%, respectively. Water deficit stress severely reduced the growth of coleoptiles, mesocotyls and radicles. The length of shoots and roots and root area were also greatly reduced. Cultivar Gambella 1107, Meko and P9403

exhibited the highest rate and percentage of germination and emergence and more vigorous seedling growth than the other cultivars.

Water deficit stress at the vegetative stage had a negative effect on plant growth attributes such as shoot height, leaf number and leaf area, root length and biomass production. Water stress also resulted in closed stomata, increased leaf diffusive resistance, reduced starch deposition in chloroplasts and increased epicuticular wax deposition on the leaf surfaces. Cultivars differed in agronomic, physiological and anatomical attributes in response to water deficits, with Jigurti, Gambella 1107 and Meko more tolerant.

Rainwater harvesting, using tied-ridging, adversely affected sorghum growth at Sirinka and had little impact at Kobo. Nitrogen fertilizer applications, in contrast, increased leaf area development, biomass production, grain yield, nitrogen uptake, grain protein content and grain protein yield, thus improving the productivity and quality of sorghum. Sorghum cultivars were found to differ in the growth, yield, grain quality, N uptake and N use efficiency. ICSV111 and 76 T1 #23 performed better for most of the parameters studied as well as in terms of grain protein content and N use efficiency.

The application of FYM and inorganic fertilizers improved the N, P, K and organic matter content, water holding capacity and N balance of the soil and thus improved sorghum biomass and grain yield, quality. The combined use of FYM and inorganic fertilizers increased sorghum yield and quality at reduced inorganic fertilizer input, thus reducing reliance on inorganic fertilizers, and consequent high fertilizer costs. Application of 5, 10 and 15 t FYM ha^{-1} in combination with 100% of the recommended fertilizer rate and 5, 10 and 15 t FYM ha^{-1} in combination with 50% of the recommended fertilizer rate can be recommended for farmers who can and can not afford to buy inorganic fertilizers, respectively.

Sorghum yield, N uptake and N use efficiency increased with increasing population density from 29 629 to 166 666 plants ha^{-1}. Biomass and grain yield increased linearly up to a planting density of 166 666 plants ha^{-1}, which is beyond the conventional

density (88 888 plant ha^{-1}) currently being used in northeastern Ethiopia. Thus, further study to determine the optimum planting density is recommended.

Key words: epicuticular wax, farmyard manure, germination, grain yield, N use efficiency, planting density, semi-arid areas, starch, stomata, water deficit stress, tied-ridging

Introduction

Sorghum (*Sorghum bicolor* L. Moench) is an important crop throughout Africa, much of India, China, the Middle East, Australia, and central and South America (Simpson, 1981). It is the major grain crop for millions of people in a number of the poorest developing countries in the semi-arid tropical regions (Doggett, 1988; House, 1997). In the drought prone semi-arid areas of NE Ethiopia it is also the dominant food crop. It stands second in total area of production and third in total production (CSA, 2000). It plays an appreciable role in supplying the population of this part of the country with protein, carbohydrates and minerals. Furthermore, sorghum stover is a major source of fuel, animal feed and construction material (Hailemichael, 1998).

Despite the importance of sorghum in the livelihood of small-scale farmers, its productivity in developing countries in general (House, 1997), and in Ethiopia (approximately 1.2 t ha^{-1}) in particular, is low and variable. This can be ascribed to several biophysical and socioeconomic constraints, of which low and erratic rainfall, poor soil fertility, and high temperatures are the most important (Doggett, 1988; Nguyen *et al*., 1997; Rosenow *et al*., 1997; Traore & Maranville, 1999).

A sorghum crop in NE Ethiopia is often confronted, either separately or concurrently, with water and nutrient limitations. Consequently, sorghum yields in this region still fall behind the national average yield of 1.2 t ha^{-1}. The environment where sorghum is largely grown in NE Ethiopia is often characterized by a combination of infertile soils, low and variable rainfall and increasing pressure on land resources. The soils are predominantly shallow, low in organic matter content, poor in water holding capacity and poor in plant nutrients (Georgis & Alemu, 1994; Bayu *et al*., 2002). Soils are mainly deficient in nitrogen (Bayu *et al*., 2002). The rainfall is usually inadequate, short in duration, poorly distributed and highly variable between and within seasons (Georgis & Alemu, 1994). The environmental conditions are also characterized by high evapotranspiration, owing to high temperatures. Monthly potential evapotranspiration usually exceeds rainfall except in July and August (Reddy & Georgis, 1993). In general, moisture deficits and nutrient limitations are the primary constraints that result in low and unstable sorghum yields.

In NE Ethiopia drought and the associated crop failure are a year-to-year challenge to small-scale farmers. Every year small-scale farmers face the increasingly difficult task of producing sufficient food for their own needs, whilst generating cash income from surpluses for other needs. Increasing and sustaining crop productivity in these areas also pose what is perhaps the greatest challenge to agricultural scientists. Traditionally, the approach has focussed on single elements of the farming system, such as improved genotypes, mineral fertilizers, or soil and water conservation measures. However, substantial impacts have often failed to materialize using this fragmented approach.

It is now realized that crop productivity, under semi-arid conditions, could best be enhanced by the integrated use of agronomic measures focussing on rainfall productivity and soil fertility management. Particularly in NE Ethiopia, recurrent droughts and crop failures necessitate the integrated use of agronomic measures that can address the prevalent problems associated with moisture deficit and poor soil fertility. This study was, therefore, initiated with the hypothesis that sorghum productivity in NE Ethiopia can best be enhanced through rain water harvesting, through the use of organic and inorganic fertilizers, through selecting cultivars, which are tolerant to drought stress and efficient in nutrient use, and through adjusting planting density to the available moisture and fertility conditions. The general objective of the study was to determine the effect of water deficit stress, rainwater harvesting, organic and inorganic fertilizers, cultivars and planting density on the growth, development, yields and nitrogen use efficiency of sorghum in order to formulate agronomic practices that can increase the productivity of sorghum under the semi-arid and infertile soil conditions of NE Ethiopia.

Specific objectives included the following:

1. To study the response of sorghum seed germination to different levels of water deficit stress and to evaluate genetic differences.
2. To examine the response of sorghum cultivars to different levels of water stress and to assess genetic variability in the expression of drought stress adaptive mechanisms.
3. To evaluate the growth, development, yield and grain quality response of sorghum

to moisture conservation, nitrogen fertilizer and cultivar selection and to examine genetic differences in nitrogen use efficiency among sorghum cultivars.

4. To assess the growth, development, yield and grain quality response of sorghum to the combined application of organic manure (FYM) and inorganic fertilizers (N and P) and to study changes in soil N, P and organic matter.
5. To assess the growth, development, yield and grain quality response of sorghum to planting density at different nitrogen fertilizer levels.

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CHAPTER 1

Literature Review

Effects of water stress on seed germination, seedling emergence and growth

Semi-arid areas are characterized by limited and erratic precipitation, frequently resulting in droughts at different periods during the growing season. Water stress is recognized as one of the most severe abiotic stresses influencing crop productivity in these areas (Blum, 1988). Most studies on drought tolerance have focused on the late vegetative and reproductive periods of growth, and the effects of drought during those periods on yield. However, since successful field establishment and vigorous stands contribute to higher yield, traits of drought tolerance should also include the ability of seeds to germinate and seedlings to develop under limited moisture availability (Baalbaki *et al*., 1999).

Soil water supply is an important environmental factor controlling germination and seedling emergence. Drought stress often limits germination and emergence in semi-arid regions either by delaying initiation of germination, by slowing the rate of germination or by decreasing final percentage germination (Hegarty, 1978; Kramer & Kozlowsky, 1979; Baalbaki *et al*., 1999). The reason for reduced germination under water stress conditions has been stated by Hadas (1976) to be the effect of low water potential on enzymatic activity, and not to limiting water uptake. Singh & Ambawatia (1988), on the other hand, indicated that low water uptake and restricted metabolic activities were causes for reduced germination under water stress. The research results of Gurmu & Naylor (1991) and Falleri (1994), however, attributed reduced germination to reduced water uptake. It is also evident from the results of Stout *et al*. (1980) that water uptake of two sorghum cultivars, germinated under a PEG 6000 induced stress, declined significantly from 0.40 and 0.35 g H_2O g^{-1} dry weight of seeds in water to 0.29-0.32 and 0.24 -0.30 g H_2O g^{-1} dry weight of seeds in stress levels ranging between –0.3 and –1.0 MPa. Decreased rate and percentage of

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germination due to drought stress have been reported for sorghum (Saint-Clair, 1976; Stout *et al.*, 1980; Smith *et al.*, 1989; Gurmu & Naylor, 1991), wheat (Lafond & Baker, 1986; Baalbaki *et al.*, 1999), triticale (Gawronska & Grzelak, 1993), sunflower (Somers *et al.*, 1983), mung bean (Fyfield & Gregory, 1989), pea (Singh *et al.*, 1990), rice (Takaki, 1990) and tree legumes (Grouzis & Danthu, 2001).

The percentage and rate of germination of crop seeds are of considerable agronomic importance. Early and rapid germination is particularly important in areas where seedlings have a short time to develop (Fady, 1992). In this regard, the results of many studies indicate that the adverse effect of drought stress is more marked on the rate of germination than on germination percentage. For instance, Lafond & Baker (1986), Baalbaki *et al.* (1999) and Smith *et al.* (1989) reported reduced germination rate in wheat, sorghum and pearl millet as drought stress increased. Falleri (1994), in his evaluation of the germination performance of six provenances of *Pinus pinaster* Ait. under five water stress treatments (0, -0.2, -0.4, -0.6, and –0.8 MPa), also noticed more adverse effects of water stress on germination rate than on germination percentage. Stout *et al.* (1980), on the other hand, reported a delay in initiation of germination in sorghum cultivars under water stress. Gurmu & Naylor (1991) and Falleri (1994) have also reported that lower water potential reduced the seed water uptake leading to slower radicle and coleoptile emergence and extension. Similarly, reduction in the imbibition rate of pea seeds with increasing levels of PEG induced water stress where imbibition rate was reduced from nearly 80% in a no stress condition to nearly 25% at a water stress level of –0.5 MPa was reported by Singh *et al.* (1990).

According to Collis-George & Williams (1968), as cited by Fyfield & Gregory (1989), measurement of radicle lengths during germination experiments can be regarded as a growth parameter for the developing seedlings, in contrast to germination itself, which simply registers the arrival at a certain stage of development. In this regard, Fyfield & Gregory (1989) reported a slowdown in the rates of radicle elongation in mung bean as water potential decreased from 0 to –2.2 MPa. Similarly, Gurmu & Naylor (1991), in their study to compare the germination and early seedling growth of two contrasting sorghum cultivars under four water stress treatments (0, -0.45, -0.73, and –1.15 MPa), found decreased radicle elongation in both cultivars as water potential become lower. The results of Singh *et al.* (1990) also demonstrated that radicle length in peas declined from 5.3 cm in the control to 2.1 cm at –0.5 MPa. De Villalobos & Pelaez (2001) reported reduced radicle growth of Prosopis from 21 mm under no stress condition to 5 mm under water stress (-1.0 MPa). According to Hsiao (1973) reduction in the extent of radicle elongation under water stress can be attributed to a reduction in cell expansion. Several other researchers have also assessed the effect of water stress at germination on the plumule growth of several crop plants. In this respect Gawronska & Grzelak (1993) reported reduction in plumule length in triticale. They reported reductions of 25, 43, 62, and 73% in the length of seedlings (radicle plus plumule) as seeds were germinated at water potentials of –0.2, -0.4, -0.6, and –0.8 MPa, respectively. Singh *et al.* (1990) also noted significant reductions in the plumule length of peas with increasing levels of water stress in which the plumule length after seven days of growth declined from 7.5 cm in the control to 7.22, 6.78, 5.81, 5.01, and 4.67 cm at stress levels of -0.1, -0.2, -0.3, -0.4, and –0.5 MPa, respectively.

Several studies have illustrated the existence of inherent variation in germination and seedling emergence under water stress in many crop species. Mali *et al.* (1979) reported substantial differences between varieties in water uptake from soil by the time of germination, and also differences within varieties in the rate of and amount of uptake, according to the water potential of the soil. They drew attention to the possible agronomic value of genotypes which may take up sufficient water for germination when soil water availability is low. Cultivar differences in sorghum, with respect to the ability of seeds to germinate under water stress, have been previously described. Stout *et al.* (1980) demonstrated that cultivar NK300 had a faster rate and higher percentage germination than the cultivar M35. Gurmu & Naylor (1991) also found cultivar variability in sorghum, where cultivar Korokolo had higher percentages of radicle and coleoptile emergence than cultivar Ariana. Saint-Clair (1976) also demonstrated cultivar differences in sorghum in which five sorghum cultivars (CE-90, 69-4, RS626, NK300 and C-42Y) had better germination performance at the highest stress level out of 11 cultivars evaluated. Baalbaki *et al.* (1999) evaluated five wheat cultivars under five water stress treatments and found two cultivars (Salamouni and Cham-6) with higher percentage germination and two cultivars (Mexipak and Memof-2) with lower germination percentages.

Water deficit stress effects and variability of tolerance in sorghum cultivars

In areas of the semi-arid tropics where sorghum is widely grown, drought is often the main factor causing low yields (Matthews *et al*., 1990). Most often water deficit affects plant water status, reducing the water potential and thus impairing many functions (Reddy & Reddi, 1992). Reduced plant water potential in turn results in reduced photosynthesis, increased stomatal diffusive resistance and consequently lower plant growth rate. Water stress can have major effects on the growth, development and yield of crop plants by affecting various physiological and morphological processes such as leaf area development, photosynthetic activity, transpiration, translocation of assimilates, leaf senescence, and stomatal conductance (Simpson, 1981). The adverse effects of water stress on one or more of these processes, on a tissue or whole plant level, reduces growth rate, carbohydrate partitioning and grain yield.

Plant growth rate under water deficit is affected in at least two ways: the rate of increase of leaf area is depressed by loss of turgor, and the rate of photosynthesis is decreased by the closing of the stomates (McCree, 1974). Lu & Neumann (1998) attributed growth inhibition, due to water deficit, to inhibition of cell expansion and new cell production. Similarly, Lorens *et al*. (1987) noted that water stress during vegetative development reduces expansion of leaves, stems, and roots and ultimately affects the development of reproductive organs and potential grain yield. The effect of water stress on the growth, development, and dry matter partitioning has been extensively studied. Bajj *et al*. (2000) reported reduced shoot and root fresh weights under PEG-induced water stress. Schulze (1986) also indicated changes in carbohydrate partitioning in crop plants due to water stress. Inuyama *et al*. (1976) noted reductions in sorghum plant height, stem length, head length and exertion length due to water deficit treatments. Blum *et al*. (1989) reported a 70% reduction in sorghum plant height as a result of water stress.

The effect of water deficit stress on leaf expansion and leaf area development, in several crop species is well documented (McCree & Davis, 1974; Turner & Begg, 1981; Parameswara & Krishnasastry, 1982; Garrity *et al*., 1984; Rosenthal *et al*., 1987). The production of dry matter by a crop depends on the solar energy that it captures and utilizes to convert carbon dioxide and water into dry matter. The capture of solar energy in turn depends on the interception of that energy by organs capable of photosynthesis. Thus, crop productivity depends on the development of leaf area to intercept radiant energy, and the rate of net photosynthesis to convert it into dry matter. Due to the fact that leaf area is the main site of assimilate production, the reduction in leaf area, due to water stress, strongly affects dry matter production (McCree & Davis, 1974; Garrity *et al.*, 1984).

The work of McCree & Davis (1974), Parameswara & Krishnasastry (1982) and Rosenthal *et al.* (1987) illustrated the adverse effects of water deficit stress on leaf area development. McCree & Davis (1974) reported a 40% reduction in sorghum leaf area as the atmospheric conditions changed from warm and humid to hot and dry conditions. According to Parameswara & Krishnasastry (1982) inhibition of leaf growth is often a primary whole plant response to moderate water deficit stress which indicates that leaf elongation is more sensitive to water deficit stress than most plant processes and can be severely inhibited at relatively low leaf water potentials. Similarly, Turner & Begg (1981) in their review indicated that water deficit stress at the vegetative stage results in smaller leaves. Water deficit also affects the total leaf number and rates of individual leaf emergence (Arkin *et al.*, 1983 cited by Rosenthal *et al.*, 1987), which determine the surface area available for transpiration and assimilate production (Myers *et al.*, 1984).

In comparing drought resistant (Gadambalia) and drought susceptible (Tabat) sorghum cultivars, Salih *et al.* (1999) reported a 13% reduction in leaf area in the susceptible line. Sivakumar *et al.* (1979) in comparing sorghum growth under irrigation and residual moisture, recorded reduced leaf area development in water stressed plants. Similarly, Rosenthal *et al.* (1987) reported reduced leaf area development and lower biomass yield, when plants were grown in soil where the plant available water was below 50%. Furthermore, Wright *et al.*, (1983) in their study on the response of two sorghum genotypes to five levels of water stress, produced evidence on a reduced rate of leaf area development due to water stress. Parameswara & Krishnasastry (1982) also observed a reduced leaf expansion rate in sorghum, which ultimately reduced leaf area and total biomass. The inhibition of cell division and cell enlargement are supposed reasons for reduced leaf area development of plants under water stress (McCree & Davis, 1974). Many researchers (McCree & Davis, 1974; Wright *et al.*, 1983; Rosenthal *et al.*, 1987; Santamaria *et* *al*., 1990; Munamava & Riddoch, 2001) have demonstrated a reduction of leaf area in sorghum grown under water stress. Garrity *et al*. (1984) also measured a leaf area index as low as 1.28 in stressed sorghum as compared to 1.92 in unstressed plants.

Many research results have revealed that in addition to its effect on leaf area development and senescence, water stress also adversely affects the rate of net photosynthesis per unit area (Turner & Begg, 1981; Parameswara & Krishnasastry, 1982). The photosynthetic capacity of plants is determined primarily by the total leaf area and the activity of each leaf unit (Boyer & McPherson, 1975). Reduced leaf area development and decreased stomatal conductance are said to be the main causes of reduced net photosynthesis under water stress (Parameswara & Krishnasastry, 1982; Ludlow & Muchow, 1990; Jones, 1998). According to Turner & Begg (1981) the immediate response of net photosynthesis rate to water stress appears to be due to stomatal closure in most species. Boyer & McPherson (1975), in their review, indicated that the rate of photosynthesis in water stressed maize was only 15% of that in the well-watered control.

Soil water deficit has been also identified as a limiting factor affecting sorghum root development and distribution in the soil profile (Blum & Arkin, 1984). Many studies have illustrated this, with an increase in the root:shoot ratio of many crops with increasing water stress (Turner & Begg, 1981; Bajj *et al*., 2000; Matsui & Singh, 2003). This could arise simply from a relatively greater decrease in shoot dry weight and greater allocation of the limited carbon available to roots (Hsiao & Acevedo, 1974; Bajj *et al*., 2000).

The existing evidence indicates that a deficiency of water during any growth stage of sorghum often results in a loss of grain yield. The magnitude of the yield reduction, however, depends on the growth stage of the crop at the time of stress, the severity and duration of the stress, and the susceptibility of the genotype to stress (Lorens *et al*., 1987). Several research results (Inuyama *et al*., 1976; Garrity *et al*., 1984; Rice & Eastin, 1986; Craufurd & Peacock, 1993; Craufurd *et al*., 1993) have revealed that sorghum is particularly sensitive, in terms of seed number and yield losses, to stress during the boot stage, which is a period of rapid plant growth and panicle development. Besides, Mastrolilli *et al*., (1995) indicated that water stress at the vegetative phase also influenced later development of the panicle and final yield.

In attempting to improve crop productivity in water-limited environments, a better understanding of plant responses and alternative tactics for coping with water stress provides a foundation for more efficient water management and exploiting genetic variability. The results of early research on the effects of water stress on plants have highlighted the various alterations in developmental, morphological and physiological mechanisms of crops to adapt to water deficits (Saneoka & Ogata, 1987). Thus, exploring the mechanisms enabling plants to adapt to water deficits has been a major goal of plant physiologists and breeders. Such efforts have resulted in identifying several mechanisms that enable sorghum to achieve economic yields under water-limited environments. Plant morphological and physiological traits that enable sorghum to adapt to drought stress and give higher yields include leaf rolling (Matthews *et al*., 1990a), increased leaf reflectance (Ludlow & Muchow, 1990), epicuticular wax deposition (Jordan *et al*., 1983; Cameron *et al*., 2002; Kunst & Samuels, 2003), ability to maintain stomatal opening at low water potential (Turner, 1974; Stout & Simpson, 1978; Blum *et al*., 1989; Ashraf & Ahmad, 1998), reduced stomatal number (Arnon, 1992), development of a large, vigorous root system (Nour & Weibel, 1978; Blum & Arkin, 1984; Bawazir & Idle, 1989; Soman & Seetharama, 1992; Salih *et al*., 1999), maintenance of green leaf area (Duncan *et al*., 1981; Xu *et al*., 2000) and high osmotic adjustment or turgor maintenance (Ludlow *et al*., 1990; Santamaria *et al*., 1990; Al-Hamdani *et al*., 1991; Tangpremsri *et al*., 1991).

Various morphological characteristics of leaves help to reduce the transpiration rate and may affect plant performance and even survival under drought conditions. Leaves with thick cuticles, waxy surfaces, sunken stomata, and hairiness are common and effective (Arnon, 1992; Reddy & Reddi, 1992). Epicuticular wax deposition increases in drought stressed plants and has been identified as a selection criterion for drought tolerance. In sorghum it was found that increases in wax load were inversely correlated with rates of cuticular transpiration (Jordan *et al*., 1984). Increased wax concentration also makes plants more tolerant of high temperature stress or of a combination of moisture and heat stress (McWhorter, 1993; Cameron *et al*., 2002; Kunst & Samuels, 2003). Several lines of evidence suggest an association between drought resistance and epicuticular wax deposition for sorghum. Jordan *et al*. (1983) reported significant variability in average epicuticular wax loads among genotypes. Saneoka & Ogata (1987) also reported an increase in cuticular resistance of bloom lines of sorghum by 90% as compared with 15% in bloomless lines under water stress.

Development of extensive root systems is another mechanism of water stress avoidance in sorghum (Salih *et al*., 1999). A large and vigorous root system, through avoidance of plant water deficits, contributes to higher yields in water-limited environments (Ludlow & Muchow, 1990). Roots are usually the sites of the highest resistance in the pathway for liquid phase movement of water through the soil-plant-atmosphere continuum (Kramer & Boyer, 1995). The efficiency of soil water uptake by the root system is, therefore, a key factor in determining the rate of transpiration and tolerance to drought (Salih *et al*., 1999). Existing evidence (Nour & Weibel, 1978; Turner & Begg, 1981; Wright & Smith, 1983; Bajj *et al*., 2000) indicates that greater partitioning of dry matter to the root system would enable better exploration of soil water reserves and may, therefore, confer increased drought resistance. The development of vigorous root systems by drought resistant crop strains was illustrated by the work of Bhan *et al*. (1973) and Bajj *et al*. (2000) who found greater root weights and higher root:shoot ratios in drought resistant strains of sorghum and wheat than in drought susceptible lines.

Several strategies have been devised to mitigate the impact of drought stress on crop production systems in semi-arid areas. Selection of plant species with drought resistance attributes has been considered an economic and efficient means of achieving these objectives (Ashraf *et al*., 1992). The available evidence indicates that there is considerable genetic variation in sorghum when it comes to those aspects of the plant that confer adaptation to drought stress (Blum *et al*., 1989; Donatelli *et al*., 1992; Blum, 1993). According to Blum *et al*. (1989) and Blum (1993), sorghum genotypes were found to differ in terms of nearly all the recognized drought resistance mechanisms. Matthews *et al*. (1990b) reported a higher leaf water potential in drought resistant sorghum lines and a lower leaf conductance in the susceptible lines. Wright *et al*. (1983), Kidambi *et al*. (1990), Santamaria *et al*. (1990) and Donatelli *et al*. (1992) have all reported genotypic variability in tolerance to drought stress after comparing a wide range of sorghum genotypes. Stout & Simpson (1978) also noted distinct cultivar responses in leaf growth in response to drought stress. In one of their varieties, M-35, water stress extended the period of leaf and stem growth, and delayed inflorescence development, but in another variety, NK 300, the leaf and stem growth period was shortened and inflorescence development advanced. Salih *et al.* (1999) comparing drought susceptible and resistant sorghum cultivars, obtained a 30% reduction in root density and a 31% reduction in nodal roots in the susceptible cultivar, while it was not affected in the resistant one. Soman & Seetharama (1992) also reported genotypic variation in the rate of nodal root elongation. Henzell *et al.* (1976) studied stomatal sensitivity to leaf water deficit in nine genotypes and found significant differences between genotypes for stomatal diffusive conductance. Where stomatal conductance in the sensitive genotypes (Alpha and Shallu) decreased rapidly as leaf water potential declined due to water stress, it declined more slowly in the tolerant genotypes (I.S.1598C and M35-1).

The importance of relative water content of leaf material as a selection criterion is widely recognized. Work done by Clarke & McCaig (1982) and Schonfeld *et al.* (1988) indicated that cultivars that maintain high leaf RWC during drought stress are more drought tolerant. Changes in the RWC of leaves are considered a sensitive indicator of drought stress (Strauss & Agenbag, 2000). Strauss & Agenbag (2000), in comparing different wheat cultivars, observed decreased RWC in stressed treatments compared to the control. It can be concluded that by measuring different physiological and morphological responses under different water stress conditions, it would be possible to evaluate essential traits and select drought tolerant cultivars.

Impact of the interactive effects of moisture conservation, nitrogen fertilization and cultivars on the growth, development and nutrient use efficiency of sorghum

In semi-arid areas water is often a limiting factor for crop production. If it were possible to retain and utilize all the rainfall received, crop losses due to water stress would be reduced. Tied-ridging (ridge and furrow system) is a technique developed for *in-situ* rainwater harvesting in semi-arid areas. It is widely used in the semi-arid areas of many African countries (Jones & Clark, 1987). Tied-ridging is a technique of forming micro basins for impounding runoff, thereby increasing the opportunity time for water to infiltrate (Hulugalle, 1987; Wiyo & Feyen, 1999). Available research evidence in Botswana (Carter & Miller, 1991), Zimbabwe (Piha, 1993; Vogel, 1993), Burkina Faso (Hulugalle *et al.*, 1990), Malawi (Wiyo & Feyen, 1999; Wiyo *et al.*, 2000) and USA (Krishna, 1989) have documented the effectiveness of tied-ridges in reducing surface runoff and increasing soil water storage. For instance, Njihia (1979) reported a reduction of runoff from 38-43%, with flat planting, to 1.2 – 4.7% with tied-ridges. Jones & Clark (1987), in the USA, observed retention of 25 to 30 mm of runoff per annum with tied-ridges. Hulugalle (1987) also observed increased profile water content, by an average of 24.6 and 30.5 mm per week, by using tied-ridges. Selvaraju *et al.* (1999) reported a 14% increase in soil water content with tied-ridges compared to flat beds. In semi-arid areas of NE Ethiopia, tied-ridging has a large potential to mitigate the devastating effect of drought stress through reduced runoff and improved retention of rainwater.

Through reducing runoff and increasing moisture availability, tied-ridges can substantially improve the growth and development and grain yield of several crops (Reddy & Kidane, 1993; Wiggins, 1995). For instance, Wiggins (1995) observed significantly greater root length, plant height, leaf and tiller number and fresh and dry weight of sorghum in ridge plantings compared with flatbed planting. Hulugalle (1987) also reported increased root growth in cowpeas planted in tied-ridges. Kanton *et al.* (2000) obtained superior grain yields from tied-ridge planting (54 – 175%) compared to sowing on the flat. Jones & Clark (1987) realized a sorghum yield increase of 2460 kg ha^{-1} from tied-ridging. The work of many other researchers (Gerard *et al.*, 1984; Saleem *et al.*, 1987; Belay *et al.*, 1998; Kanton *et al.*, 2000; Jensen *et al.*, 2003) have also illustrated many-fold grain yield increases in several crops.

It has been indicated that the vigorous root system development under ridges can enable plants to explore larger volumes of soil which in turn can lead to improved uptake of water and nutrients (Selvaraju *et al.*, 1999). In this regard, Gordon *et al.* (1993) found higher total N uptake in the ridge system (126 kg ha^{-1}) compared with chisel (102 kg ha^{-1}) and moldboard (106 kg ha^{-1}) tillage systems. They also observed a higher apparent N recovery in the ridge system than in the other two tillage systems. The higher N uptake and recovery in the ridge system was attributed to the greater amount of soil water availability.

Apart from the effects of drought stress, the growth, development and yield of sorghum are also strongly affected by poor soil fertility. The problem of nitrogen deficiency is often acute in semi-arid areas where soils typically have low organic matter contents (Broadbent, 1981). Nitrogen deficit is the most severe and widespread nutrient constraint limiting sorghum productivity in NE Ethiopia (Bayu *et al*., 2002). Mamo *et al*. (1988) reported that due to a long cropping history and low manure and fertilizer inputs, the nutrient status of Ethiopian soils is generally low and nitrogen is the most limiting nutrient for crop production. It is well known that many physiological processes associated with crop growth are enhanced by N supply (Eck, 1984; Muchow, 1998). Nitrogen plays a central role in plant biochemistry as an essential constituent of cytoplasmic proteins, nucleic acids, chlorophyll, cell walls and a vast array of other cell components. Consequently, a deficiency in the supply of nitrogen has a profound influence upon crop growth and can lead to a total loss of grain yield in extreme cases (Hay &Walker, 1989). Numerous studies have shown the limiting effects of N deficiency on the growth and development of crop plants (Muchow, 1988; Muchow & Davis, 1988; Muchow, 1990; McCullough *et al*., 1994; Muchow, 1994). Delayed phenological development in response to N deficiencies has also been illustrated by many research results. Muchow (1990 & 1994) and Kamoshita *et al*. (1998) observed delayed anthesis and maturity in sorghum and maize. Muchow (1988, 1989) and McCullough *et al*. (1994) observed reduced plant growth and development arising from reduced leaf emergence rate and leaf area development. The adverse effects of N deficiency on plant height, shoot weight, plant N uptake, leaf area index, leaf area duration, crop photosynthetic rate, radiation interception (PRI) and radiation use efficiency (RUE) are well documented in the review of Novoa & Loomis (1981) and the work of many others (Muchow, 1988; Muchow & Davis, 1988; Youngquist & Maranville, 1992; Pandey *et al*., 2000; Van Oosterom *et al*., 2001). Biomass production, which is largely dependent on leaf area index, is also strongly dependent on leaf N (Muchow & Davis, 1988; Muchow & Sinclair, 1994).

Thus, improving crop production and productivity in these areas requires the use of nitrogen fertilizer, with great emphasis on the efficiency of N utilization. Considering the high cost and the detrimental effects of nitrogen deficiencies on crop production, the efficient use of nitrogen in crop production has become a desirable agronomic, economic, and environmental goal (Le Gouis *et al*., 2000). Nitrogen use efficiency could be improved through improved agronomic practices and through growing cultivars efficient in nutrient use. Many soil, plant and other environmental factors affect nitrogen use efficiency (NUE). Environmental factors such as rainfall also affects nutrient use efficiency. Water limitations affect N-related traits such as N content, N utilization, and N harvest index in crop plants (Zweifel *et al*., 1987; Bennett *et al*., 1989). The availability, movement and uptake of nutrients are affected by moisture availability. For instance, Pandey *et al*. (2000) observed decreased N uptake in maize under deficit irrigation. Nonetheless, various plant characteristics have been suggested to be important in the acquisition and utilization of nitrogen (Stewart, 1991). For instance, Mengal (1983) indicated that NUE is related to crop morphological and physiological traits. Similarly, Lafever (1981) and Jackson *et al*. (1986) as cited by Akintoye *et al*. (1999) indicated that the differences in genotypic responses to nutrient stresses are affected by several crop traits including root morphology and extension, and biochemical and physiological mechanisms involved in nitrate assimilation and use. This indicates that selecting cultivars with vigorous root growth can lead to more efficient recovery of applied fertilizers.

The existence of genotypic differences in terms of N uptake, partitioning and NUE have been reported for several crops including sorghum (Maranville *et al*., 1980; Pal *et al*., 1983; Youngquist & Maranville, 1992; Gardner *et al*., 1994; Buah *et al*., 1998; Traore & Maranville, 1999), maize (Ma & Dwyer, 1998; Akintoye *et al*., 1999; Ma *et al*., 1999) and wheat (Cox *et al*., 1985; Van Sanford & MacKown, 1987; Dhugga & Waines, 1989). For instance, Buah *et al*. (1998) evaluated the agronomic responsiveness of 13 sorghum genotypes, differing in NUE, to three N rates (0, 50 & 100 kg N ha^{-1}) and observed greater yields in the high NUE sorghum types than in the low NUE types. This was attributed to differences in the efficiency of recovery of applied N fertilizer. Muchow (1998) cited the work of Kamoshita *et al*. (1996) where they examined the extent of genotypic variation in grain sorghum under variable water and N supply, and found significant variation among 14 hybrids in grain yield, NUE and grain N concentration. Ma *et al*. (1999) also observed variation in N uptake in two maize hybrids where Pioneer 3902 accumulated 60 to 160 kg N ha^{-1} in the grain as compared to 40 to 110 kg N ha^{-1} for Pride 5. McCullough *et al*. (1994) also evaluated the same hybrids for their N uptake, partitioning and NUE and observed higher NUE for Pioneer 3902 than Pride 5 under the lowest N supply. Traore & Maranville (1999), comparing the nitrate *reductase* activity in seven sorghum genotypes, found greater pre-anthesis nitrogen uptake, accumulation and NUE in tropical lines than in hybrids and U.S. adapted lines. Akintoye *et al*. (1999) found variability among 10 maize lines in N uptake, utilization, NUE and N harvest index. Hibberd & Hall (1990) compared the NUE of two sorghum hybrids under irrigation and rainfed conditions and observed varietal differences with regard to N use, where variety Goldfinger was superior to variety E-57. Prolonged maintenance of green leaf area for photosynthate production during grain filling and the ability to take up available soil N during grain filling, are traits that can facilitate greater NUE. In this regard, Ma & Dwyer (1998) assessed N uptake and utilization in two maize hybrids and noted greater NUE and uptake in the "stay-green" hybrid (Pioneer 3902). However, selection of genotypes with efficient N use could be complicated by their interaction with management practices (Zweifel *et al.*, 1987). Uptake and utilization of N is dependent upon genotype, plant age, available N in the soil, and other environmental parameters that influence plant growth (Youngquist & Maranville, 1992). For instance, Hirel *et al.* (2001) indicated that expression of genetic variability for the components of NUE is largely dependent on the level of nitrogen fertilizers supplied to the crop. Thus, the development of cultivars with predictable N use efficiency requires an understanding of how various production environments affect genotypic N utilization.

Many studies have also reported genotypic differences in dry matter production and partitioning in response to nitrogen fertilizer. Utzurrum *et al.* (1998) found differences in dry matter accumulation between two sorghum hybrids in response to N application, where Y3 produced significantly more total dry matter than X3. Maman *et al.*, (1999) also observed differences in dry matter accumulation between pearl millet genotypes in response to N fertilization. Similarly, Greef *et al.* (1999) compared eight forage maize cultivars and observed variability among the cultivars for dry matter production in response to N fertilization. Hons *et al.* (1986) observed variations among sorghum hybrids in height, leaf number and leaf area index (LAI) in response to fertilization. Pal *et al.* (1983) obtained 20% more dry matter per plant in sorghum supplied with 129 kg N ha^{-1} than the ones supplied with 80 kg N ha^{-1}. The physiological processes of carbohydrate partitioning and N metabolism are associated. Thus, genotypes with differences in grain yield potential may differ in N accumulation and NUE (Buah *et al.*, 1998). This review suggests that by adopting moisture conservation practices, applying nitrogen fertilizer and selecting nitrogen efficient cultivars the productivity of crops could be enhanced in drought stressed semi-arid areas.

Integrated use of farmyard manure and inorganic fertilizers in the improvement of soil fertility and crop yield

The farming systems in NE Ethiopia generally do not include crop rotation and fallowing due to rapid population growth. Continuous and intensive cropping, without the restoration of the soil fertility, is the dominant feature of the farming systems. Consequently, the inherent fertility status of the soils in these areas has been dangerously depleted (Georgis & Alemu, 1994). Increasing crop production on such degraded soils, therefore, becomes an enormous challenge. Soil fertility depletion in smallholder farms of Africa, including Ethiopia, is recognized as the fundamental biophysical limiting factor responsible for the declining per-capita food production of the continent (Alexandratos, 1995; Smaling & Braun, 1996; Sanchez & Leakey, 1997). Studies in other parts of the continent have revealed that the magnitude of soil nutrient mining is huge on small-scale farms (Stoorvogel *et al.*, 1993; Bationo *et al.*, 1998; De Jager *et al.*, 1998; Nandwa & Bekunda, 1998; Van den Bosch *et al.*, 1998). It could be even worse in the densely populated countries like Ethiopia, Kenya, Malawi and Rwanda (Stoorvogel *et al.*, 1993; Smaling *et al.*, 1997).

A basic challenge to agricultural research and development is to better understand and arrest this trend. To increase food production in Africa, a sustainable soil fertility replenishment strategy must be implemented that has the potential to supply nutrients and to arrest the mining of soil fertility taking place (Stangel *et al.*, 1994). The soils of NE Ethiopia can no longer be productive with the existing fertility status. Thus, to increase food production on the existing degraded soils, inexpensive soil fertility replenishment technologies need to be available to the resource poor small-scale farmers. A key resource that could be useful in achieving a sustainable soil fertility management system is animal manure, which is important in maintaining soil quality through replenishing the organic matter content of the soil (Murwira *et al.*, 1995). According to Carter *et al.* (1992), the use of animal manure to improve soil fertility and crop yield assumes particular importance where financial or logistic constraints on the availability of inorganic fertilizers exist, and where inherently infertile soils are used for the continuous production of grain crops.

The use of animal manure for the improvement of soil condition and crop yields is an ancient practice and is an integral part of many low-input farming systems (Francis *et al.*, 1990). The application of animal manure generally aims at two major goals: (i) increased supply of nutrients to the crop and (ii) increasing organic matter content in the soil, resulting in more favourable soil physical and chemical properties (De Ridder & Van Keulen, 1990). Animal manures provide N, P, K and other mineral nutrients (Lupwayi *et al.*, 2000; Hoffmann *et al.*, 2001). According to De Ridder and Van Keulen (1990) and Eck & Stewart (1995), manure can contain, on average 2.0, 0.5 and 1.5% (on dry weight basis) of N, P and K respectively, as well as significant amounts of Ca, Mg, Na and many of the trace elements.

Significant increases in total and NH_4^+- and NO_3^--N contents of the soil with addition of animal manure have been reported by several researchers in Africa (Powell, 1986; Kaihura *et al.*, 1999; Warman & Cooper, 2000; Hoffmann *et al.*, 2001). The addition of animal manure also increases the availability and mobility of P (Meek *et al.*, 1982; Powell, 1986). Organic anions formed during the decomposition of animal manure can compete with P for the same sorption sites and thereby increases P availability in the soil (Reddy *et al.*, 1999). Animal manure applications also result in a build up of exchangeable K and Mg (Meek *et al.*, 1982; Lupwayi & Haque, 1999). In Nigeria, Powell (1986) analyzed N and P balances after maize crops in an animal manuring study and found a three-fold increase in N in manured plots (128 kg ha^{-1}) as compared to the non-manured plots (42 kg ha^{-1}). Similarly, in Ethiopia the application of cattle manure to maize in a hedgerow intercropping system reversed nutrient balances from net negative balances of –7 to –19 kg N ha^{-1}, – 4 to –12 kg P ha^{-1} and –10 to –26 kg K ha^{-1}, where no nutrients were applied, to net positive balances of 59 to 62 kg N ha^{-1}, 9 to 35 kg P ha^{-1} and 74 to 80 kg K ha^{-1}, where 3 t ha^{-1} dry cattle manure was applied (Lupwayi & Haque, 1999). Significant increases in soil total N and available P and K from farmyard manure applications were also reported in Ghana (Kwakye, 1988) and Nigeria (Agbenin & Goladi, 1997). The restoration of soil nutrients and other soil fertility parameters by animal manure additions was also illustrated by data from Niger (Bationo & Mokwunye, 1991) in which the N and P content of the soil was significantly elevated when the soil was analyzed after two years of manure applications. In Tanzania, in a study conducted at eight locations, Kaihura *et al.* (1999) reported an increase in soil N level by 0.03%, P by six-fold and K by two-fold as a result of animal manure applications. Improvements in the soil chemical quality, with farmyard manure addition, can be explained by its potential to release CO_2, NH_4^+, NO_3^-, PO_4^- and undecomposed humic products to the soil through mineralization (Stevenson, 1994 as cited by Kaihura *et al.*, 1999).

Unlike the commonly used commercial fertilizers, one of the benefits of fertilizing with animal manure is the provision of secondary nutrients. This was illustrated by the data of Warman & Cooper (2000) who found higher levels of B, Cu, Fe, Mn and Zn in manured than in unmanured soils after three years of fresh and composted manure applications at rates ranging from 5 to 10 t ha^{-1}. Similarly in a greenhouse study in Egypt, Abou-ElNaga *et al.* (1996) found increased availability of Mn and Zn with applications of farmyard manure at rates ranging from 0 to 238 m^3 ha^{-1}. In Tanzania, Kaihura *et al.* (1999) found a significantly increased level of Mg in manured plots (0.72-2.53 cmol kg^{-1}) as compared to farmers practice (0.38-2.04 cmol kg^{-1}) and inorganic fertilizer (N and P) application (0.48-2.13 cmol kg^{-1}).

The available evidence indicates that animal manure amendments can increase the pH of acid soils and decrease that of calcareous soils (Lungu *et al.*, 1993; Wong *et al.*, 1998; Hoffmann *et al.*, 2001; Whalen *et al.*, 2002). The reaction of acid soils, with applications of composts and animal manure, results in increased soil pH and decreased Al saturation (Hue, 1992). Animal manure applications supply important elements like K, Mg and Ca, which contribute to maintaining base saturation at higher levels (De Ridder & Van Keulen, 1990). The mechanism resulting in increased soil pH during organic manure additions is not fully understood but is thought to be due to specific adsorption of organic anions and the corresponding release of hydroxyl ions (Hue, 1992). Lungu *et al.* (1993) compared the effects of lime and farmyard manure application in correcting soil acidity and found a reduction in exchangeable Al of at least 50% above the values obtained with lime alone, and an increase of one unit in the pH of the topsoil with farmyard manure application. With 6 t lime ha^{-1} the reduction in exchangeable Al compared to the control was 36-52%, but the corresponding reduction with 30 t ha^{-1} farmyard manure application was 71-80%. In Nigeria, Powell (1986) reported an increase in soil pH on manured plots (pH 5.8) as compared to non-manured plots (pH 5.1). A similar effect has been reported in Ghana (Kwakye, 1988), Rwanda (Rutunga *et al.*, 1998), Tanzania (Kaihura *et al.*, 1999) and Canada (Whalen *et al.*, 2002).

Other important soil chemical properties affected by animal manure applications include the cation exchange capacity (CEC), electrical conductivity and sodium adsorption ratio (Powell, 1986; De Ridder & Van Keulen, 1990; Hoffmann *et al*., 2001). In a long-term experiment established in 1960 in Burkina Faso the CEC of the soil increased with manure addition (especially at the higher rate) while in the fertilizer only plots the CEC remained unchanged. Similarly, in Nigeria in a savanna alfisol cultivated continuously for 45 years, Goladi & Agbenin (1997) reported an increase in CEC with farmyard manure application as compared to inorganic fertilizer.

Regular manure addition to arable soil either increases its organic matter content or reduces its rate of loss (Powell, 1986; De Ridder & Van Keulen, 1990; Schjonning *et al*., 1994; Eck & Stewart, 1995; Palm *et al*., 1997; Haynes & Naidu, 1998; Hoffmann *et al*., 2001). Mokwunye (1991) reported that application of manure in Nigeria once every three years at rates of 5 and 20 t ha^{-1}, resulted in a two-fold increase in soil organic matter levels in the first three years of the study, as compared to the non-fertilized plots. Soil organic matter level in the manured plots was also significantly superior to mineral fertilizer treated plots. Similar effects of farmyard manure on the level of soil organic matter in many African soils were reported by several researchers (Agbenin & Goladi, 1997; Goladi & Agbenin, 1997; Rutunga *et al*., 1998; Kaihura *et al*., 1999). Shirani *et al*. (2002) also reported a significant increase in soil organic matter content, ranging from 7.6 g kg^{-1} in the control to 24.5 and 38.4 g kg^{-1}, at 30 and 60 t manure ha^{-1}.

The maintenance of soil organic matter, by adding animal manure, has important benefits such as retention and storage of nutrients, increased buffering capacity in low activity clay soils, increased aggregate stability, improved soil macro-structure, improved infiltration, improved water holding capacity, erosion resistance and prevention of soil hardening (De Ridder & Van Keulen, 1990; Bationo & Mokwunye, 1991; Schjonning *et al*., 1994; Hoffmann *et al*., 2001). The application of animal manure has been found to increase the water holding capacity of soils (Girma & Endale, 1995). Powell (1986) also reported a 1% greater available water capacity and 2% greater water holding capacity in manured plots over non-manured plots, in Nigeria. A much more significant effect of manure addition on the water holding capacity of sandy soils was reported by Carter *et al*. (1992) in Botswana who reported 19 and 27% increases after four years of manure addition at the rate of 9 t ha^{-1}.

By improving the chemical and physical properties of the soil, application of animal manure often results in improved growth, development and yield of crops. Several studies have reported substantial yield increases from animal manure applications (Ikombo, 1984; Powell, 1986; De Ridder & Van Keulen, 1990; Lungu *et al*., 1993; Gibberd, 1995; Bekunda *et al*., 1997; Kaihura *et al*., 1999; Satyanarayana *et al*., 2002), although crop responses were found to be variable, and effects were highly site- and season-specific (Carter *et al*., 1992). In an experiment conducted in Niger, Bationo & Mokwunye (1991) reported a doubling of millet yield after one year of application at the rate of 5 t ha^{-1}. Similarly, Powell (1986) indicated that in Central Nigeria annual animal manure applications, at 3 t ha^{-1}, were found to be sufficient to maintain sorghum and millet yields at the same levels as those obtained after three years of fallow. In another study, in the semi-arid areas of West Africa, De Ridder & Van Keulen (1990) reported substantial increases in millet yield by applying animal manure. Similarly, in Nigeria Powell (1986) reported a 1 t ha^{-1} maize grain yield increase in manured plots over the non-manured plots. In eastern Kenya, Ikombo (1984) reported high and consistent maize yields with manure additions of 8 t ha^{-1}, which is close to that obtained by applying mineral fertilizer at the rates of 40 kg N ha^{-1} and 17 kg P ha^{-1}. In another study in Kenya, Gibberd (1995) reported a 58% yield increase in pure crops and a 75% yield increase in intercrops following animal manure application at the rates of 5 and 10 t ha^{-1}. In Tanzania, Kaihura *et al*. (1999) reported maize grain yield increases of 1732 kg ha^{-1} across eight locations with animal manure application. In India, Satyanarayana *et al*. (2002) reported a 25% increase in rice yields with the application of farmyard manure at the rate of 10 t ha^{-1}. Similarly, in Ghana significant sorghum and millet grain yield increases were reported with the application of manure at 10 t ha^{-1} (Kwakye, 1988). In Egypt, several researchers (El-Attar *et al*., 1982; Attia, 1999; Hegazi *et al*., 1999; Mohamed & ElAref, 1999) have also reported increased grain yields of various crops with the addition of varying rates of farmyard manure over the control and mineral fertilizer application. These results suggest that farmyard manures provide growth factors and microelements in addition to supplying the major nutrients (Badaruddin *et al*., 1999).

In the preceding sections the relevance of animal manure in restoring soil fertility has been clearly demonstrated, however, animal manure cannot meet crop nutrient demand over large areas because of the limited quantities available and the relatively low nutrient content of the material (Palm *et al*., 1997; Bationo *et al*., 1998; Brouwer & Powell, 1998). Larger amounts of animal manure than of mineral fertilizers are required, as their elemental concentrations are lower than that of mineral fertilizers (De Ridder & Van Keulen, 1990). Moreover, the rate of nutrient release from animal manure is slower, as the organic material must be decomposed to release the nutrient elements, which might lead to nutrient deficient periods (De Ridder & Van Keulen, 1990). On the other hand, although application of mineral fertilizers is an efficient means of increasing yields in arable farming systems, mineral fertilizers alone cannot sustain yields in the long run due to deterioration in soil organic matter content and soil acidification (Bationo *et al*., 1998).

Under smallholder conditions it is rarely possible either to purchase mineral fertilizer or generate animal manure to meet the rates reported in research studies (Bekunda *et al*., 1997). Thus, the combined use of animal manure and mineral fertilizers is often suggested as a promising alternative to smallholder farmers in Africa (Palm *et al*., 1997; Bationo *et al*., 1998). Since the rate of decomposition of manure, and the mineralization of nutrients contained in it, can be fairly slow, complementary use of inorganic fertilizers is essential to hasten the decomposition process. The beneficial effects of the combined use of organic and inorganic nutrients have been repeatedly shown in field trials (Palm *et al*., 1997). Available information indicates that high and sustainable crop yields can be obtained with judicious and balanced N, P, K fertilization, combined with organic material amendments. Effectiveness of mineral fertilizers is greatly enhanced when they are used in conjunction with organic amendments such as animal manure (Lal, 1993). It is commonly believed that combining organic with inorganic fertilizer will increase synchrony and reduce nutrient losses (Kramer *et al*., 2002). This is important not only in enhancing the efficiency of the fertilizers but also in reducing environmental problems that may arise from their use.

Effect of nitrogen fertilizer and planting density on the growth, development and yield of sorghum

Establishment of optimum plant population densities in different regions is essential to obtain maximum yields. Especially in crops grown on stored or conserved soil moisture under rainfed conditions, optimising the population density is critical as too high population densities can result in the depletion of most of the moisture before the crop matures, and too low population densities may leave moisture unutilised (Reddy & Reddi, 1992). The optimum plant population density for any crop varies considerably according to the environment under which it is grown. For instance, a dense plant stand is necessary in a fertile soil to fully utilize the available nutrients in the soil to realize potential yields. In contrast, higher plant populations under low fertility conditions can lead to development of nutrient deficiencies. Many workers have indicated that optimum planting densities for grain production are lower when water and nutrients are in short supply (Novoa & Loomis, 1981; Arnon, 1992). For instance, Hussein *et al*. (2000), studying plant density in maize under different amounts of seasonal rainfall, reported that during seasons of high rainfall (>600 mm in the growing season), each 10 000 increase in plants, up to 80 000 plants ha^{-1}, increased yield by 200 to 300 kg ha^{-1}. But during dry seasons, increasing plant population over 50 000 ha^{-1}decreased grain yields by 5 to 16%.

Plant density strongly affects leaf area, and therefore light interception and canopy photosynthesis (Gan *et al*., 2002). Investigations of the influence of population density upon crop dry matter yield have generally shown increases up to a plateau value at moderate densities and a significant reduction in production only at very high densities (Donald, 1963 as cited by Hay & Walker, 1989). The level of the plateau yield and the population density at which it is achieved depend on other factors, particularly the nitrogen supply (Hay & Walker, 1989). Dry matter production is directly related to the utilization of solar radiation, which is influenced by canopy development. Canopy light interception and photosynthesis are closely related to LAI up to a critical LAI, that which is required to intercept 95 % incident irradiance (Modarres *et al*., 1998).

The primary effect of increasing plant population density is to increase competition between adjacent plants. The resultant shading of plant tissues has a profound influence upon the balance of plant growth regulators, notably an increase in tissue levels of gibberellins, the overall effects of which are the promotion of leaf sheath and blade extension and the acceleration of all crop development processes. Thus, closer spacing of cereal plants is associated with larger and more rapidly growing leaf canopies, however, this effect is relatively short-lived because later leaves are smaller and the senescence of the leaf canopy is also faster (Hay & Walker, 1989).

The challenge to agronomists is to reconcile the requirements of optimising radiant energy interception and water use efficiency by manipulating inputs like plant population and nitrogen fertilizer. The total amount of biomass produced by a crop is determined by the crop growth rate and the duration of growth. Crop growth rate, in turn, is the product of net assimilation rate and LAI. In most crops, planting density is a major determinant of LAI (Van Averbeke & Marais, 1992). Novoa & Loomis (1981) have also indicated that leaf area is the main factor in biomass formation, and that it varies with plant population. Modarres *et al.* (1998) indicated that increasing the plant density is one management tool for increasing the capture of solar radiation within the canopy. Van Averbeke & Marais (1992) indicated that higher critical LAI values obtained by increasing planting density resulted in higher crop growth rates during grain filling, and consequently in higher grain yields. Tetio-Kagho & Gardner (1988) reported an increase in critical LAI from 2.6 to 4.0 by increasing planting density of maize from 35 000 to 63 000 plants ha^{-1}.

In maize, Tetio-Kagho & Gardner (1988) indicated that dry matter accumulation per unit area increased with increasing planting density and LAI until light is completely absorbed. In semi-arid conditions, the optimum LAI is determined by the amount of water available to the crop, and a LAI much lower than the critical LAI will be required. Grain yields have been found to increase with an increase in planting density up to an optimum density and to decline as planting density is increased above that optimum. Excessive population pressure has been shown to interfere with seed set producing lighter and fewer grains per head, which depresses total grain yield (Stewart & Lenga, 1982). On the other hand Berenguer & Faci (2001) indicated that at low planting densities yield could be compensated by an increase in the number of grains per panicle and high weight of grain. As plant density increases, changes may occur in the allocation of assimilates to different parts of the plant, as a result of which a greater proportion of the reproductive parts of an individual plant may become barren. For instance, Ogunlela & Okoh (1989) reported a significant increase in panicle weight, grain and straw yields in three sorghum varieties by increasing plant density from 33 300 to 50 000 plants ha^{-1}, but at 66,600 plants ha^{-1} these parameters declined significantly. Under very high population density levels, plants become barren. Van Averbeke & Marais (1994) reported a lower harvest index and an increase in barren plants in maize with increased population density above an optimum density under limited water supply, whereas, with a lower population density, competition is absent during the early stages of growth, as a result more flowers are initiated per plant. The load of inflorescence is more, which leads to competition among inflorescences of the plant. This loss of efficiency at the widest spacing is evident in fewer seeds per inflorescence and reduced seed size compared with more dense stands. In moderately dense stands, as a result of inter-plant competition at the time of flower initiation, the numbers of flowers produced are reduced and the plant is capable of filling all the seeds that set. The seeds per inflorescence and size of seeds per unit area are more in such conditions (Reddy & Reddi, 1992). Similarly, Berenguar & Faci (2001) found that at a low planting density yield could be compensated for by an increase in the number of grains per panicle, and increased size of the grain. Jones & Johnson (1991) have indicated that sorghum plants adjust yield components so that yields are maintained over a wide range of populations. Duncan (1984) reported that grain yield increased with an increase in planting density up to an optimum density and declined as planting density increased above the optimum. Decreases in the yield of individual plants at high population densities in crops like sorghum are due to the reduced size of panicles. Early maturing sorghum genotypes produce smaller and fewer functional leaves in which an increase in plant population should enable them to develop a large leaf area (Villar *et al*., 1989).

High plant population densities bring out certain modifications in the growth of plants. Plant height increases with increase in plant population due to competition for light. Sometimes it may happen that a moderate increase in plant population may not increase but decrease plant height, due to competition for water and nutrients but not for light (Reddy & Reddi, 1992). According to Reddy & Reddi (1992) increases in plant height due to higher population densities are advantageous for better light interception due to exposure of individual leaves over a wider vertical interval. Another adaptation of dense plant stands is the reduction in leaf thickness. Leaf orientation is also altered due to population pressure. The leaves tend to be more erect, narrower and arranged at longer vertical intervals under high plant densities (Reddy & Reddi, 1992). These are desirable architectural features to intercept more light.

Improvement in the productivity of dryland sorghum may be possible by manipulating agronomic practices like plant population. The productivity response and the compensation phenomena between the yield components of sorghum sown at different densities under variable nitrogen fertilizer supply are not well documented for the semi-arid areas of NE Ethiopia.

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CHAPTER 2

Prepared according to the guidelines of Seed Science and Technology

Influence of water deficit stress on germination, emergence and growth of sorghum cultivars

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Summary

Experiments were conducted in a laboratory and growth chamber to investigate the effect of water deficit stress on the germination, emergence and seedling growth of five sorghum cultivars. Germination tests were conducted at 0, -0.20 and -0.85 MPa using PEG 6000 and emergence and seedling growth tests at 100, 60, 40 and 20% of field capacity in sand. The design in both experiments was a completely randomized block design with four replications. Differences among water deficit treatments and cultivars in the PEG experiment, and among water deficit treatments, cultivars and their interactions in the sand experiment, were significant for all parameters. Good agreement of results between the two experiments was observed for many of the parameters. In both experiments, water deficit stress significantly reduced the rate and percentage of germination and emergence, as well as early seedlings growth. Coleoptile, mesocotyl and radicle lengths were adversely affected by water deficit stress. Variability among cultivars was observed for the rate and percentage of germination, emergence and seedling growth. Gambella 1107, Meko and P9403 had significantly higher rates and percentages of germination and emergence. Gambella 1107 had significantly longer coleoptiles and radicles. Mesocotyl length in Gambella 1107 and P9403 was least affected by water stress. Shoot lengths of all cultivars decreased as the level of sand water content decreased. Root length and area were severely reduced by increasing water stress for all cultivars, except 76 T1 #23.

Introduction

A major constraint of dryland sorghum production in semi-arid regions is the lack of sufficient water in the seeding zone at planting (Brar and Stewart, 1994). Semi-arid areas, such as those of NE Ethiopia, are characterized by high temperatures, high evaporative demands, and limited and erratic precipitation, resulting in rapid drying of the soil surrounding the seed, a marked decrease in water potential and soil crusting. The particular climatic conditions of this area, and of arid and semi-arid regions in general, often adversely affect germination, emergence and seedling establishment (Hegarty, 1978).

An important step in growing a successful sorghum crop is obtaining an adequate plant population. Sorghum stand establishment can be adversely affected by soil water deficiency (Brar *et al.*, 1992). When establishment is poor, higher seeding rates are required, yield is reduced, and replanting is often necessary. Reduction in yields result from suboptimal plant densities, uneven stands, increased weed competition and lost sowing opportunities (Radford and Henzell, 1990).

Thus, soil water supply is an important environmental factor governing germination and seedling establishment. If the water potential of the growing media is reduced, germination will be delayed or prevented due to restricted water uptake (Falleri, 1994). After imbibition, low water potential can affect seedling establishment by delaying and slowing the rate of radicle and coleoptile emergence (Gurmu and Naylor, 1991). Germination and seedling establishment is very important for the early establishment of plants under water deficit stress conditions. Most studies on drought tolerance have focused on the late vegetative and reproductive period of growth. Nonetheless, traits of drought tolerance should also include the ability of seeds to germinate and for seedlings to develop under limited moisture availability, since successful field establishment and vigorous stands contribute to higher yield. Drought tolerance is regarded as the presence of favourable attributes at different growth stages, and thus tolerant cultivars should be those that can withstand periods of low water availability starting at germination (Baalbaki *et al.*, 1999).

Water deficit affects germination of sorghum seed, but with varying response among cultivars (Evans and Stickler, 1961). Stout *et al.* (1980) observed variability in sorghum cultivars with respect to the ability of seeds to germinate in solutions of low water potential. Gurmu and Naylor (1991) found decreased radicle elongation in two sorghum cultivars as water potential decreased. They also found significantly longer radicles and coleoptiles in the drought resistant cultivar (Korokolo), at all water potentials, than in the drought susceptible cultivar (Ariana). Similarly, Donaldson (1996) found considerable variability in wheat cultivars with respect to emergence and seedling development in response to water deficit stress. Thus, selecting sorghum cultivars for rapid and uniform germination under a wide range of water potentials would be important for early seedling establishment in the field.

Brar *et al*. (1992) reported reduced seedling emergence in sorghum at low water potential (-0.1 MPa) and high soil temperature (35.8^0 C), which they ascribed to poor seed-water contact. According to these authors, declining water potential retarded the imbibition rate and thereby delayed germination and emergence.

Little is known about the extent of genetic differences in germination, emergence and seedling growth among different sorghum cultivars grown in Ethiopia under water deficit stress conditions. The objective of these experiments was to study the effect of water deficit stress on germination, emergence and seedling growth of different sorghum cultivars.

Materials and methods

Germination and seedling growth in an osmoticum

An experiment was conducted in the laboratory of the Department of Plant Production and Soil Science of the University of Pretoria. Five sorghum cultivars (Jigurti, Gambella 1107, Meko, 76 T1 #23 and P9403) from Ethiopia, were evaluated for germination under three water deficit stress levels, representing no stress (0 MPa), mild stress (-0.20 MPa) and severe stress (-0.85 MPa). These water deficit treatments were based on the results from a preliminary trial. Seeds were placed in petri dishes, 9 cm in diameter, lined with a double layer Whatman No. 3 filter paper disks. The filter papers were moistened with 7 ml of either pure water or PEG 6000 solutions of 10 or 20% (w/v). The equivalent water potentials were 0, -0.20 and -0.85 MPa, respectively. According to McWilliam and Phillips (1971) and Gawronska and Grzelak (1993) the high molecular weight PEG does not enter seed and inhibits germination only by reducing the availability of water. Seeds were germinated in an incubator maintained at a constant temperature of 26^0 C in complete darkness, for five days.

The osmolality (C) of the PEG 6000 solutions was determined with a digital Micro-osmometer and converted from mOsmol kg^{-1} to MPa using Vant Hoff's equation: Ψ_s (MPa) = RTΣCj where R is the gas constant (8.314×10^{-6} m^3 MPa $mol^{-1}K^{-1}$), T is temperature in Kelvin ($^0C + 273$) and Cj is osmolality (concentration of particles in one litre of water).

Two petri dishes, each with 25 seeds, were used as an experimental unit. The petri dishes were hermetically sealed with parafilm to prevent evaporation. The experiment was laid out in a completely randomised block design with four replications. The experimental layout was arranged in a factorial experiment with osmotic potential and cultivars as factors.

Germination counts were made every 24 hours. Seeds with a radicle protrusion of 2 mm or greater were considered germinated. After five days the lengths of radicles, coleoptiles and mesocotyls of 10 seedlings were measured.

Mean time to final germination (MTG) was calculated according to Brar and Stewart (1994) and Brenchley and Probert (1998) from the formula:

MTG (d) = Σ (nxd)/N where n is the number of seeds germinated between scoring intervals; d is the incubation period in days at that time point and N is the total number of seeds germinated in the treatment. Average germination rates (AGR, % d^{-1}) were calculated according to Roundy, Young and Evans (1985) and Emmerich and Hardegree (1990) from the formula: AGR (%, d^{-1}) = $\Sigma\ [(G_i-G_{i-1})/i]$ where i is the germination count day, G_i is the percentage of seeds germinated through Day i, and G_{i-1} is the percentage of seeds germinated through the previous count day.

Emergence and seedling growth in sand medium

Seedling emergence and growth of the five sorghum cultivars were studied in a pot experiment with four soil water content levels. The experiment was conducted as a factorial experiment with soil water content levels (100% FC, 60% FC, 40% FC and 20% FC) and cultivars (Jigurti, Gambella 1107, Meko, 76 T1 #23 and P9403) as factors in a completely randomised block design with four replications. Field capacity of air-dried sand was estimated by saturating the sand in vertical glass cylinders. The top end of the cylinders was covered with aluminium foil to prevent evaporation. The glass cylinders were placed on dry sand and allowed to equilibrate for 72 hours. Water content of the sand at field capacity was estimated from three glass cylinders and from three points in each cylinder. The water content at field capacity was determined by the gravimetric method. The four soil water content levels (100%, 60%, 40% and 20% FC) were achieved by adding 64, 38, 26 and 13 ml of water, respectively. The water was thoroughly mixed with 2 kg of air-dried sand using an electric mixer. The sand and water mixture was then placed in polyethylene bags in pots and left for three days to equilibrate. The bags were closed to avoid evaporation. Fifty seeds of each cultivar were planted in each pot. The pots were placed in a growth chamber adjusted to a constant temperature of 25^0 C and complete darkness, until emergence was noticed. After emergence the growth chamber was adjusted to a 12 hour photoperiod and at 310 µ mol m^{-2} s^{-1} photosynthetic radiation.

Seedling emergence was recorded for four days starting from the first observation of emergence. Four days after emergence all but eight uniform seedlings were removed from each pot. Seedling growth was estimated by measuring shoot elongation of the eight seedlings every other day from five days after emergence. Eleven days after emergence the total root length and root area were measured by scanning the roots and analysing the image with a "GSRoot" analyser. The total dry mass of seedlings was determined after oven drying at 50^0 C for 40 hours.

From emergence data the Emergence Index (Ie, % d^{-1}) was calculated using the formula of Brar *et al.* (1992) where: Ie (% d^{-1}) = Σ ei/di where ei is the cumulative number of seedlings emerged on day i, and di is number of days from planting to day i. Shoot Index (Is, cm d^{-1}) was also calculated using the formula of Brar *et al.* (1992) where: Is = ΣPhi/di where Phi is plant height (cm) at day i.

In both experiments, data were ranked prior to analysis of variance to meet the requirements for ANOVA. Analysis of variance for the measured parameters was performed using the SAS statistical program (SAS V8.2, SAS Institute Inc., Cary, NC, USA).

Results and discussion

Germination and seedling growth in osmotica

Germination percentage and rate

An analysis of variance indicated that water deficit treatments and cultivars had highly significant effects on the final germination percentage. The water deficit x cultivars interaction was, however, non-significant. The results of the main effects of water deficit stress treatments on final germination percentage are illustrated in figure 1A. The percentage germination, averaged over all cultivars, was significantly reduced under severe water deficit (-0.85 MPa) conditions. Germination percentage under mild water deficit (-0.20 MPa) was comparable to the control (0 MPa). The reduction in germination may have resulted from low seed water uptake, as the uptake of water is an essential and initial step toward germination (Bewley and Black, 1994). According to Gardner *et al*. (1985) a less-than-optimum water content usually results in partial imbibitions and slowed or arrested germination. The reduction in percentage germination under water deficit conditions suggest, according to Gurmu and Naylor (1991), that the reduced water availability impaired cell elongation thereby inhibiting radicle protrusion. Reduced water uptake by sorghum seeds under low water potential was also reported by Gurmu and Naylor (1991). Likewise, Falleri (1994) observed reduced germination of *Pinus pinaster* Ait. under water deficit conditions, which he attributed to restricted water uptake. Singh *et al*. (1990) also reported reduced imbibition rates in peas under water deficit conditions created by PEG 6000. Although all the sorghum cultivars germinated and grew to some extent at –0.85 MPa, seedlings had a dehydrated appearance and were not growing vigorously.

The results of cultivar differences in germination percentage are illustrated in figure 1B. Gambella 1107, Meko and P9403 had the highest germination percentages, while 76 T1 # 23 had the lowest germination percentage. Varietal differences in germination percentage for sorghum were previously reported by Stout *et al*. (1980).

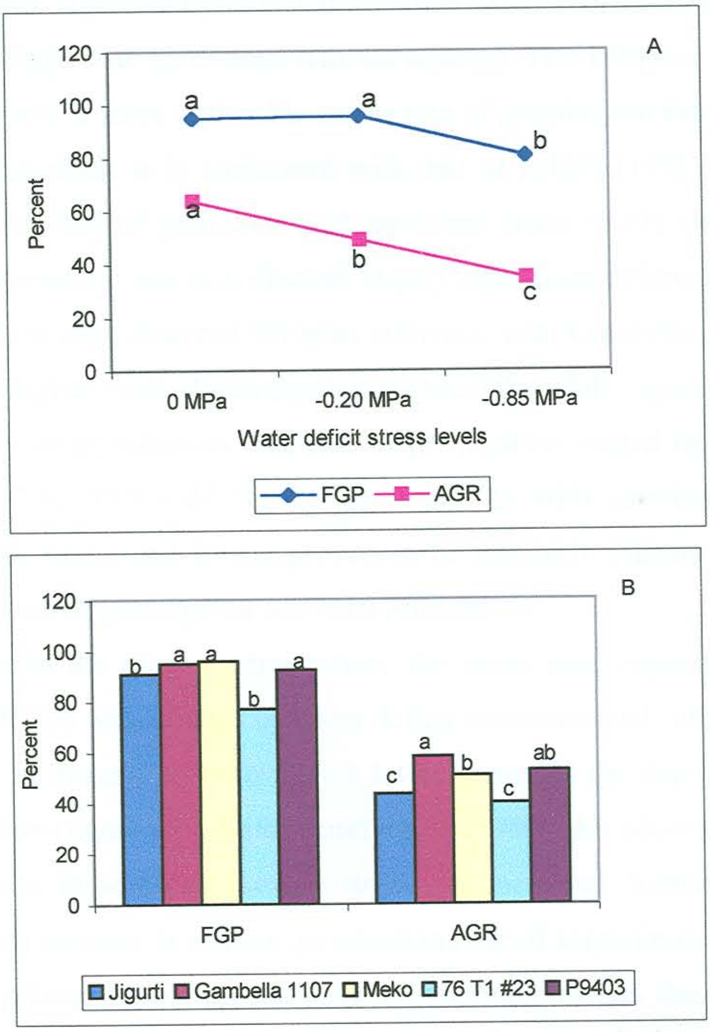

Figure 1. Effect of water deficit stress (A) and cultivar differences (B) on final germination percentage (FGP) and average germination rate (AGR). Means followed by the same letters for each parameter are not significantly different at $P \leq 0.05$.

Rapid germination and seedling establishment permits the secondary root system to access wet soil ahead of the drying front in semi-arid environments. Thus, the speed or rate of germination may be an appropriate criterion to select genotypes tolerant to water deficit stress (Baalbaki *et al.*, 1999). In this study, differences in the rate of germination (% d^{-1}) were observed among the main effects of water deficit treatments and between cultivars. However, the water deficit x cultivar interactions were not significant indicating that the rate of germination of the cultivars was similarly affected by water stress levels. The results of the effect of water deficit stress on germination rate is shown in figure 1A. Each increment in water deficit stress caused a further decrease in the rate of germination. At –0.20 and -0.85 MPa the rate of germination was reduced by 23% and nearly 50%, respectively. The rate of germination was significantly affected by mild water deficit stress (-0.20 MPa) although the germination percentage was not affected. This indicates that the effect of water deficit stress is more noticeable on the rate of germination than on germination percentage. This result is in agreement with that of Falleri (1994) who observed a reduction in the rate of germination at moderate stress levels (-0.2 MPa) where germination percentage was not affected. Highly significant differences in the rate of germination were also observed between cultivars, with Gambella 1107, Meko and P9403 having higher rates of germination (figure 1B), while Jigurti and 76 T1 # 23 had lower rates of germination. The rate of germination ranged from 58.2% d^{-1} for Gambella 1107 to 39.9% d^{-1} for 76 T1 # 23. As with germination percentage, Gambella 1107, Meko and P9403 proved to be relatively tolerant to water deficit stress, as their rate of germination was least affected.

Similar to the rate of germination, the mean time required to reach final germination (MTG) was affected by water deficit treatments and cultivars. The results indicated that an increase in water deficit levels increased the time required to reach final germination (figure 2A). Lafond and Baker (1986) also observed an increase in germination time in wheat as osmotic stress was increased. Similarly, Smith *et al.* (1989) found an increase in median germination time of sorghum from 1.04 days at 0 MPa osmotic pressure to 5.3 days at 1.2 MPa osmotic pressure. Raccuia *et al.* (2004) reported increased mean germination time in wild cardoon as osmotic potential increased. The sorghum cultivars differed in the time required to reach final germination, with Gambella 1107, Meko and P9403 requiring a shorter time while Jigurti and 76 T1 # 23 required a longer time to reach final germination (figure 2B).

The percentage germination and rate of germination of crop seeds are of considerable agronomic importance. Reduction in the rate of germination and lengthening of the time required to reach final germination due to water deficit would be particularly critical in semi-arid areas where moisture availability in the seed zone occurs for a brief period. Thus, one of the more important agronomic aspects of crop establishment is the rate at which a sufficient number of seeds germinate and establish a stand during the limited period when environmental conditions are suitable. Early and rapid germination are all the more important in areas where the suitable period for seedling establishment is short (Fady, 1992).

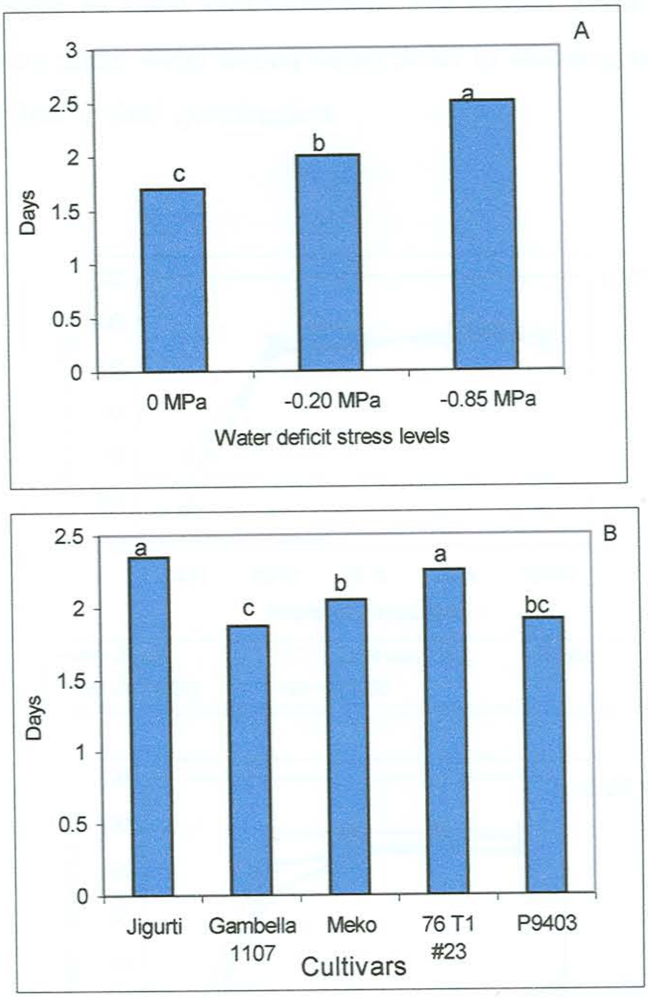

Figure 2. Effect of water deficit stress (A) and cultivar differences (B) on mean time to final germination. Bars with the same letters are not significantly different at $P \leq 0.05$.

The kinetics of germination was variable between water deficit treatments and between cultivars (figure 3). Under the no stress (0 MPa) condition, all cultivars reached at least 80% germination within 48 hours of incubation. At a mild water deficit (–0.20 MPa), Gambella 1107, Meko and P9403 attained 80% germination within 48 hours, while Jigurti and 76 T1#23 required 72 hours to reach 80% germination and 96 hours to attain maximum germination. Under severe water deficit (-0.85 MPa), the time required to reach 80% germination was extended for all cultivars. Gambella 1107, Meko and P9403 reached 80% germination after 72 hours, and maximum germination after 96 hours. Jigurti needed 96 hours to reach 80% germination and 76 T1 # 23 did not reach 50% germination, even after 120 hours. In semi-arid areas where water in the upper soil layers is available for only a short period, rapidly germinating cultivars such as Gambella 1107, Meko and P9403 may have an advantage in stand establishment. The results of this study indicate that sorghum cultivars under water deficit stress differ in attaining maximum germination and in average time to final germination.

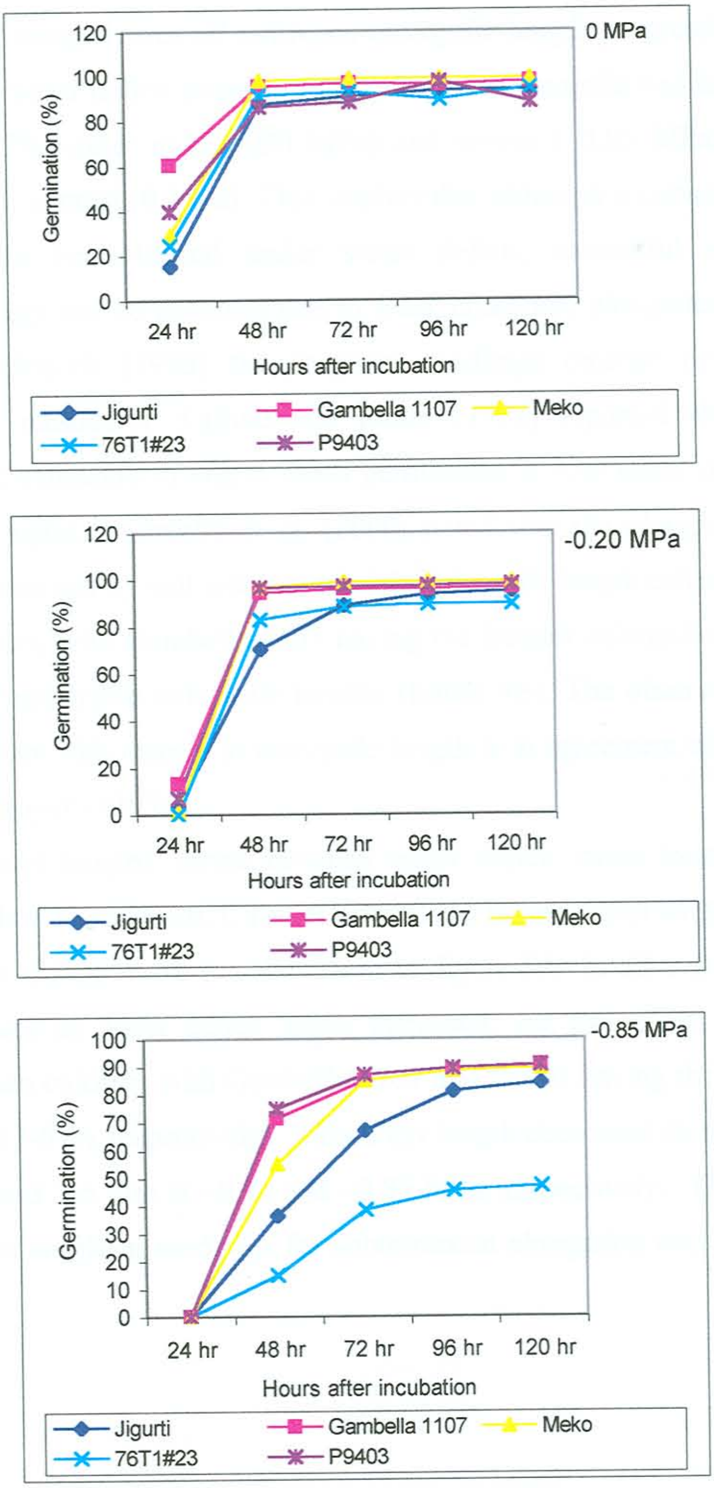

Figure 3. Effect of water deficit stress on the time course of germination of sorghum cultivars.

Coleoptile, mesocotyl and radicle length

The effect of water deficit stress on the early growth of seedlings of different sorghum cultivars was estimated by measuring coleoptile, mesocotyl and radicle lengths. Significant differences in coleoptile lengths were observed between water deficit treatments and between cultivars. The water deficit x cultivars interactions were not significant. Figure 4A shows the effect of water deficit treatments on coleoptile development. Averaged over all cultivars, coleoptile length progressively decreased with increasing water deficit stress. The length of the coleoptile was severely reduced by 34% and 77% under mild (-020 MPa) and severe (–0.85 MPa) water deficit, compared to the control (0 MPa). This implies that although a certain percentage of germination can be achieved under water deficit, successful emergence and establishment may not be achieved due to weak coleoptile elongation. According to Radford and Henzell (1990) the sorghum seedlings emerge by elongation of coleoptile and mesocotyl. Lafond and Baker (1986) reported slower coleoptile emergence and extension in wheat seeds germinated at low water potentials due to reduced water uptake. Forcella et al. (2000) noted that the elongation rate of the coleoptile is governed by soil water potential. Coleoptile length differed significantly between cultivars, with Gambella 1107 having the longest coleoptile. The other four cultivars had comparable coleoptile lengths (figure 4B). The observed variability in sorghum cultivars with respect to coleoptile length is in agreement with the results of Wanjari and Bhoyar (1980).

Mesocotyl lengths varied between water deficit stress treatments, between cultivars and their interactions. Cultivar differences in mesocotyl length in response to different water deficit levels are illustrated in figure 5A. In all cultivars, mesocotyl length decreased as water deficit stress increased, but the extent of the decrease differed for each cultivar, with Gambella 1107 and P9403 having the least reductions (27-70% and 13-67% respectively). Mesocotyl length decreased from 11-33 mm at 0 MPa to 8-20 and 2-6 mm at –0.20 and –0.85 MPa, respectively. This indicates that the potential of sorghum seedlings for subterranean elongation may vary with water stress.

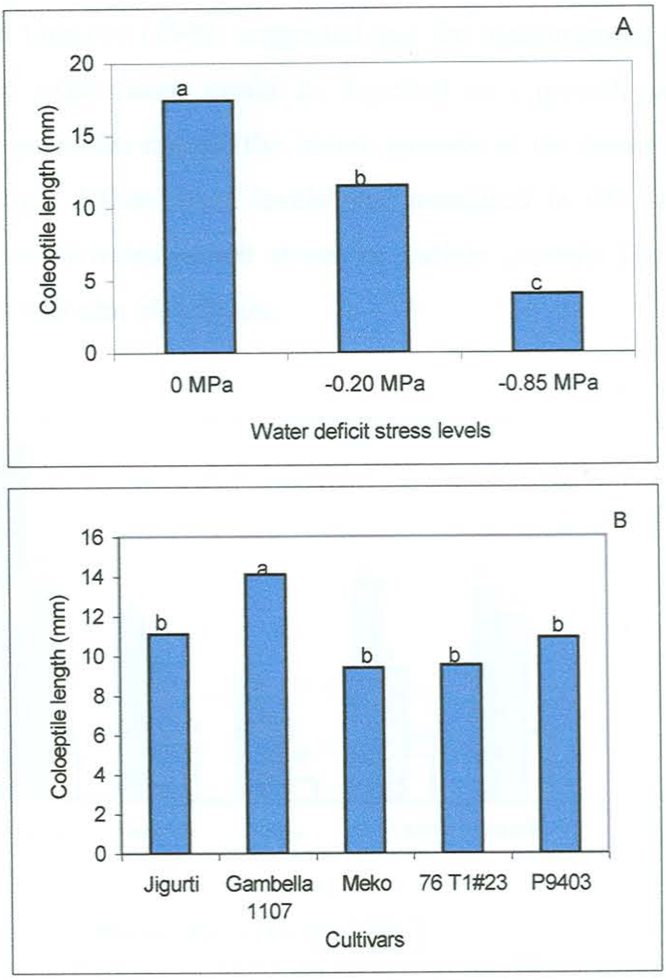

Figure 4. Effect of water deficit stress (A) and cultivar differences (B) on coleoptile length. Bars with the same letters are not significantly different at $P \leq 0.05$.

The observed reduction in mesocotyl and coleoptile lengths due to water deficit stress agrees with the findings of Takahashi (1978) who observed inhibited mesocotyl and coleoptile growth in rice under water deficit. Radford and Henzell (1990) noted the importance of selection for sorghum genotypes with long coleoptiles and mesocotyls as there is a strong relationship between coleoptile and mesocotyl length and emergence. Cultivars Gambella 1107 and P9403 with longer coleoptiles and mesocotyls, respectively, under water deficit stress may have better potential for rapid emergence from the soil. Because sorghum seedlings emerge from the soil by elongating the mesocotyl and coleoptile, reduction in mesocotyl and coleoptile growth has agronomic implications in that although seeds could germinate under water deficit conditions they may not be able to emerge. Thus, cultivar selection for better water deficit tolerance during the germination stage should include coleoptile and mesocotyl elongation parameters in addition to the rate and percentage of germination.

Fyfield and Gregory (1989) suggested that the measurement of radicle length during germination experiments could be regarded as a growth parameter for the developing seedling. In this regard, the radicle growth of the five sorghum cultivars under different water deficit stress levels was measured in this study. Figure 5B illustrates the effect of water deficit stress on radicle growth. The water deficit x cultivar interaction was also significant.

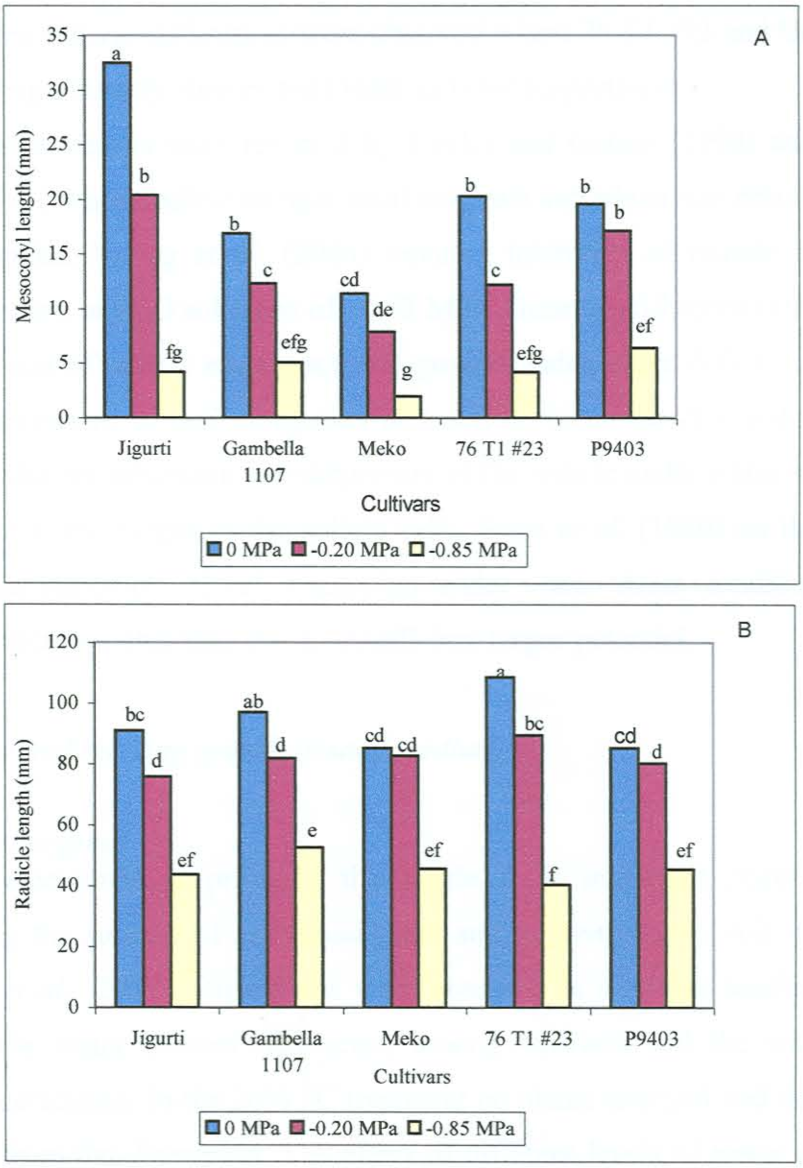

Figure 5. Effect of water deficit stress on the mesocotyl (A) and radicle (B) lengths of sorghum cultivars. Bars with the same letters are not significantly different at $P \leq 0.05$.

For cultivars Jigurti, Gambella 1107 and 76 T1 #23, radicle growth decreased progressively as the level of water deficit increased. Whereas for Meko and P9403 radicle growth decreased significantly only under severe water deficit conditions (-0.85 MPa). Radicle growth decreased from 85-109 mm at 0 MPa to 75-90 and 40-50 mm at -0.20 and -0.85 MPa, respectively. Under mild (-0.20 MPa) and severe (-0.85 MPa) water deficit stress conditions, radicle growth decreased by 17 to 52% for Jigurti, 16 to 46% for Gambella 1107, 3 to 47% for Meko, 18 to 63% for 76 T1 #23 and 6 to 47% for P9403 relative to 0 MPa. Under mild water deficit condition only 76 T1 #23 differed significantly from the rest of the cultivars. But under severe water deficit, more cultivar differences were observed where 76 T1 #23 and Gambella 1107 developed significantly shorter and longer radicles respectively.

Similar results were reported by Naylor and Gurmu (1990) and Gurmu and Naylor (1991) where radicle elongation of sorghum and wheat was retarded under low water potential. Young *et al*. (2000) reported inhibition of radicle length in rice cultivars grown in PEG solutions of –0.63 MPa. Gurmu and Naylor (1991) suggested that inhibition of radicle emergence and growth under water deficit stress could be due to impairment of cell elongation and cell division. Bewley and Black (1994) suggested that the inhibition in enlargement of the radicle under water stress is due to a reduction in the turgor of the radicle cells. Stout *et al*. (1980) on the other hand, argued that inhibition of cell expansion under water stress conditions is due to metabolic factors rather than due to insufficient turgor potential.

Emergence and seedling growth in sand medium

Seedling emergence

Seedling emergence is probably the single most important phenological event influencing the success of an annual plant and is governed by soil water potential (Forcella *et al*., 2000). Differences were observed in sorghum seedling emergence between the water content treatments, among cultivars and the water content x cultivar interactions. In the 20% FC treatment no plants emerged and this treatment is excluded from the discussion. The effect of different levels of water content on the emergence percentage of sorghum cultivars after 96 hours, is illustrated in figure 6A.

The results indicate that for all cultivars, except Jigurti and P9403, emergence declined significantly at 40% FC. Emergence of Jigurti and P9403 declined at 60%

FC. At 60% FC Gambella 1107, Meko and P9403 and at 40% FC Gambella 1107 and P9403 registered significantly higher percentages of emergence than Jigurti and 76 T1 #23. The better emergence in Gambella 1107 and P9403 in the sand medium agrees with the observation in the PEG experiment where these two cultivars developed longer coleoptiles and mesocotyls. Compared to emergence at field capacity (100% FC), the reductions in emergence at 60% and 40% FC were greater for Jigurti (21 and 34%) and 76 T1 #23 (6 and 35%). Gambella 1107 (3 and 8%) and P9403 (6 and 15%) were the least affected.

Gurmu and Naylor (1991) reported reduced emergence of sorghum cultivars at lower soil water potentials (-0.45 to -1.15 MPa). The reduction in seedling emergence at lower levels of water content possibly resulted from a low seed-water contact (Hunter and Erickson, 1952; Brar *et al.*, 1992). This is apparently due to the fact that the water is adsorbed on the surface of the sand particles with a force greater than the absorbing capacity of the seed. Furthermore, at low water contents the rate of soil moisture movement is too slow to supply sufficient water to the immediate environment of the seed for its germination (Hunter and Erickson, 1952). According to Cardwell (1984) germination is the physiological process that starts with the addition of liquid water to a dry seed.

Emergence index (% day^{-1}), a parameter indicating the rate of emergence, also decreased as the level of water content decreased (figure 6B). Gambella 1107, Meko and P9403 had the highest and Jigurti and 76 T1 #23 the lowest rates of emergence at all levels of water content. These cultivars had similar performances in the PEG experiment for the rate of germination.

The kinetics of seedling emergence were also variable between the levels of water content and the effect was different for each cultivar (figure 7). Gambella 1107 and P9403 attained above 80% emergence within 24 hours after the first observation of emergence at all levels of water content. This observation agrees with the PEG experiment where Gambella 1107 and P9403 attained 80% germination earlier than the rest of the cultivars under severe water deficit conditions. Jigurti never approached 80% emergence at 60 and 40% FC even after 96 hours, while 76 T1 # 23 and Meko took 48 hours to attain above 80% emergence at 60% FC, but never reached 80% emergence at 40% FC. Similarly, 76 T1 #23 did not attain even 50% germination in the PEG experiment under severe water deficit (-0.85 MPa) conditions.

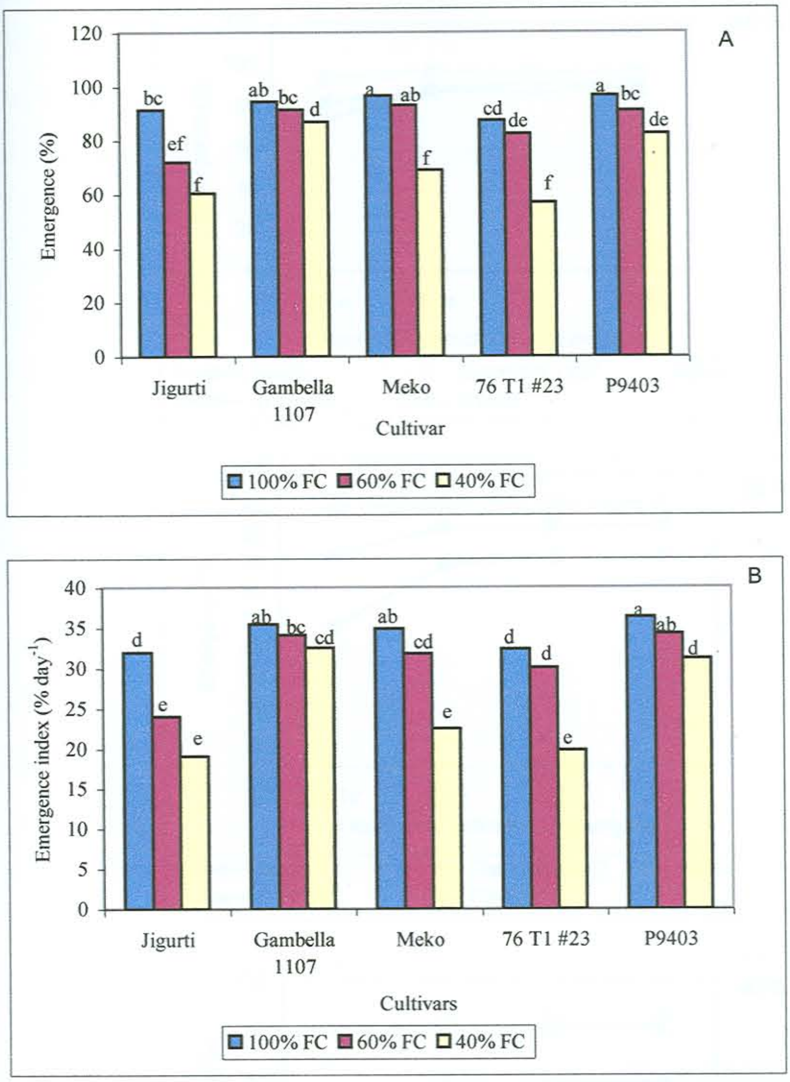

Figure 6. Effect of level of growing media water content on final seedling emergence (A) and emergence index (B). Bars with the same letters are not significantly different at P≤0.05.

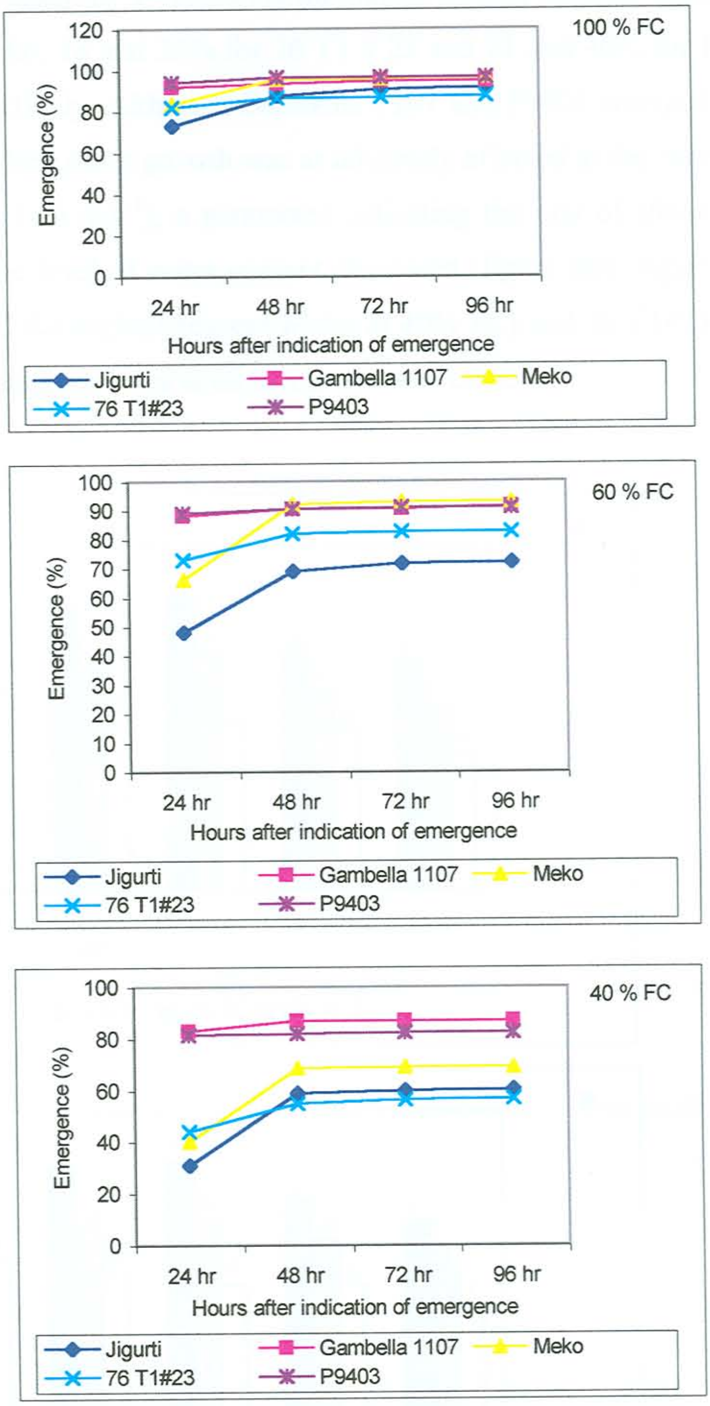

Figure 7. Effect of level of growing media water content on the time course of emergence of sorghum cultivars.

Seedling shoot length, total root length and total root area

Figure 8A illustrates seedling shoot length of cultivars in response to various levels of growing media water content. Seedling shoot length was affected by the levels of water content, cultivars and the water content x cultivar interactions. At 11 days after emergence, decreasing water content resulted in reduced shoot length in all cultivars.

Shoot length was reduced by 14 and 27% for Jigurti, 24 and 38% for Gambella 1107, 19 and 42% for Meko, 18 and 35% for 76 T1 # 23 and 21 and 40% for P9403 at 60 and 40% FC, respectively. Although Gambella 1107 and P9403 emerged better than the other cultivars, their shoot growth was as adversely affected as the other cultivars.

Shoot index (cm day^{-1}), a parameter indicating the rate of shoot elongation, also decreased as the level of water content decreased (figure 8B). Jigurti, Gambella 1107 and Meko had the highest (except Meko at 40% FC) and 76 T1#23 and P9403 the lowest shoot elongation rates at all levels of water content.

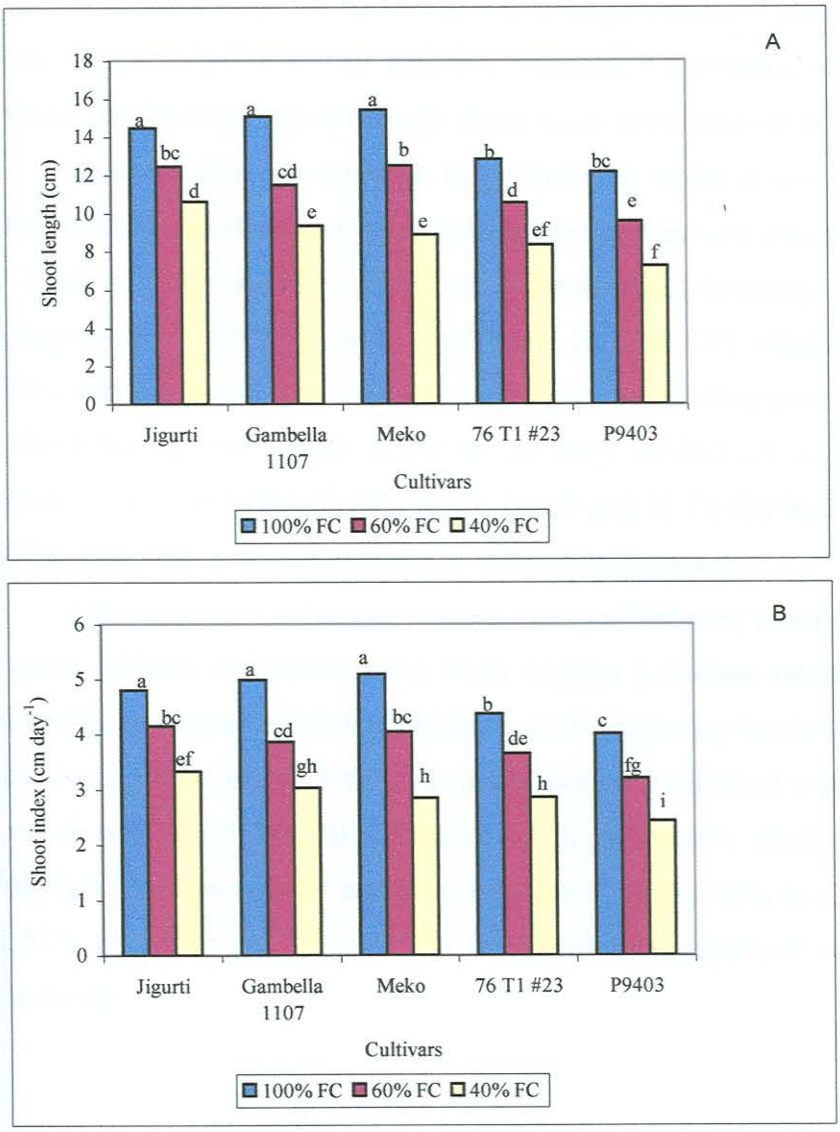

Figure 8. Effect of level of growing media water content on shoot length (A) and shoot index (B) of sorghum cultivars. Bars with the same letters are not significantly different at $P \leq 0.05$.

Seedling root length was affected by the levels of growing media water content, cultivars and their interactions. The data indicated that decreasing levels of water content had adversely affected the root length of all cultivars, except in 76 T1 #23 (figure 9A). The root length of cultivars decreased by 41 and 51% for Jigurti, 34 and 41% for Gambella 1107, 30 and 36% for Meko and 33 and 49% for P9403 under 60% and 40% FC, respectively. Under no stress condition (100% FC), Jigurti produced significantly longer roots, while the remaining cultivars had comparable root lengths, indicating the presence of genetic variability. At lower levels of water content (60% and 40% FC) both Jigurti and 76 T1 #23 produced significantly longer roots. Root length in 76 T1 #23 was even promoted by increasing water deficit stress, which is probably an adaptive reaction. Gawronska and Grzelak (1993) reported similar responses in triticale under water stress conditions.

Cultivars that can establish long extensive seedling root systems may have better seedling establishment because their root systems are able to rapidly penetrate the upper soil layers and continue water uptake, thus avoiding water deficit stress (M'Ragwa *et al*., 1995). Townley-Smith and Hurd (1979), cited by M'Ragwa *et al.* (1995), also suggested that selection for a vigorous and deep penetrating root system on the basis of root length could be an easy method of selecting for drought resistance. Thus, in terms of root growth Jigurti and 76 T1 #23 had potential for better seedling establishment at decreasing levels of water content.

Differences in total root area were observed between water content treatments, between cultivars and between the water content x cultivar interactions. Similar to root length, root area declined significantly with decreasing levels of water content for all cultivars, except in 76 T1 #23, where the root area increased with decreasing levels of water content (figure 9B). Relative to the respective well watered condition, reduction of root area by 37 and 50% for Jigurti, 33 and 48% for Gambella 1107, 32 and 57% for Meko and 25 and 53% for P9403 were observed at 60 and 40% FC, respectively.

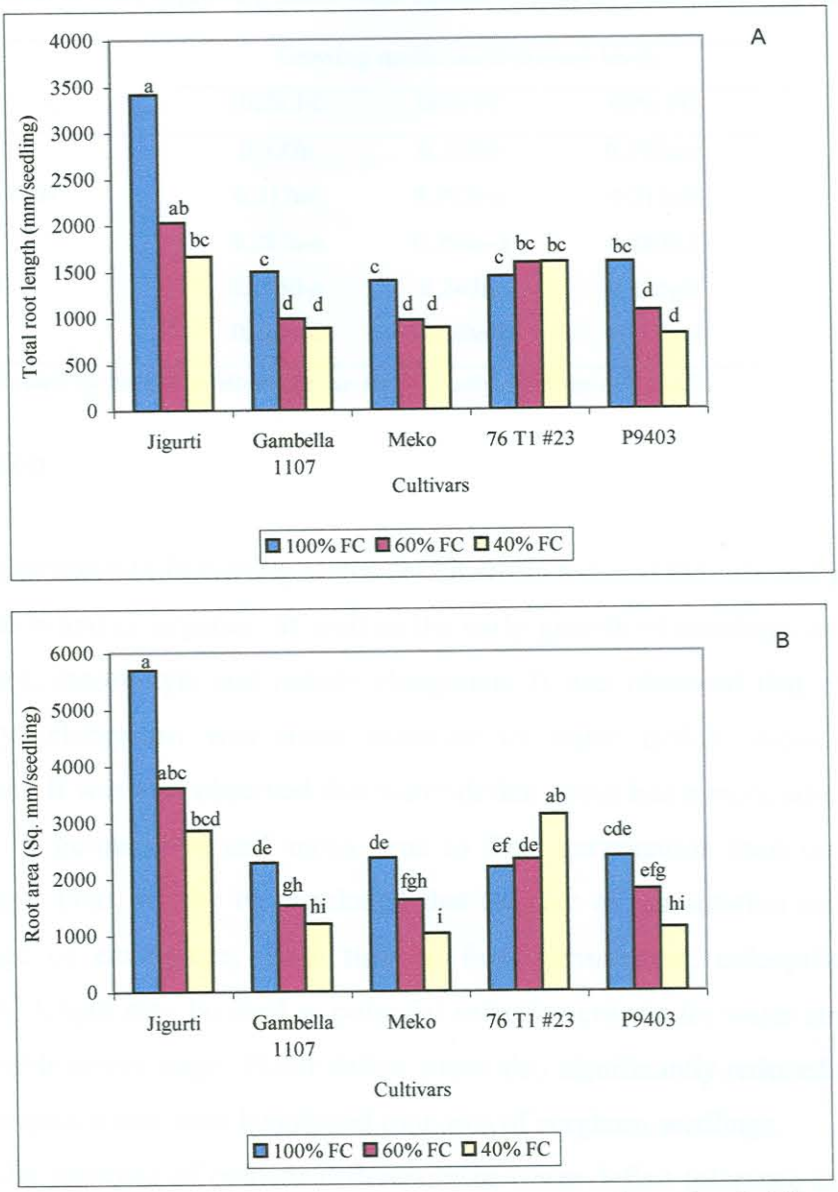

Figure 9. Effect of level of growing media water content on total root length (A) and area (B) of sorghum cultivars. Bars with the same letters are not significantly different at $P \leq 0.05$.

Total dry mass

The results of total dry mass of sorghum cultivars, in response to decreasing levels of water content of the growing media, are presented in table 1. Total dry mass was significantly affected by water content treatments, cultivars and by the water content x cultivar interactions. Relative to 100% FC, total dry mass was significantly reduced only in P9403 at 40% FC. For the rest of the cultivars, total dry mass under water deficit stress was comparable to the dry mass in unstressed condition. In all cases, Jigurti, Gambella 1107 and Meko had significantly greater dry mass, while 76 T1 #23 and P9403 accumulated significantly lower dry mass.

Table 1. Effect of level of growing media water content on total dry mass (g pot^{-1}) of sorghum cultivars.

Cultivars	Growing media water content levels		
	100% FC	60% FC	40% FC
Jigurti	0.327a	0.317ab	0.295abc
Gambella 1107	0.312ab	0.292a-d	0.315ab
Meko	0.287a-e	0.290a-d	0.280b-f
76 T1 #23	0.255d-g	0.247fg	0.225gh
P9403	0.267c-f	0.250efg	0.217ghi

Means followed by the same letters are not significantly different at $P \leq 0.05$.

Conclusion

In both experiments increasing water deficit stress reduced the rate and percentage of germination and emergence, as well as the early growth of seedlings as indicated by coleoptiles, mesocotyls and radicle elongation. It was observed that coleoptile and mesocotyl elongation was more sensitive to water deficit stress than radicle elongation. It was also observed that water deficit stress had a more adverse effect on the rate of germination and mean time to final germination than on germination percentage. Thus, it may be concluded that the rate of germination and emergence, percentage of emergence, mean time to final germination, coleoptile length and mesocotyl length may be used as potential selection criteria for water stress tolerance at the establishment stage. Water deficit stress also significantly reduced shoot length, shoot elongation rate, root length and root area of sorghum seedlings.

The presence of cultivar differences in water deficit tolerance at germination was demonstrated in these studies. High percentage and rate of germination are attributes that identify tolerant cultivars at the germination stage (Baalbaki *et al*., 1999). In this regard, Gambella 1107, Meko, and P9403 were found to be tolerant to water deficit stress as they had a significantly higher rate and percentage of germination and emergence and also had a higher rate of shoot elongation, with the exception of P9403. They required less time to reach final germination. Moreover, Gambella 1107 developed significantly longer coleoptiles, mesocotyls and radicles, which are important attributes for better emergence under water deficit stress. In terms of shoot length and root system development, Jigurti and Meko were tolerant. Jigurti and 76 T1 #23 developed a longer root system with a larger root area, which are important attributes that can help the cultivars to establish early under water stress conditions, as deep growing root systems can rapidly penetrate the upper soil layer and access deeper soil water reserves (Wright and Smith, 1983). Although Jigurti and 76 T1 #23 had a poor rate and percentage of both germination and emergence, they may have the capacity to establish better under water stress condition once the seeds germinated as they can develop extensive root systems.

Results of these studies suggest that there is potential to breed for increased drought tolerance within the Ethiopian sorghum gene pool. Thus, the results are very useful for breeders for future development of drought tolerant cultivars and for agronomists to predict sowing rates depending upon expected soil moisture conditions.

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CHAPTER 3

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EFFECT OF WATER DEFICIT STRESS ON THE GROWTH, PHYSIOLOGICAL PROCESSES AND LEAF CELL ULTRASTRUCTURE OF SORGHUM

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An experiment was conducted in growth chambers to study the response of sorghum cultivars to water deficit stress. Seven sorghum cultivars were evaluated under three water deficit levels [control (-0.05 MPa), mild stress (-0.27 MPa), and severe stress (-0.96 MPa)] in a nutrient solution (Nitch solution) with a completely randomised block design with three replications. The three water deficit levels were created by adding 0, 10 and 20% (w/v) PEG 6000 to the nutrient solution. Water deficit, especially severe water deficit (-0.96 MPa), severely affected the growth and physiological processes. Water deficit stress markedly reduced plant height, leaf number, cumulative leaf area, dry matter accumulation (leaf, stalk and total shoot), water use efficiency, root length, and stomatal density. Water deficit stress also increased leaf diffusive resistance. Water deficit stress increased root dry mass. Water stress increased stomatal closure. Stressed plants deposited larger amounts of epicuticular wax on the leaf surface and on the stomatal openings. Water stress significantly reduced the amount of starch grains in the chloroplasts. The seven cultivars displayed distinctive responses to water deficit stress for many of the parameters. Jigurti, Gambella 1107 and Meko grew better than P9403 and SA1486 under water deficit conditions. Jigurti showed no significant reduction in any of the growth parameters even under severe water deficit (-0.96 MPa) conditions.

Keywords: epicuticular wax, sorghum, starch, stomata, water deficit stress

Introduction

Water deficit stress is one of the most important environmental stresses affecting agricultural productivity in the semi-arid areas of NE Ethiopia and often results in considerable yield reductions. One of the prevalent features of the climate of the area is the uncertainty of rainfall during the vegetative stage of sorghum. A deficiency of water during any growth stage of sorghum often results in a loss of grain yield (Munamava and Riddoch 2001). Water deficiency reduces plant water potential and thus, impairs many physiological and biochemical functions (Daie 1996).

Among several strategies devised to overcome the problem of drought stress, the selection of crop species or cultivars with drought tolerance traits has been considered an economical and efficient strategy (Ashraf et al. 1992). Existing evidence indicates that genetic variation for drought tolerance in grain sorghum is wide (Blum et al. 1989). Blum et al. (1989) indicated that sorghum genotypes differ for nearly all recognized drought tolerance mechanisms, such as maintenance of high leaf water status, deeper root growth, stomatal sensitivity and epicuticular wax deposition. Genotypic differences in dry matter production and partitioning in response to drought stress have also been reported (Ashraf and Ahmad 1998). This indicates that the opportunity for selecting drought tolerant cultivars is considerable.

Most of the techniques for estimating drought responses indicated that drought response at early vegetative stages were reasonably well correlated with drought response of mature plants (Wright and Jordan 1970). Thus, it appears that drought response at an early vegetative stage give a reasonable estimate of the response of mature plants.

In NE Ethiopia drought escaping sorghum cultivars have been bred and released for production considering only drought escaping traits and yield performance. However, unpredictable and intermittent periods of water deficit often occur during the vegetative stages. Under such conditions the use of varieties which combine drought tolerance and drought escape strategies should be advantageous. However, the agronomic and physiological attributes of these cultivars in response to water deficit at the vegetative stage have never been studied. Knowledge of the drought tolerance attributes of the cultivars should provide a good foundation for more efficient water management and for exploiting genetic variability. The objective of this investigation was to study the effect of water stress on the growth of sorghum and to examine variability in the agronomic, physiological and anatomical response of sorghum cultivars to water deficit in the early vegetative stages.

Materials and Methods

This experiment was conducted in growth chambers at the University of Pretoria. Five sorghum cultivars from Ethiopia (Jigurti, Gambella 1107, Meko, 76 T1 #23 and P9403) and two from South Africa (SA1486 and SA1488) were evaluated at three water deficit levels [control (-0.05 MPa), mild stress (-0.27 MPa), and severe stress (-0.96 MPa)]. The three water stress treatments were created by adding 0, 10 and 20 % (w/v) PEG 6000 to the nutrient solution (Nitch solution), respectively. These water deficit treatments were based on the results of a preliminary trial. The stress period lasted for 12 days. The osmolality of the pure nutrient solution and nutrient solution with PEG 6000 added was determined with a digital Micro Osmometer and converted from mOsmol kg^{-1} to MPa using the Van't Hoff equation. The experiment was designed as a completely randomised block with three replicates. Fifteen day old plants were planted into the trial pots and grown for 24 days under no-stress conditions before water deficit stress treatments were applied for a period of 12 days. Two uniform seedlings per pot were inserted in holes in polystyrene lids fixed on 91 pots containing a nutrient solution at pH (H_2O) 5.4. Plants were grown in growth chambers ($25^0/17^0$ C in 12h day/night cycle, 334-399 μ mol m^{-2} s^{-1} PAR).

Growth measurements

Plants were harvested 51 days after emergence (12 days after the commencement of treatments) at which time leaf, stem (including leaf sheaths) and root dry mass were determined after oven drying at 75^0 C to constant weight. Leaf area (LA) at harvest was measured with a LI-3100 leaf area meter (LI-COR, Inc., Lincoln, NE, USA). Root length was estimated by measuring the longest root. Plant height to the tip of the longest leaf was recorded.

Leaf diffusive resistance (LDR) was determined between 10h00 and 13h00 using a LI-1600 steady state porometer (LI-COR, Inc., Lincoln, NE, USA) on three occasions during the drought cycle. Measurements were made on the mid-portion of the adaxial surface of the second and third youngest leaves of each plant. Leaf relative water content of the third and fourth youngest leaves was determined between 10h00 and 13h00 on days 1, 4 and 9 after treatments commenced, using five leaf discs (each 0.65 cm^2). RWC was determined using the method of Nepomuceno et al. (1998). Water use was calculated from the difference in water supplied and water left at harvest. Water use efficiency (WUE) was calculated as the ratio between total dry matter and the corresponding amount of water used.

Scanning (SEM) and Transmission (TEM) electron microscopy

After eight days of treatment application, leaf samples from three plants of the cultivars Jigurti, Meko, 76 T1 #23 and SA 1488 were taken from the third youngest leaf. Specimens of ca. 10 mm^2 size for SEM and ca. 2 mm^2 size for TEM were fixed in 2.5% glutaraldehyde in a 0.1 M phosphate buffer (pH 7.4) for 3 h at 4^0 C. Specimens were post-fixed in 1% osmium tetraoxide, rinsed in buffer and dehydrated in a graded series of ethanol, spending 15 minutes in each one of the series, and subsequently critical point dried in liquid CO_2. Specimens for SEM observation were mounted on aluminium stubs, coated with gold and viewed with a JEOL JSM-840 scanning electron microscope (JEOL, Tokyo) at 5 kV. Stomatal density was counted for three randomly selected fields per leaf sample. Stomata dimensions were measured for three randomly selected fields, each with four stomata. The dimensions of 12 stomata per leaf sample were measured with an Image Tool (version 2.00) computer program. Epicuticular wax deposition on the adaxial leaf surfaces was also examined. Specimens for TEM observation were embedded in Quetol 651resin. A Reichert ultracut E microtome was used to cut thin cross-sections (0.1 μm) with a diamond knife. Sections were double-stained with uranyl acetate and lead citrate. Electron micrographs were obtained with a Philips EM 301transmission electron microscope.

Analysis of variance for the measured parameters was performed using the SAS statistical program (SAS V8.2, SAS Institute Inc., Cary, NC, USA). Whenever treatment differences were found to be significant, based on the results of *F*-test, critical differences were calculated at 5% level of probability using the least significant difference (LSD) technique.

Results and Discussion

Results of the ANOVA revealed that highly significant differences existed between both water deficit stress treatments and cultivars for most parameters. Significant cultivar x stress interactions existed only for plant height, leaf area and for leaf, stem and shoot dry mass.

Plant growth

Water deficit stress adversely affected plant growth in most of the cultivars. Plant height was markedly reduced by the level of water deficit stress (table 1). Compared to the well watered plants, plant height under severe water stress was significantly reduced in all cultivars, except in Jigurti. The reduction in plant height was more pronounced in P9403 and SA1486 with 15 and 34% reduction in P9403 and 11 and 20% reduction in SA1486 under mild and severe water stress conditions, respectively. In terms of plant height, Jigurti, Gambella 1107, Meko, 76 T1 #23 and SA1488 showed better tolerance to water deficit. The response of Jigurti is interesting in that its shoot height was enhanced by mild water stress and the reduction under severe water stress was not significant. Growth response to stress in terms of plant height was regarded as one component of a multiple selection index for drought tolerance in maize (Fischer et al. 1983).

Table 1

Effect of water deficit stress on plant height (cm) and leaf area (cm^2 plant^{-1}, % of control) of sorghum cultivars

Cultivars	Plant height			Leaf area		
	-0.05 MPa	-0.27 MPa	-0.96 MPa	-0.05 MPa	-0.27 MPa	-0.96 MPa
Jigurti	126.67b-e	134.67bc	126.33cde	100bc	131.8a	96.5bcd
Gambella 1107	147.00a	138.00ab	122.33def	100bc	87.6cd	66.6efg
Meko	133.67bcd	137.50abc	116.33e-h	100bc	116.1ab	77.0def
76 T1 #23	122.67def	121.33ef	108.67ghi	100bc	92.6cd	61.7fg
P9403	126.33cde	107.67ghi	83.00k	100bc	82.5cde	38.8h
SA1486	117.67efg	105.00hij	94.00jk	100bc	77.9def	50.9gh
SA1488	117.50e-h	113.67f-i	104.00ij	100bc	98.6bc	59.5fg

Means in rows and column for each parameter followed by the same letter do not differ significantly at P≤0.05.

Data on the number of leaves indicate that water stress had significant effects on the production of leaves per plant. Leaf production under severe water deficit stress (-0.96 MPa) was significantly reduced compared to well-watered and mild water deficit (-0.27 MPa) conditions (fig.1). Similar results were reported by Heitholt (1989) in wheat and De Costa et al. (1997) in faba bean who observed reduced leaf number under water deficit stress.

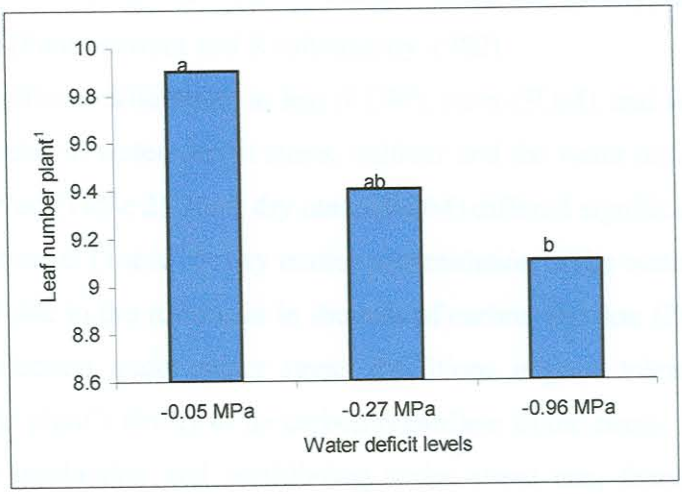

Fig.1 Effect of water deficit stress on leaf number in sorghum. Bars with the same letter do not differ significantly at P≤0.05.

Significant differences in leaf area development were observed between water deficit treatments, between cultivars and their interaction effects. In all cultivars, except Jigurti, leaf area development was significantly impaired by the severe water deficit treatment (table 1). The reductions in leaf areas of Jigurti, Gambella 1107 and Meko were, however, relatively small. Under severe water deficit conditions, P9403 and SA1486 developed significantly smaller leaf areas.

Leaf area development in the susceptible cultivar SA1486 was significantly reduced by even mild water stress. Leaf area was significantly correlated to leaf number (r=0.48), suggesting lower leaf production as one of the reasons for reduced leaf area development per plant under water stress conditions. The reduction in leaf number implies that leaf surface area per plant available for transpiration and assimilate production will also be reduced, thereby reducing the growth of plants. Rosenthal et al. (1987) also reported reduced leaf area development in sorghum due to fewer leaves produced under water stress conditions. Reduced leaf area development under water deficit conditions could also occur due to inhibition in cell division and enlargement as a result of loss of cell turgor (Lu and Neumann 1998). Reduced leaf area development under water stress conditions will reduce the quantity of solar radiation intercepted by the canopy, thereby reducing dry matter production. Thus, assessment of the ability of a genotype to continue leaf growth or expansion, and maintain a high leaf area, during water deficit stress would help in characterizing the genotypes as drought tolerant or susceptible (Parameswara and Krishnasastry 1982).

Significant differences in leaf (LDM), stem (SDM), and shoot (SHDM) dry matter production due to water deficit stress, cultivar and the water deficit x cultivar interaction were observed (Table 2). Root dry mass (RDM) differed significantly only between water deficit treatments (Table 3). Dry matter accumulation under water stress conditions could be reduced due to the reduction in the rate of carbon fixation (Daie 1996). Effective dry matter production under water stress conditions implies tolerance to the stress as it indicates the plant's ability to fix carbon regardless of the stress. Genotypic differences in dry matter production and partitioning under stress can, therefore, be used as useful indicators of relative tolerance to water deficit stress (Ashraf and Ahmad 1998). In all cultivars, LDM, SDM and SHDM reductions were markedly higher under severe water deficit than under mild water deficit conditions (table 2). Dry matter reduction under mild water deficit conditions, was significant only for the susceptible cultivar SA1486. Under severe water deficit conditions, although LDM, SDM and SHDM tend to decline in all cultivars, except Jigurti, significant reductions were observed in 76 T1 #23 (except for LDM), P9403, SA1486, and SA1488 with 54, 41 and 34% reduction in LDM, 40, 69, 45 and 38% reduction in SDM and 33, 60, 42 and 35% reduction in SHDM. Dry matter accumulation in Jigurti, Gambella 1107 and Meko was relatively less affected (tables 2 and 3). SHDM was closely correlated to leaf area development (r = 0.93) and root to shoot ratio (r = -0.50) suggesting that the reduction in SHDM under water deficit conditions could be explained by the reduction in leaf area development and increased dry matter partitioning to the roots. Under water stress conditions, owing to low carbon supply, the fixed carbon will be used in osmotic adjustment rather than for growth/storage thus reducing crop growth (Daie 1996).

RDM accumulation was enhanced both by mild and severe water deficit treatments (table 3). In agreement with this observation, Ren et al. (2000) found increased root growth in wheat under PEG-induced drought stress. There is no clear explanation for the increased RDM accumulation under water stress, except the hypothesis by Kramer (1983) that there could be occasional situations where RDM could increase in mildly stressed plants due to more effective osmotic adjustment in roots than in shoots.

Root length was impaired by the water stress treatments, with the highest reduction observed under severe water stress (table 3). Root length also varied between cultivars with Jigurti followed by Gambella 1107 and Meko having the longest, and 76 T1 #23, P9403 and SA1486 having the shortest roots. Root to shoot ratio (RSR) also differed both between water deficit treatments and cultivars (table 3). Water deficit stress enhanced RSR with increases of 33 and 44% under mild and severe water deficit treatments respectively, indicating more dry matter partitioning into the roots relative to the shoot. Cultivars P9403, SA1486 and SA1488 appeared to partition a greater proportion of assimilate into their root systems (table 3).

Table 2

Effect of water deficit stress on leaf, stem and shoot dry matter (g plant^{-1}) of sorghum cultivars

Cultivars	Leaf dry matter			Stem dry matter			Shoot dry matter		
	-0.05 MPa	-0.27 MPa	-0.96 MPa	-0.05 MPa	-0.27 MPa	-0.96 MPa	-0.05 MPa	-0.27 MPa	-0.96 MPa
Jigurti	6.45efg	9.07abc	7.59b-f	3.95d-h	5.92a	4.91a-d	10.40efg	14.98ab	12.49b-e
Gambella 1107	11.91ab	10.66ab	8.30abc	7.45a	6.91a	5.10a-d	19.36ab	17.56ab	13.40a-d
Meko	8.02a-e	9.91abc	6.83d-g	5.63ab	7.14a	4.62b-e	13.65a-d	17.05a	11.44c-f
76 T1 #23	10.12abc	9.45abc	7.27c-f	5.91ab	5.50a-e	3.52e-i	16.02ab	14.95abc	10.79d-g
P9403	8.10a-d	7.29cdef	3.73g	5.23abc	4.07c-g	1.64i	13.33a-d	11.36c-f	5.37g
SA1486	8.25a-d	6.07fg	4.88g	4.41b-f	2.79ghi	2.41hi	12.67a-e	8.86fg	7.29g
SA1488	9.530abc	8.88abc	6.33fg	4.93a-e	4.50b-f	3.08f-i	14.46abc	13.38a-d	9.41fg

Means in rows and column for each parameter followed by the same letter do not differ significantly at P≤0.05.

Table 3

Effect of water deficit stress and cultivar differences on root dry matter (RDM), root length (RL) and root to shoot ratio (RSR) of sorghum cultivars

Water deficit stress levels	RDM (g plant^{-1})	RL (cm plant^{-1})	RSR
-0.05 MPa	5.25b	32.98a	0.37c
-0.27 MPa	7.33a	30.93b	0.55b
-0.96 MPa	6.49a	27.06c	0.66a
Cultivars			
Jigurti	6.28a	35.83a	0.49bc
Gambella 1107	7.58a	32.44b	0.46c
Meko	6.18a	31.63b	0.46bc
76 T1 #23	6.84a	28.86cd	0.52bc
P9403	5.41a	27.89cd	0.59a
SA1486	5.66a	26.28d	0.61a
SA1488	6.57a	28.94bc	0.56ab

Means within a column for each comparison followed by the same letter do not differ significantly at $P \leq 0.05$.

This indicates that water deficit not only reduces the rate of dry matter production but also affects partitioning. Greater partitioning of dry matter to the root system would enable more thorough exploration of soil water reserves and may, therefore, enhance survival during subsequent drought exposure (Munamava and Riddoch 2001). Surviving a drought may, however, not make cultivars able to perform well under drought condition. The observed increase in RSR under water deficit conditions agrees with the results of Munamava and Riddoch (2001).

Water use (WU) and water use efficiency (WUE)

Differences in WU between water deficit treatments and between cultivars were significant (table 4). The amount of water used by plants under severe water deficit conditions was 34% less than water used by plants under well-watered conditions. Among cultivars, Gambella 1107, Meko and 76 T1 #23 followed by Jigurti used the most water. Differences in WUE were also observed between water deficit treatments and between cultivars (table 4). The results indicate an increase in WUE as the level of water deficit stress was increased. WUE increased by 14 and 24% under mild (-0.27 MPa) and severe (-0.96 MPa) water deficit treatments, respectively. This result is in agreement with the reports of Misra and Chaudhary (1985), who reported increased WUE in sorghum under water deficit conditions. Among cultivars, SA1488 followed by Gambella 1107 were the most efficient in water use, while P9403 was the least efficient cultivar. In terms of WUE Gambella 1107 is a drought tolerant cultivar combining high WUE and superior growth under water deficit condition.

Table 4

Effect of water deficit stress and cultivar differences on water use and water use efficiency

Water deficit stress levels	Water use (kg)	Water use efficiency (g kg^{-1})
-0.05 MPa	9.121a	4.270c
-0.27 MPa	8.707a	4.860b
-0.96 MPa	6.031b	5.277a
Cultivars		
Jigurti	8.091bc	4.708bc
Gambella 1107	9.718a	4.977ab
Meko	8.768ab	4.596bc
76 T1 #23	8.492abc	4.632bc
P9403	6.992cd	4.446c
SA1486	6.404d	4.919b
SA1488	6.972cd	5.339a

Means within a column for each comparison followed by the same letter do not differ significantly at $P \leq 0.05$.

Leaf relative water content (RWC)

No significant differences were observed in RWC of leaves for any of the treatment effects. However, RWC tended to decrease as the level of water deficit increased, although differences were not statistically significant (data not shown). The absence of significant differences in leaf RWC in this study may be explained by the hypothesis suggested by Davis et al. (1994) that roots exposed to water deficit conditions may induce a root hormonal signal to the shoot, thus causing stomatal closure and retardatory growth without any detectable changes in leaf water potential or leaf turgor.

For instance, Cruz de Carvalho et al. (1998) reported stomatal closure in *Phaseolus vulgaris* even before detecting any leaf water deficit.

Leaf diffusive resistance (LDR)

LDR differed between water deficit treatments where marked increases in LDR were observed under severe water deficit condition (fig. 2). The increase in LDR under water deficit conditions could be associated with stomatal closure (fig. 3) arising from non-hydraulic root signals (hormonal, e.g. ABA signals) as suggested by Li et al. (2001). The increased diffusive resistance could also be associated with the wax deposition on the stomatal openings as evidenced by the SEM observations (fig. 5). Differences in cultivars in stomatal resistance in response to water deficit stress were not observed.

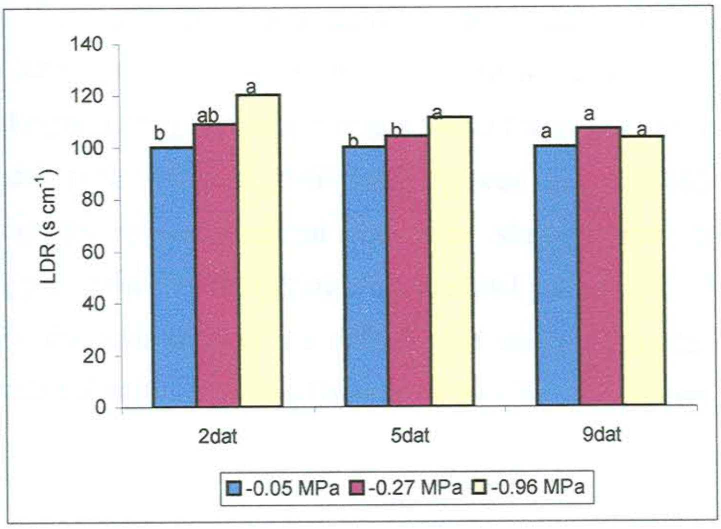

Fig. 2 Effect of water deficit stress on leaf diffusive resistance (LDR) (% of control) of sorghum at 2, 5 and 9 days after application of water stress treatment (dat). Bars with the same letter do not differ significantly at P≤0.05.

Effect of water stress on leaf cell ultrastructure

Stomatal density and pore size

Differences in stomatal density on the abaxial leaf surface were observed among water deficit treatments. Both mild and severe water deficit treatments significantly reduced stomatal frequency by 18 and 21%, respectively (table 5). This observation is in accordance to the findings of Younis et al. (1993) in *Vicia faba* and Sam et al. (2000) in tomato. It has been indicated that stomatal density and pore size affects diffusion resistance of the epidermis (Muchow and Sinclair 1989). Decreases in stomatal frequency increase drought tolerance through decreasing transpiration (Heichel 1971 as cited by Turner and Begg 1981). Cultivar differences in stomatal density were, however, not observed.

Stomatal pore size (length) on the abaxial surface varied significantly between water stress treatments, but with an inconsistent trend (table 5). Stomatal pore length also varied significantly between cultivars where Meko and 76 T1 #23 had significantly larger stomatal pore sizes on both leaf surfaces and SA1488 (a tolerant cultivar) had significantly smaller stomatal pore size. Muchow and Sinclair (1989) also reported genotypic variability in sorghum for stomatal pore length. According to Fitter and Hay (1987), the resistance to the diffusion of water molecules offered by the stomata is inversely proportional to the diameter of the stomatal aperture.

Table 5

Effect of water deficit stress and cultivar differences on stomata pore length (μ m) and stomata density (number mm^{-2})

Water deficit levels	Abaxial stomata pore length	Adaxial stomata pore length	Abaxial stomata density
-0.05 MPa	25.74b	26.22a	123.78a
-0.27 MPa	28.32a	28.08a	101.31b
-0.96 MPa	22.75ab	27.28a	102.05b
Cultivars			
Jigurti	26.82b	26.32ab	102.66a
Meko	28.49ab	29.40a	101.68a
76 T1#23	29.50a	28.65a	108.07a
SA1488	24.26c	24.41b	123.78a

Means within a column for each comparison followed by the same letter do not differ significantly at $P \leq 0.05$.

Stomatal closure

Differences between the effect of water stress treatments on the degree of stomatal closure were observed. The micrographs from SEM clearly show the progressive closure of stomata following the level of water stress (fig. 3). Compared to the well-watered condition, stomatal openings under both mild and severe water stress conditions were either completely or partially closed. This effect was also confirmed by the increased stomatal diffusive resistance under water deficit conditions (fig. 2).

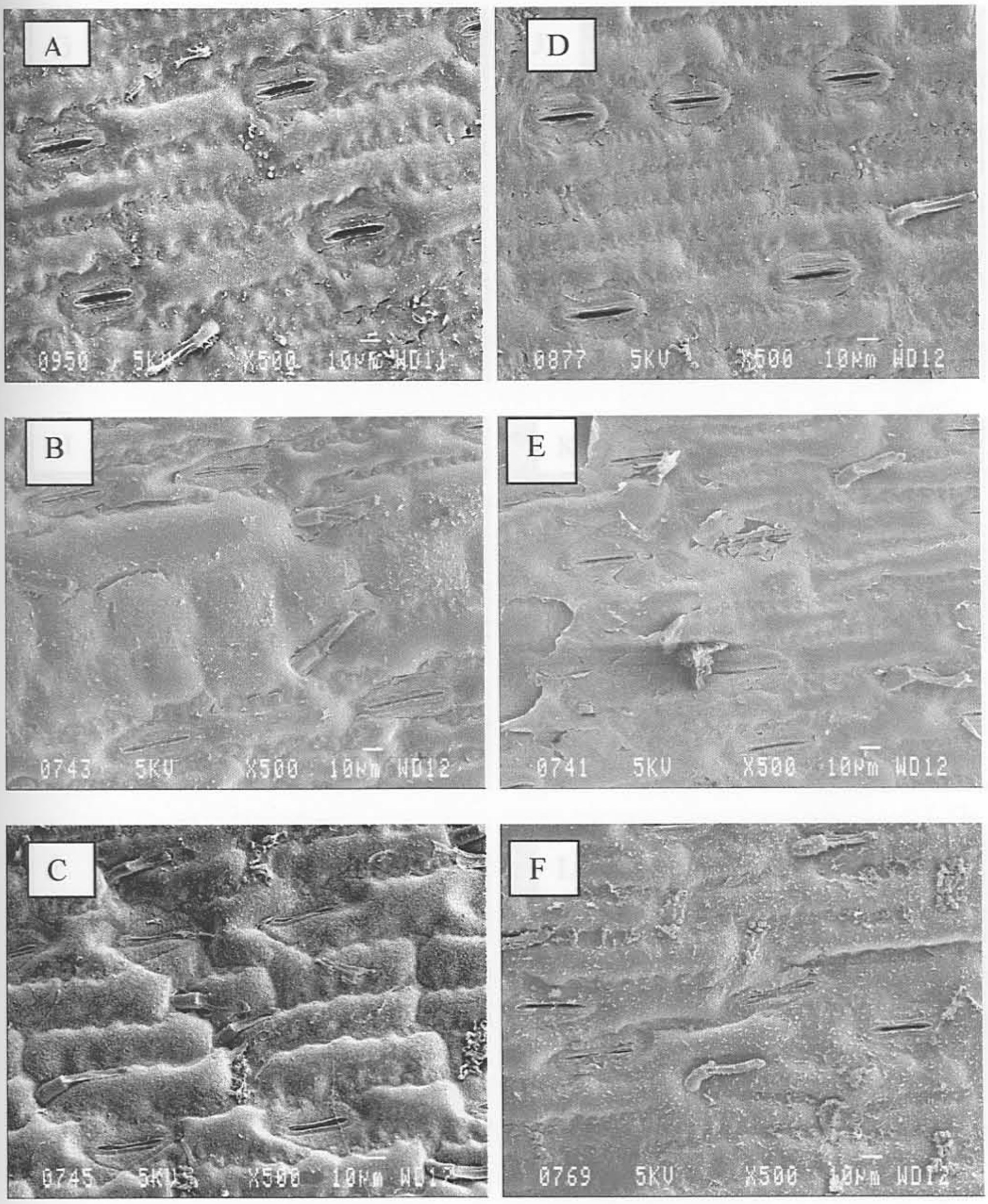

Fig. 3 Scanning electron micrographs of stomata on the adaxial leaf surface of sorghum cultivars (bars 10µm). Note the closure of stomata under water stressed conditions. A, B, C (Jigurti at control, -0.27 MPa, & -0.96 MPa); D, E, F (Meko at control, -0.27 MPa, & -0.96 MPa).

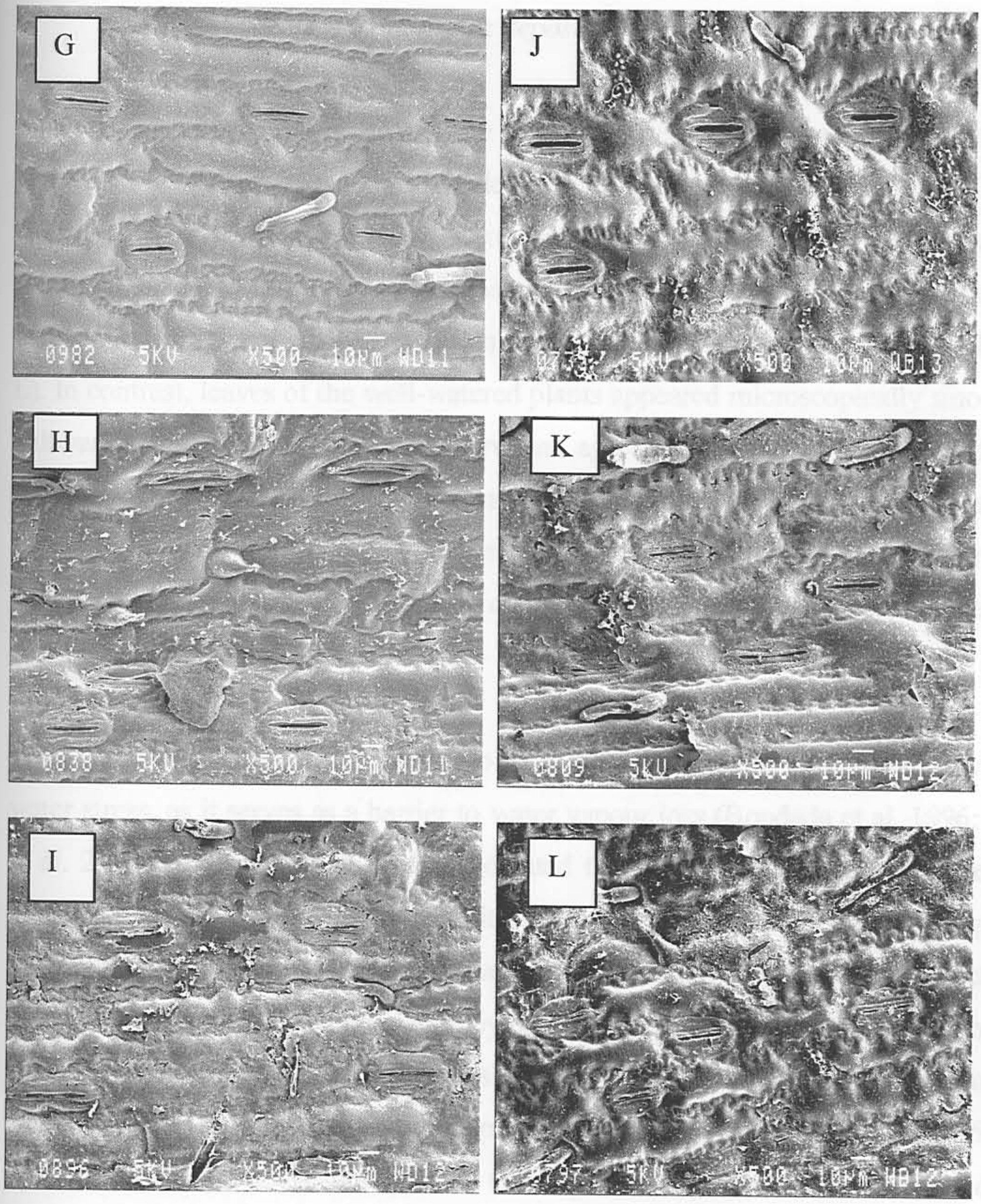

Fig. 3 (Continued). G, H, I (76 T1 #23 at control, -0.27 MPa, & -0.96 MPa); J, K, L (SA1488 at control, -0.27 MPa, & -0.96 MPa).

Epicuticular wax deposition on leaf surfaces

Considerable differences were observed between water stress treatments in relation to epicuticular wax (EW) deposition on sorghum leaf surfaces. The SEM micrographs reveal that plants grown under well watered and water stressed conditions exhibited different degrees of EW deposition (fig. 4). In all cultivars, leaves from stressed plants showed extensive EW deposition on the adaxial surfaces (fig. 4B, C, E, F, H, I, K, L). In contrast, leaves of the well-watered plants appeared microscopically smooth for all cultivars (fig. 4A, D, G, J). This observation agrees with the findings of Bondada et al. (1996) who reported significant increases in wax concentration in water stressed cotton leaves compared to well-watered plants. Jordan et al. (1983) also found greater EW deposition in water stressed sorghum compared to well-watered plants. Increased wax deposition with drought stress has also been reported in wheat (Johnson et al. 1983) and cotton (Oosterhuis et al. 1991).

The development of EW is known to be advantageous for plants growing under water stress, as it serves as a barrier to water vapour loss (Bondada et al. 1996; Cameron et al. 2002). Cameron et al. (2002) indicated that drought tolerance and increased EW deposition are positively associated traits. The mechanism of reduction in transpiration is supposed to be that wax filaments lower the net radiation by increasing reflectance and thickening the boundary layer, thereby increasing the diffusive resistance to gas and water vapour exchange (Jenks and Ashworth 1999). The thick EW deposition is also associated with reduced cuticular transpiration (Jordan et al. 1983). Blum (1975) as cited by Jordan et al. (1983) also suggested that thick EW layer enhances stomatal control of water loss. Sanchez et al. (2001) indicated that, apart from genetic factors, environmental factors, such as drought, could affect epicuticular wax load, which may explain the observed difference between water stressed and well-watered plants in this study. Thus, the ability to deposit more epicuticular wax could be used as a screening criterion for drought tolerance selection as plants with greater epicuticular wax exhibited higher ability in the retention of tissue water (Jordan et al. 1983).

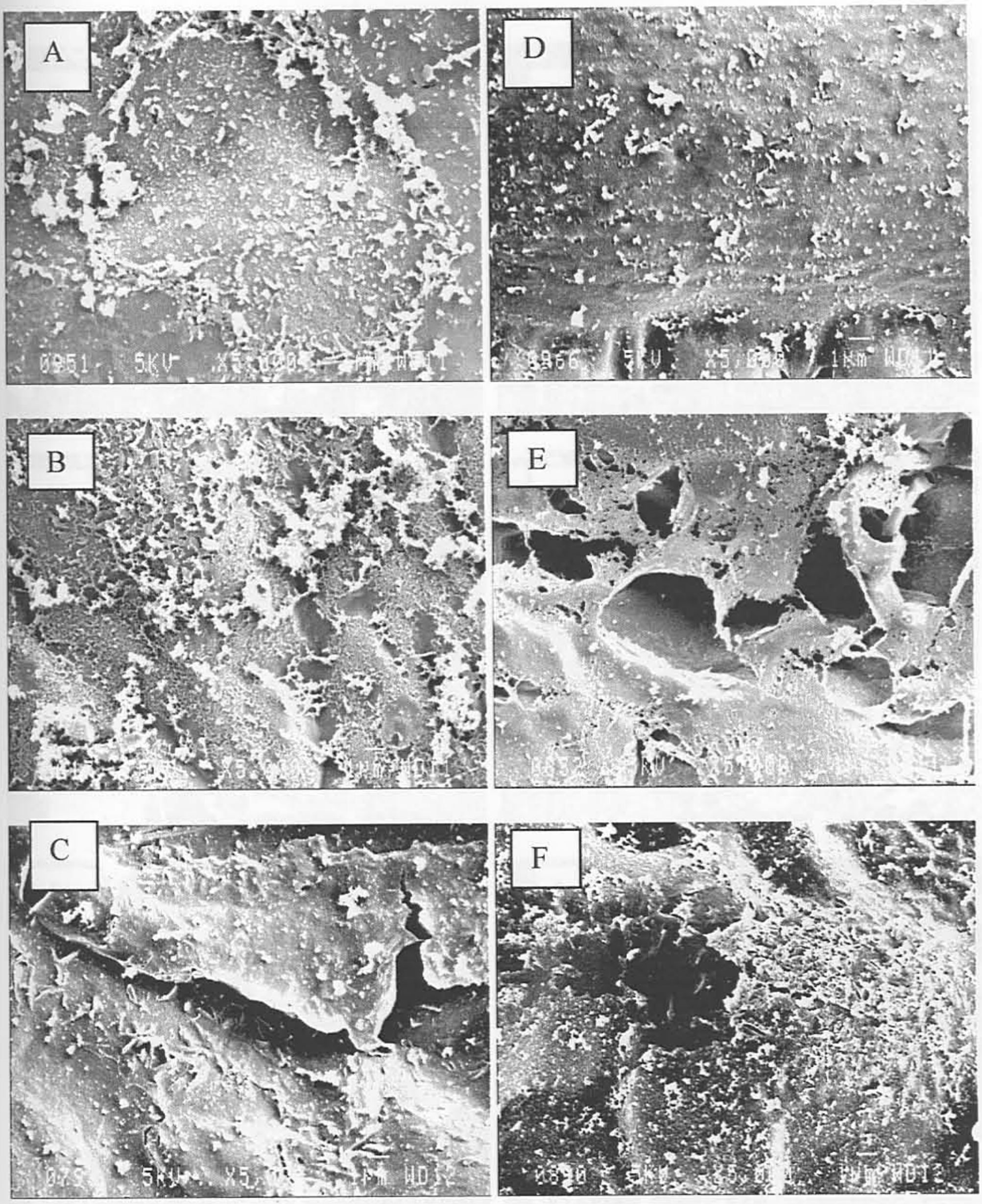

Fig. 4 Scanning electron micrographs showing EW on the adaxial leaf surfaces of sorghum cultivars (bars 1µm). Note the sparse and dense EW deposition on the well watered and water stressed leaves, respectively. A, B, C (Jigurti at control, -0.27 MPa, & -0.96 MPa); D, E, F (Meko at control, -0.27 MPa, & -0.96 MPa).

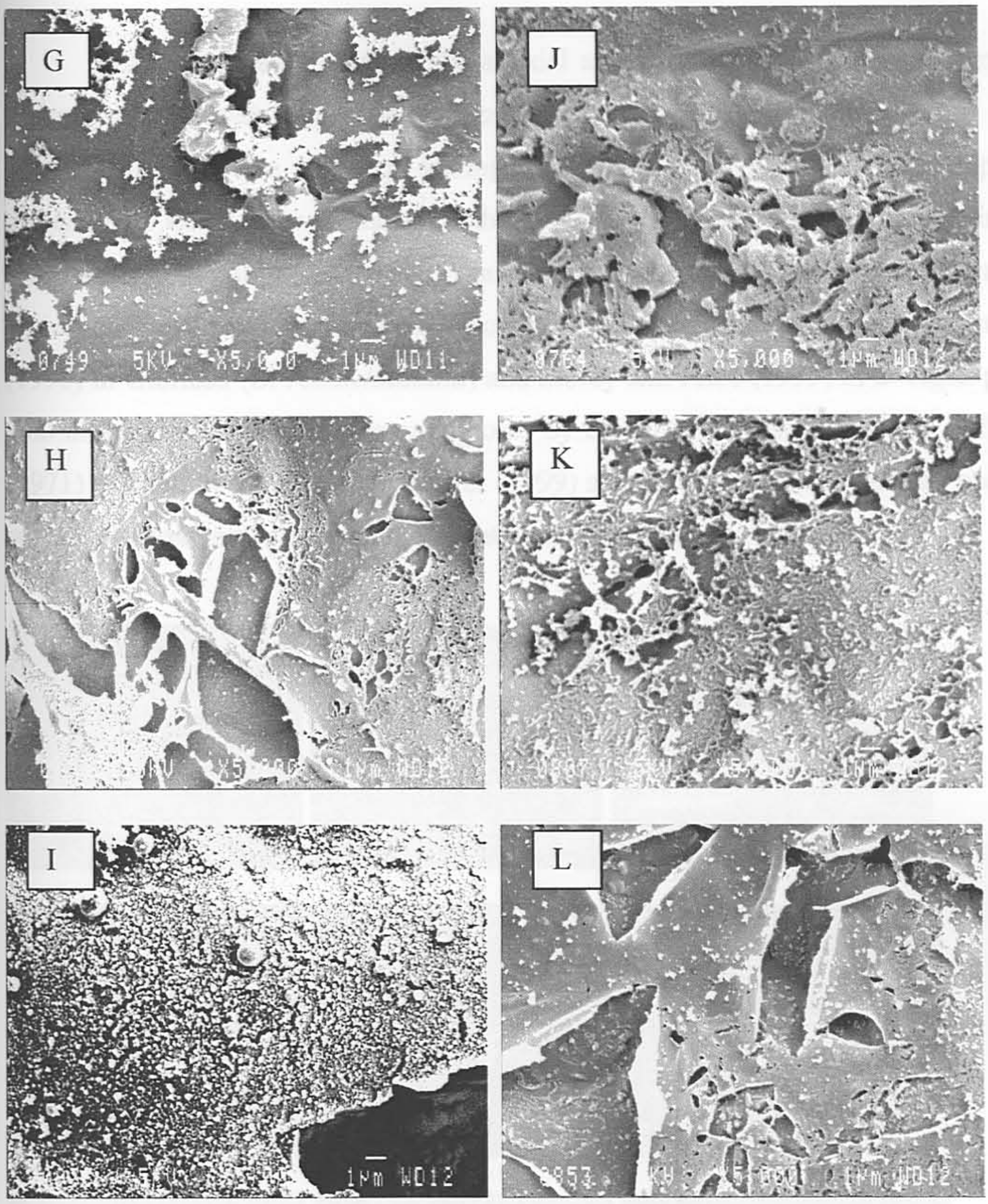

Fig. 4 (Continued). G, H, I (76 T1 #23 at control, -0.27 MPa, & -0.96 MPa); J, K, L (SA1488 at control, -0.27 MPa, & -0.96 MPa).

Epicuticular wax deposition on stomatal apertures

SEM examination of both the adaxial and abaxial leaf surfaces of plants grown under water stress showed partial or complete insulation of stomatal openings with wax deposits (fig. 5). The apparent sealing of the stomatal slit might have impeded the diffusion of water vapour and CO_2 through the stomata. Stomata covered in wax as shown in the bottom panel of fig. 5 are probably dysfunctional. This observation is in agreement with the reports of McWhorter et al. (1990) in sorghum, Ponsamuel et al. (1998) in Gloriosa (*G. rothschildiana*) and Storey and Price (1999) in d' Agen plum fruit who all observed occluded stomatal pores by epicuticular wax deposition. Jeffree et al. (1971) as cited by Jenks and Ashworth (1999) suggested that increased wax occlusion of stomatal openings could increase stomatal resistance to water vapour.

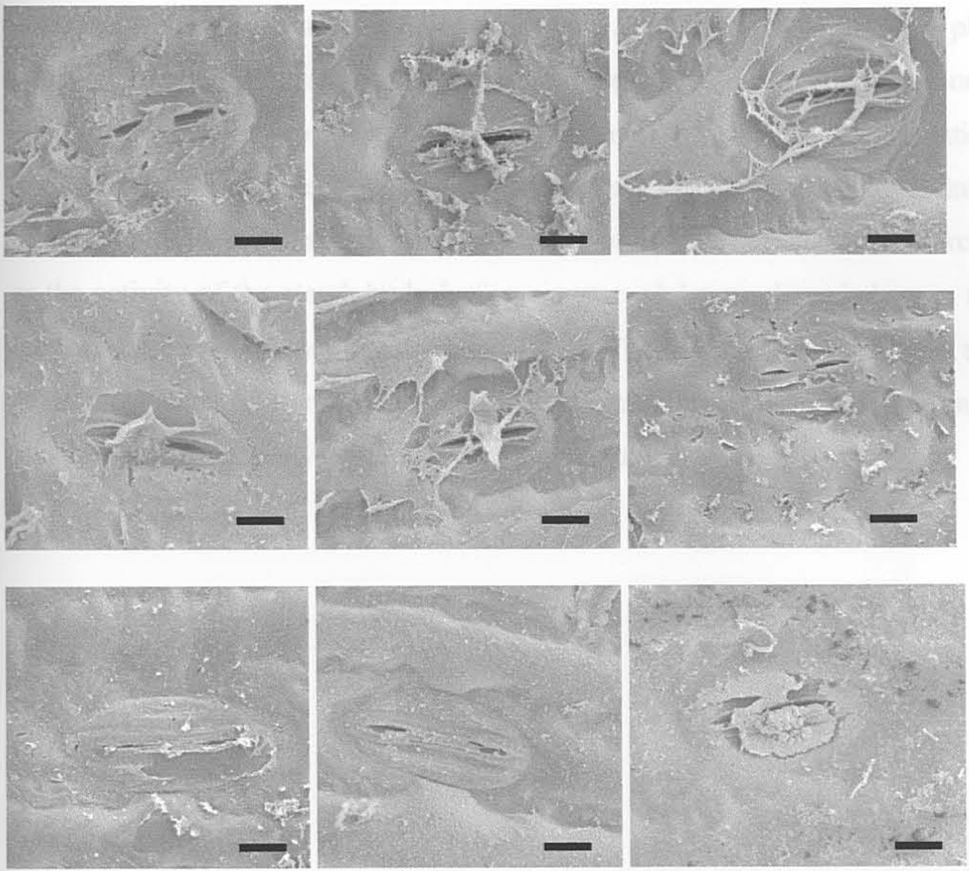

Fig. 5 Scanning electron micrographs showing different levels of epicuticular wax deposition on stomatal openings in 76 T1 #23 under sever water deficit stress (-0.96 MPa) (bars 10µm).

Starch deposition in chloroplasts

Variability in the amount of starch grains deposited in the bundle sheath chloroplasts was observed between water stress treatments and between cultivars (fig. 6). Clear differences in starch deposition between the stressed and unstressed plants were observed in 76 T1 #23 and Meko. In these cultivars plants under severe water deficit (-0.96 MPa) conditions (fig. 6 D and F) showed a marked reduction in the amount of starch grains in the chloroplasts. Cultivars also tended to differ in terms of starch deposition in the chloroplasts. Clear differences between the stressed and unstressed plants were not observed in Jigurti (fig. 6A and B). SA1488 (tolerant cultivar) deposited more starch grains under water stress compared to the well-watered plants (fig. 6G and H). Giles et al. (1971) also reported a marked reduction in starch deposition in the bundle sheath chloroplasts of stressed sorghum leaves. In the leaf the fixed carbon is temporarily stored in chloroplasts as starch grains during active carbon fixation by photosynthesis (Daie 1996). Considering the low carbon supply under drought conditions, a shift in chemical partitioning of carbon occurs in favor of sucrose accumulation or starch remobilization in the leaf cells of stressed plants (Daie 1996). Moreover, due to a decline in newly fixed carbon, sucrose accumulation could have resulted from starch breakdown as the activity of the starch hydrolyzing enzyme, alpha-amylase, is known to increase in leaves of drought stressed plants (Daie 1996). These justifications suggest that the small amount, or lack, of starch deposition in the stressed sensitive cultivars could be due to less carbon fixation and/or breakdown of starch into sucrose.

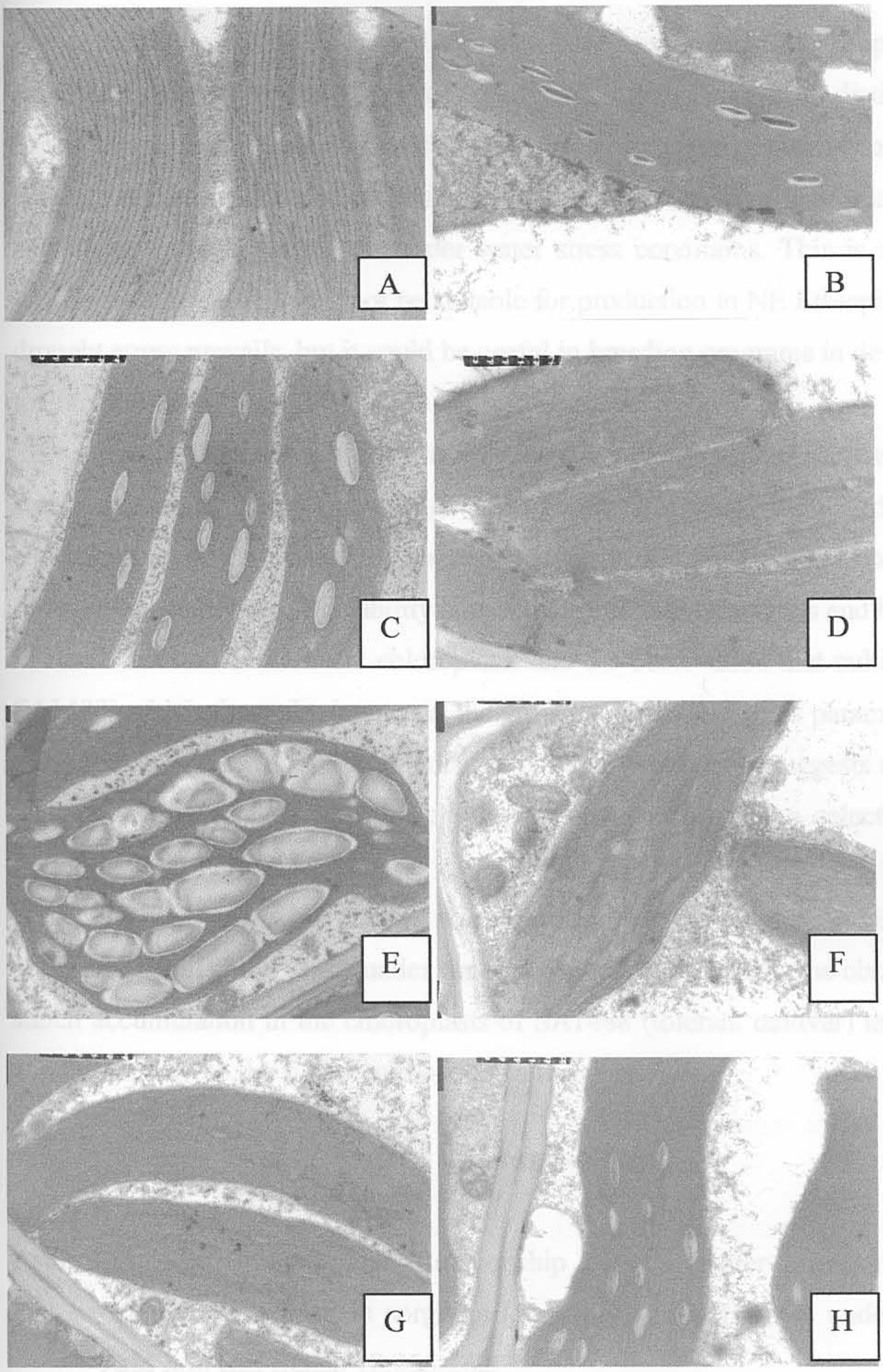

Fig. 6 Starch deposition in unstressed and stressed bundle sheath chloroplasts. A & B = Jigurti unstressed & stressed, C & D = 76 T1 #23 unstressed & stressed, E & F = Meko unstressed & stressed, G & H = SA1488 unstressed & stressed X 13 000.

Conclusion

Water deficit stress caused significant changes in most morphophysiological and anatomical characteristics. The seven cultivars evaluated displayed distinctive responses to water deficit stress for many of the measurements. Jigurti, Gambella 1107 and Meko consistently showed tolerance in most of the parameters. Jigurti showed no reduction in any of the growth parameters under water stress conditions. This is a relatively slow growing genotype and may not be suitable for production in NE Ethiopia where terminal drought stress prevails, but it could be useful in breeding programs in developing drought tolerant cultivars.

The observed variability in epicuticular wax deposition between water deficit stress treatments implies that high epicuticular wax deposition under water deficit conditions could be used as a screening criterion for identifying materials possessing drought tolerance traits. Variability between water stress treatments and between cultivars in starch accumulation in the chloroplasts and the observation that cultivars (Jigurti and SA1488) which showed tolerance in the growth and physiological parameters accumulate more starch in the chloroplasts under water stress conditions, suggests that selection for high starch accumulation in the chloroplasts can be used as a selection criterion for drought tolerance in sorghum.

To our knowledge there is no report in literature indicating an increase in starch accumulation in chloroplasts under water stress conditions. Thus, the observed increase in starch accumulation in the chloroplasts of SA1488 (tolerant cultivar) under water stress conditions may be the first record of such a response.

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CHAPTER 4

Prepared according to the guidelines of South African Journal of Plant and Soil

Effects of moisture conservation, nitrogen fertilizer and cultivars on the growth, yield and nitrogen use efficiency of Sorghum

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An experiment was conducted at two locations in NE Ethiopia with the objective of determining the potential for improving the productivity of sorghum through combinations of rainwater harvesting, N fertilization and cultivar selection. It was designed in split-split plot with moisture conservation (tied-ridge planting vs flatbed planting) as main plots, three N fertilizer levels (0, 40 and 80 kg N ha^{-1}) as sub-plots and three sorghum cultivars (Jigurti, ICSV111 and 76 T1 #23) as sub-sub plots, with three replications. The main effects of moisture conservation treatments were not significant for all the parameters studied. Nitrogen fertilizer applications increased grain and biomass yields and N use efficiency attributes. Cultivars differed in grain and biomass yields and N use efficiency attributes. Early maturing cultivars ICSV111 and 76 T1 #23 were superior in grain yield, grain and stover N concentrations and uptake, N harvest index and N use efficiency for grain production. In terms of NUE$_g$ ICSV111 was 29 to 43%, and 76 T1 #23 34 to 52%, better than Jigurti. Cultivars with high grain and stover N concentrations and uptake, grain protein content, NHI and grain N use efficiency were high yielders. ICSV111 and 76 T1 #23 with their higher NUE$_g$, grain yield and grain protein should be important cultivars in NE Ethiopia where soils are infertile and farmers cannot afford to apply large amounts of inorganic fertilizers. It was concluded that the effect of tied-ridging needs further study. To increase the yield and quality of sorghum 40 kg N ha^{-1} should be applied. ICSV111 and 76 T1 #23 are recommended for cultivation on the nutrient poor soils in NE Ethiopia.

Keywords: grain yield, grain protein content, nitrogen use efficiency, sorghum, tied-ridges

Introduction

Sorghum is the major staple crop in the lowland areas of NE Ethiopia. It plays an appreciable role in supplying the population of this part of the country with protein, carbohydrates and minerals (Hailemichael, 1998). Its productivity is, however, largely limited by water shortage and poor soil fertility. Crop production in this region is entirely rainfed. The rainfall is usually inadequate, short in duration, poorly distributed and highly variable between and within seasons (Georgis & Alemu, 1994).

This limited availability of water in the semi-arid areas of NE Ethiopia emphasizes the need to focus on on-farm harvesting and utilization of rainwater. Among the various water conservation techniques, which could be considered, tied-ridging offers the maximum potential for water conservation (Jensen *et al*., 2003). Tied-ridges work by increasing water content in the soil profile, thus ensuring crop survival during prolonged dry spells. However, contradictory reports on the effectiveness of tied-ridging are common (Hudson, 1987), partly as a result of the variation in soil and climatic characteristics between sites and years.

Soils in these areas are often deficient in nutrients, with nitrogen being the main limitation (Bayu, Getachew & Mamo, 2002). Limitations in sorghum productivity, due to poor N status of the soils, are large and are further exacerbated by lower rates of N fertilizer application *visa vis* the amount removed in crop harvests or lost by other processes. Nitrogen is the mineral element required in the greatest quantities by cereal crop plants (Ma & Dwyer, 1998). The use of commercial nitrogen fertilizer for sorghum production in NE Ethiopia is, however, generally low because of cost and climatic risks. Thus, N uptake and use by the crop plants is of fundamental importance to nitrogen economy in crop production. Therefore, agronomic techniques along with cultivar selection, which can improve crop N uptake and use, should be tailored into the production system in order to improve sorghum productivity. Under low or sub-optimal N levels, efficiency of N use can be improved through agronomic practices that can improve water availability and through breeding and selection for genotypes exhibiting greater N use efficiency (Ma & Dwyer, 1998). The ability of plants to take up limited amounts of soil N could be crucial in determining grain yields and grain N concentrations (Kamoshita *et al*., 1998). There may also be genotypic differences for the utilization of absorbed N for biomass and grain production. The proportion of absorbed N that is partitioned to the grain is another attribute that could affect yield and grain N concentration (Kamoshita *et al*., 1998). Grain protein concentration is an important quality component related to the N economy of cereals, and genotypic variation for this trait has been reported in sorghum (Kamoshita *et al*., 1998). Because sorghum is a major source of protein in the lowlands of NE Ethiopia, cultivars with high grain N concentration and high grain yields are required. High yielding sorghum cultivars that can efficiently use nutrients on poor soils can contribute towards improved crop productivity on the nutrient poor soils of the resource poor farmers.

Traditionally, the development approach has focused on the use of single elements of the farming system such as improved cultivars, mineral nutrition or water conservation measures. However, substantial impacts can be realized through the integrated use of these inputs. Thus, it is envisaged that productivity of sorghum in these areas can be improved by a combination of rainwater harvesting, N fertilization and selecting N efficient cultivars. This study was, therefore, designed with the objective of determining the potential for improving the productivity of sorghum through combinations of rainwater harvesting, nitrogen fertilization and cultivar selection by determining the grain and biomass yields and N use efficiency attributes in semi-arid environments.

Materials and methods

Study sites

This experiment was conducted at Sirinka (11^0 45’ N latitude, 39^0 36’ E longitude; 1890 m. a. s. l. altitude) and Kobo (12^0 9’ N latitude, 39^0 38’ E longitude; 1470 m. a. s. l. altitude) in NE Ethiopia. The soil type at both locations was a Eutric vertisol. Details of the physicochemical characteristics of the soils are presented in Appendix 4.1. The growing season at the experimental sites is characterized by high temperatures, high evaporative demand and unevenly distributed rainfall.

Experimental design and procedure

The experiment was laid out as a split-split plot design with moisture conservation (tied-ridge planting and flatbed planting) as main plots, three N fertilizer levels (0, 40 and 80 kg ha^{-1}) as sub-plots and three sorghum cultivars (Jigurti, ICSV111 and 76 T1 #23) as sub-sub plots, with three replications. Jigurti is a late maturing local cultivar, while ICSV111 and 76 T1 #23 are improved early maturing cultivars. Tied-ridges were constructed with oxen- and tractor-drawn implements at Sirinka and Kobo, respectively. Due to unusually high rainfall events ties had to be opened temporarily to release excess water from the tied-ridge fields. Urea was used as the source of N. All plots received P as triple superphosphate at the rate of 20 kg P ha^{-1}.

N was applied in a band at 20 kg ha^{-1} at planting and the remainder sidedressed at approximately six to eight leaf stage of the crop. All the P was applied in a band at planting. Both fertilizers were incorporated into the soil. The sorghum cultivars were hand drilled in 75 cm rows and thinned to an interplant spacing of 15 cm to obtain a plant population of 88 888 plants ha^{-1}. Gross plot size was 5.25 m (6.0 m at Kobo) wide by 5 m long. Hand weeding and insect control were conducted on an as-needed basis. Prior to planting, composite surface (0-15 cm) and subsurface (15-30 cm) soil samples from nine points across the experimental field were collected and analyzed for soil physicochemical properties following the procedure outlined by Page, Miller & Keeney (1982). Leaf area was determined from three plants per plot at 41, 55, 72, 87, 105 and 115 DAE at Sirinka and 48, 69, 90, and 95 DAE at Kobo. Leaf area was calculated as the product of leaf length, maximum leaf breadth, and a shape factor of 0.75 (Oosterom, Carberry & Muchow, 2001). Two rows, at Sirinka and three rows at Kobo were hand harvested at maturity for grain yield determination after discarding border rows. The panicles were air-dried and hand threshed. Grain moisture content was determined and grain yield was adjusted to 12.5% moisture.

Sorghum plant samples for determination of N uptake were collected at harvest. Plant samples were oven dried at 70^0 C to constant weight. Grain and stover samples were ground separately to pass a 1 mm sieve. The N content of plant samples was determined by the micro-Kjeldahl method (Page *et al.*, 1982). N uptake in the grain and stover was estimated by multiplying their concentrations with grain and stover yields respectively. Total aboveground biomass N uptake was calculated by adding the uptake in the grain and stover. Grain protein concentration was calculated as %N in the grain x 6.25 (Kudasomannavar, Kulkarni & Patil, 1980) and total grain protein yield per hectare as grain protein concentration x grain yield/100 (Ogunlela & Okoh, 1989). The nitrogen harvest index (NHI), used to evaluate partitioning of N to the grain, was calculated as the ratio of grain N uptake to total aboveground N uptake.

The determination of N use efficiency followed the definitions suggested by Maranville, Clark & Ross (1980) and Traore & Maranville (1999). The term NUE_b (N use efficiency for total aboveground biomass production) was defined as the total aboveground biomass divided by total N content in aboveground biomass (kg dry matter kg^{-1} N), and NUE_g (N use efficiency for grain production, kg grain kg^{-1} N), which emphasizes economic yield, was defined as grain yield divided by the total N content in the aboveground biomass.

Analysis of variance for the measured parameters was performed using the MSTATC statistical program (MSTATC, 1989). Whenever treatment differences were found significant based on results of the F-test, critical differences were calculated at 5% level of probability using Duncan's Multiple Range Test.

Results and Discussion

Data on the growing season rainfall and maximum and minimum air temperatures, as well as the long-term average rainfall are presented in Table 1. Growing season rainfall at Sirinka was comparable with the long-term mean. The growing season at Kobo was relatively wet, with 524 mm of precipitation, 65 mm above the long-term average. Soil conditions were excessively wet in August and September. The greater and more intense seasonal rainfall at Kobo created runoff, which resulted in the silting up of tied-ridges.

Table 1 Monthly precipitation and air temperatures of the 2002 season and average long-term precipitation for the growing season at Sirinka and Kobo

Month	Sirinka				Kobo			
	Precipitaion (mm)		Temperature (^{O}C)		Precipitaion (mm)		Temperature (^{O}C)	
	2002	Long term*	Max.$^{\varphi}$	Min.$^{\Re}$	2002	Long term*	Max.$^{\varphi}$	Min.$^{\Re}$
July	229.5	192.1	30.5	17.1	99.8	108.2	34.0	19.6
August	280.6	266.3	27.8	15.7	296.0	200.4	30.9	17.6
September	134.0	95.0	26.6	14.7	112.4	95.2	29.9	15.7
October	12.0	57.7	26.6	12.4	16.0	43.7	30.5	13.0
November	0.0	21.7	25.5	11.6	0.0	11.9	29.5	12.0
Total	656	633			524	459		

* Long term average rainfall (1980-2002 for Sirinka and 1973-2002 for Kobo). $^{\varphi}$Maximum. $^{\Re}$Minimum.

No significant effects were observed for moisture conservation x N fertilizer, N fertilizer x cultivar and moisture conservation x N fertilizer x cultivar interaction effects for most parameters. However, the interaction between moisture conservation and cultivars was significant at Kobo for stover, grain and total biomass yields, grain and total N uptake, N harvest index, grain protein yield and NUE$_g$. In the absence of interaction effects, results are presented as moisture conservation main effect averaged over N fertilizer and cultivar treatments, as N fertilizer main effect averaged over moisture conservation and cultivar treatments and as cultivar main effect averaged over moisture conservation and N fertilizer treatments.

Effect of moisture conservation treatments

The main effects of moisture conservation treatments were not significant for almost all parameters studied at both locations. The 2002 season at Sirinka was a typical season in terms of rainfall and results are assumed to be representative. Tied-ridge planting at Sirinka had a negative effect on crop growth in the early stages. This could be due to the temporary water logging on the clayey soil. However, in spite of the reduced growth in tied-ridges early in the season, the final grain and biomass yields were not reduced possibly due to the fact that plants in tied-ridges might have benefited from the stored water during later growth stages while plants in the flatbed planting might have experienced some water stress at that time. It was in fact observed that plants in tied-ridge planting were greener towards the end of the season than plants in flatbed planting. Contrary to the present result, Jones *et al.* (1987) and Jones & Nyamudeza (1991) as cited by Nyakatawa (1996) reported yield benefits from tied-ridges over flatbed planting even on heavy clay soils. Belay, Gebrekidan & Uloro (1998) also reported a 35 to 50% yield increase in maize in Ethiopia with tied-ridge planting on a black clay soil. Nyamudeza *et al.* (1993) as cited by Nyakatawa (1996) reported a 26% increase in sorghum yield due to tied-ridging on vertisols. However, it has also been documented that tied-ridges could have either no effect or negative effects on clayey soils in wet years due to water logging (Nyakatawa, 1996, Jensen *et al.*, 2003).

At Kobo the effect of tied-ridging was apparently observed as an interaction effect with cultivars. The season, at Kobo, was unusually wet. It was characterized by heavy and torrential rains early in the season, which resulted in ridge overtopping and destruction of the tied-ridges. Therefore, responses to the main effects of tied-ridging were not large owing to wetness of the season and siltation of tied-ridges by runoff. At Kobo, the effect of tied-ridging was more prominent as an interaction effect with cultivars. This is in agreement with the results of Hulugalle (1987), Selvaraju *et al.* (1999) and Jensen *et al.* (2003) who observed no significant differences between tied-ridges and flatbed planting in wet years. The above results suggest that tied-ridges work best in medium to moderately dry years, but, as these are unpredictable, should be standard practice in all years.

Although significant differences between moisture conservation treatments were not observed for most parameters at both locations, there were trends of increase in most parameters with flatbed planting at Sirinka and with tied-ridge planting at Kobo (Table 2). For instance, at Sirinka plants in flatbed planting headed earlier (853 GDD) than in tied-ridge planting (869 GDD). Stover yield, aboveground biomass yield, grain yield and harvest index tended to increase with flatbed planting at Sirinka and with tied-ridge planting at Kobo (Table 2). Although increasing trends with tied-ridging were observed at Kobo significant differences were not observed, perhaps because the test with few degrees of freedom (1) was not sensitive enough to detect the differences. In general the effect of moisture conservation treatments was not strong enough to detect as a main effect but was detected as an interaction effect mainly with cultivars.

Table 2 Effect of moisture conservation treatments on stover, total biomass (TBY) and grain yield, harvest index, and 1000-seed weight (TKW) (averaged across nitrogen fertilizer treatments and cultivars)

Location	Moisture conservation	Stover (kg ha^{-1})	TBY (kg ha^{-1})	Grain yield (kg ha^{-1})	Harvest index	TKW (g)
Sirinka	Tied-ridge	5886a	8877a	2991a	0.36a	27a
	Flat	6749a	9965a	3216a	0.35a	28a
Kobo	Tied-ridge	5940a	8992a	3052a	0.37a	22a
	Flat	6007a	8112a	2105a	0.27b	20a

Means within columns followed by the same letters are not significantly different at $P \leq 0.05$.

Effects of N fertilizer treatments

Stover and aboveground biomass yield at harvest

Stover and aboveground biomass yields were significantly affected by the main effects of N fertilizer treatments at both locations (Table 3). Stover yield increased from 5 695 kg ha^{-1} to 6 708 kg ha^{-1} at Sirinka and from 5 440 kg ha^{-1} to 6 209 kg ha^{-1} at Kobo with the application of 80 kg N ha^{-1}. Similarly, total aboveground biomass yield increased from 8 218 kg ha^{-1} to 10 235 kg ha^{-1} at Sirinka and from 7 843 kg ha^{-1} to 8 943 kg ha^{-1} at Kobo. Although the highest stover and aboveground biomass yields were found at the higher N rate, the application of more than 40 kg N ha^{-1} did not significantly increase stover and total biomass yields. The greater stover and aboveground biomass yields with N fertilization could be due to the increase in leaf area development and thus photosynthetic potential with N fertilization. Increased leaf area development with N fertilization was observed at Sirinka where the average LAI for 0 and 80 kg N ha^{-1} at anthesis (72 days after emergence) were 1.81 and 2.16 respectively (Figure 1). Muchow (1988) indicated that N application increases leaf area index, leaf area duration, radiation interception and radiation use efficiency, thus resulting in greater crop growth and yield.

Table 3 Effect of nitrogen fertilizer on stover, total biomass (TBY) and grain yield, harvest index and seed number

Location	Nitrogen (kg ha^{-1})	Stover (kg ha^{-1})	TBY (kg ha^{-1})	Grain yield (kg ha^{-1})	Harvest index	Seed number panicle^{-1}
Sirinka	0	5695b	8218b	2523b	0.34b	1683b
	40	6550b	9810a	3260a	0.36a	2164a
	80	6708a	10235a	3528a	0.36a	2168a
Kobo	0	5440b	7843b	2403a	0.33a	2425a
	40	6273a	8870a	2597a	0.31a	2149a
	80	6209a	8943a	2734a	0.33a	2289a

Means within columns for each location followed by the same letters are not significantly different at $P \leq 0.05$.

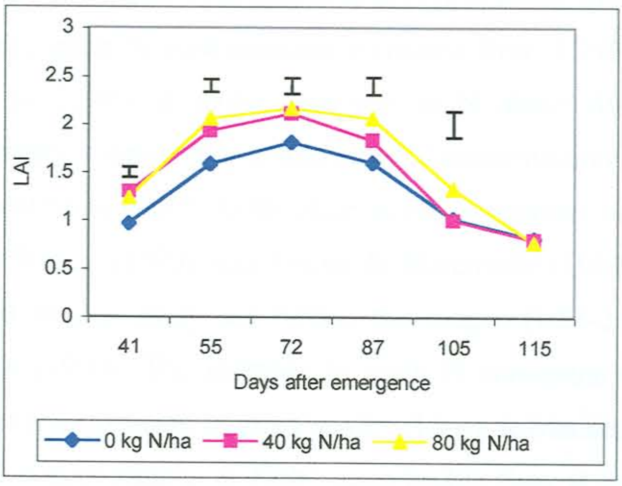

Figure 1 Effect of N fertilizer on leaf area index at Sirinka. Vertical lines on each period of measurement indicate LSD values at $P<0.05$.

Grain yield

Grain yield differed between the main effects of N fertilizer treatments at Sirinka, but not at Kobo (Table 3). Nitrogen application increased grain yield with the highest grain yield of 3 528 kg ha^{-1} being obtained with the application of 80 kg N ha^{-1}. Yield increases with the application of more than 40 kg N ha^{-1} were not, however, significant. At Kobo, although significant differences were not observed, grain yields tended to increase with increasing N fertilizer levels. Increased grain yields due to N application could be ascribed to increased biomass production, improved harvest index and increased seed set with N fertilization. At Sirinka, N applications increased the number of seeds produced per plant (Table 3). Buah *et al.* (1998) reported a similar increase in seed number in sorghum with increasing rates of N application. The harvest index increased with N fertilization at Sirinka, similar to the observations of Muchow (1990) and Nyakatawa (1996).

N concentration

Stover and grain N concentrations were significantly improved by the application of N fertilizer at both locations (Table 4). Stover N concentration increased from 0.35% to 0.40% at Sirnka and from 0.52% to 0.73% at Kobo with the application of 80 kg N ha^{-1}. Similarly, grain N concentration increased from 1.29% to 1.42% at Sirinka and from 2.03% to 2.24% at Kobo. Increase in N above 40 kg N ha^{-1} did not, however, significantly improve stover and grain N concentrations. The observed increase in grain N concentration with N fertilization in this experiment was consistent with the findings of Roy & Wright (1973) and Traore & Maranville (1999). Grain N concentration values obtained in this study are within the ranges (1.23-2.44%) reported for sorghum by Muchow (1990). The increase in grain N concentration with N fertilizer application indicates improvement in grain quality (Liang & Mackenzie, 1994). The mean stover and grain N concentrations at Kobo were higher than at Sirinka, which could be due to a concentration effect due to relatively poor plant growth at this site. Inskeep & Bloom (1987) noted that stunted plants contained higher tissue concentrations of several nutrients because of lower dry mass accumulation in relation to their uptake rates.

Table 4 Effect of nitrogen fertilizer on stover and grain N concentration, N harvest index, protein concentration, grain protein yield, NUE_b and NUE_g

Location	Nitrogen (kg ha^{-1})	SNC (%)	GNC (%)	NHI (%)	GPC (%)	GPY (kg ha^{-1})	NUE_b (kg kg^{-1}N)	NUE_g (kg kg^{-1}N)
Sirinka	0	0.35b	1.29b	0.64b	8.1b	203b	159a	50a
	40	0.34b	1.38ab	0.68a	8.6ab	283a	149b	50a
	80	0.40a	1.42a	0.67a	8.9a	314a	137c	48a
Kobo	0	0.52b	2.03b	0.62a	12.7b	304b	108a	31a
	40	0.65a	2.22a	0.57a	13.9a	358a	96b	26b
	80	0.73a	2.24a	0.58a	14.0a	383a	85c	26b

SNC, stover N concentration; GNC, grain N concentration; NHI, N harvest index; GPC, grain protein concentration; GPY, grain protein yield. Means within columns for each location followed by the same letters are not significantly different at $P \leq 0.05$.

N uptake and N harvest index

Plant N uptake (stover, grain and total plant) differed significantly between N fertilizer treatments at both locations (Figure 2). N uptakes in the control plots were 19 and 29 kg ha^{-1} for stover, 33 and 49 kg ha^{-1} for grain and 51 and 77 kg ha^{-1} for total plant, while the highest N uptakes of 25 and 45 kg ha^{-1} in the stover, 50 and 61 kg ha^{-1} in the grain and 76 and 103 kg ha^{-1} in the total plant were obtained with the application of 80 kg N ha^{-1}. However, applying N fertilizer above 40 kg ha^{-1} did not improve N uptake significantly. Despite the initial low N status of the soil at Kobo, N uptake with no fertilizer application was higher than N uptake with the application of the highest rate of N at Sirinka. This could possibly be due to N mineralization during the season owing to the warm and wet weather. Stover, grain and total plant N uptake values obtained in this experiment are within the ranges reported for sorghum by Pal *et al*. (1983). These results are also in accordance with the results of Kamoshita *et al*. (1998) who reported increased grain and total plant N uptake with N fertilizer application. Rao *et al*. (1991) indicated that fertilizer N can increase N availability from the other N pools and/or stimulate root growth and thus increase plant N uptake. Adu-Gyamfi *et al*. (1996) suggested that the increased N uptake with N fertilization could also be explained by the development of a larger and more effective root system which would improve N recovery.

Nitrogen fertilizer affected NHI only at Sirinka where NHI increased from 0.64 in the control to 0.68 in plots receiving 40 kg N ha^{-1} (Table 4). The increase in NHI with N fertilization indicates that plants under N stress accumulate more N in vegetative parts and only partition N to grains in amounts sufficient to ensure viable seed. This observation is in accordance with the results of Sinebo, Gretzmacher & Edelbauer (2003).

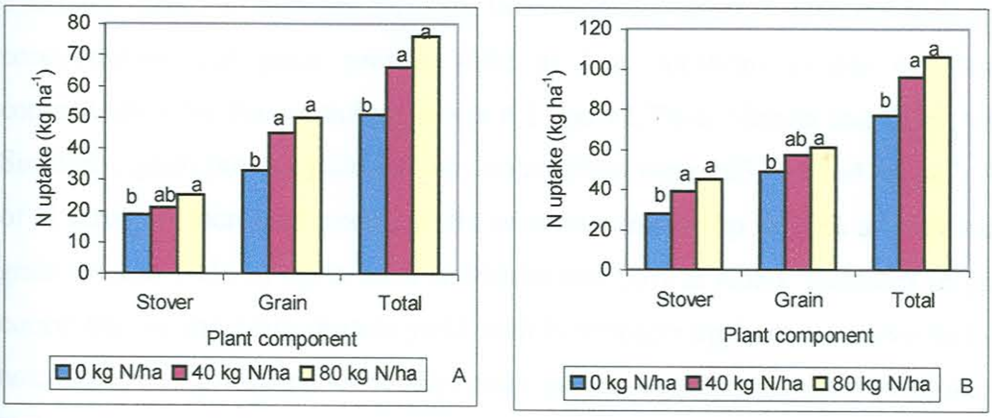

Figure 2 Effect of N fertilizer on stover, grain and total plant N uptake at Sirinka (A) and Kobo (B). Bars with the same letters for each parameter are not significantly different at P≤0.05.

Nitrogen use efficiency

Nitrogen fertilizer had significantly influenced N use efficiency for biomass production (NUE_b) at both locations and N use efficiency for grain production (NUE_g) at Kobo (Table 4). N use efficiencies for biomass and grain production declined with the increased levels of N fertilizer, similar to the findings of Maranville *et al*. (1980) and Traore & Maranville (1999). According to Buah *et al*. (1998), this relationship generally occurs because plant N content increases proportionally more than dry matter production with increased fertility levels. Akintoye, Kling & Lucas (1999) also noted that as increases in yield diminish with increases in the amount of fertilizer N used, the efficiency of nutrient utilization declines as yield increases. The average NUE_b declined from 159 kg dry matter kg^{-1} N with 0 kg N ha^{-1} to 137 kg dry matter kg^{-1} N with 80 kg N ha^{-1} at Sirinka and from 108 kg dry matter kg^{-1} N to 85 kg dry matter kg^{-1} N at Kobo. Similarly NUE_g declined from 50 kg grain kg^{-1} N with 0 kg N ha^{-1} to 48 kg grain kg^{-1} N with 80 kg N ha^{-1} at Sirinka and from 31 kg grain kg^{-1} N to 26 kg grain kg^{-1} N at Kobo. More biomass and grain yields were produced per unit absorbed N at Sirinka than at Kobo possibly due to the better growing condition at Sirinka.

Grain protein concentration and protein yield

The main effects of nitrogen fertilizer treatments significantly affected both grain protein concentration and grain protein yield at both locations (Table 4). Grain protein concentration for the control plots was 8.1 and 12.7% at Sirinka and Kobo, respectively. Similarly, grain protein yield for the control plots were 203 and 304 kg ha^{-1}. Application of N fertilizer increased grain protein concentration by up to 10% at both locations and grain protein yield by up to 55% at Sirinka and 26% at Kobo. Increases in grain protein concentration and grain protein yield with N fertilizer application above 40 kg ha^{-1} were not, however, significant. Generally, grain protein concentration and yield were higher at Kobo than at Sirinka. These results agree with those of Grant *et al*. (1991) who reported increased grain protein concentration and yield in barley with N fertilizer application. This implies that in areas like NE Ethiopia where cereal grains are a major source of protein, the protein diet of farmers can be improved through the judicious application of N fertilizer.

Effects of cultivars and interaction effects

Stover and aboveground biomass yield at harvest

Averaged over moisture conservation and N fertilizer treatments, cultivars differed in stover and aboveground biomass yields at Sirinka (Table 5). The highest stover yield of 10 140 kg ha^{-1} and total aboveground biomass yield of 13 155 kg ha^{-1} were produced by the late maturing local cultivar Jigurti which were 140% and 74% higher, respectively, than that produced by the lowest yielder cultivar 76 T1 #23. At Kobo, stover and aboveground biomass yields differed between the interaction effects of moisture conservation and cultivars (Table 6). Under both tied-ridge and flatbed planting, Jigurti produced the highest stover and total aboveground biomass yields. The greater biomass production by Jigurti could be due to greater interception of radiation resulting from its larger LAI maintained through out the growing period (Figure 3). In all cultivars, except ICSV111, total aboveground biomass yield tended to decline with flatbed planting compared with tied-ridge planting. ICSV111 and 76 T1 #23 did not differ significantly in stover and biomass yields under both tied-ridge and flatbed planting. The greater biomass production under tied-ridge planting could possibly be due to improved moisture availability.

Table 5 Stover, total biomass (TBY) and grain yields, harvest index, 1000-seed weight (TKW) and seed number of sorghum cultivars at Sirinka

Cultivar	Stover (kg ha^{-1})	TBY (kg ha^{-1})	Grain yield (kg ha^{-1})	Harvest index	TKW (g)	Seed number panicle^{-1}
Jigurti	10140a	13155a	3015a	0.23c	32a	1637b
ICSV111	4591b	7569b	2978a	0.40b	26b	2096a
76 T1 #23	4222b	7540b	3318a	0.44a	23c	2283a

Means within columns followed by the same letters are not significantly different at $P \leq 0.05$.

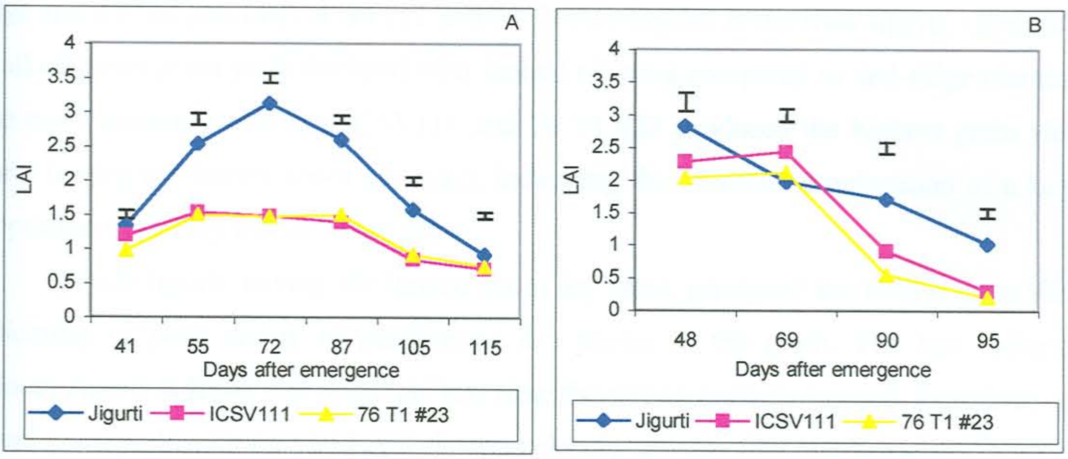

Figure 3 Leaf area index of sorghum cultivars at Sirinka (A) and Kobo (B). Vertical lines on each period of measurement indicate LSD values at $P<0.05$.

Table 6 Effect of moisture conservation x cultivar interaction on stover (SY), aboveground biomass (TBY) and grain (GY) yields (kg ha^{-1}) at Kobo

Moisture conservation	Cultivars	SY	TBY	GY
Tied-ridge	Jigurti	9562a	12245a	2682bc
	ICSV111	4100d	7220c	3120ab
	76 T1 #23	4158d	7511c	3352a
Flat	Jigurti	8635b	9780b	1145d
	ICSV111	5035c	7716c	2681c
	76 T1 #23	4352cd	6840c	2488c

Means within columns followed by the same letters are not significantly different at $P \leq 0.05$.

Grain yield

Differences in grain yield were observed only at Kobo where grain yield differed between the interaction effects of moisture conservation and cultivars (Table 6). The highest grain yield of 3 352 kg ha^{-1} was obtained from 76 T1 #23 with tied-ridge planting while Jigurti with flatbed planting produced the lowest grain yield (1 145 kg ha^{-1}). Under both tied-ridge and flatbed plantings ICSV111 and 76 T1 #23 yielded better than Jigurti. Generally, in all cultivars grain yield declined with flatbed planting compared to tied-ridge planting. The early maturing cultivars ICSV111 and 76 T1 #23 produced the highest grain yield while having the lowest shoot dry mass, indicating the efficient translocation of a large proportion of the dry matter to the grain.

While Jigurti, having the largest shoot dry mass, produced the lowest grain yield indicating its poor ability in partitioning dry matter to the grain. The late maturing cultivar Jigurti at Kobo had relatively less time for carbon assimilation and, therefore, had lower grain yields. Grain yield at Kobo was closely and significantly associated with HI ($r = 0.99$) indicating that grain yield differences between cultivars could be attributed partly to differences in harvest index. Cultivar differences in grain yield could also be attributed to differences in seed number per plant where the high yielding cultivars had greater number of seeds per panicle (Table 7). Cultivars also differed in seed size with Jigurti having the largest seed size (Table 7). The larger seed size of Jugurti seems, however, to be counter balanced by the lower number of seeds and thus did not play a determining role on the final yield.

Table 7 Harvest index, 1000-seed weight (TKW) and seed number of sorghum cultivars at Kobo

Cultivar	Harvest index	TKW (g)	Seed number panicle^{-1}
Jigurti	0.17b	25a	1715c
ICSV111	0.39a	21b	2243b
76 T1 #23	0.41a	17c	2905a

Means within columns followed by the same letters are not significantly different at $P \leq 0.05$.

At Sirinka grain yield differences between cultivars were not observed. However, cultivars differed in harvest index, grain size and seed number per panicle (Table 5). Greater harvest indices and seed number per panicle were recorded in 76 T1 #23 and ICSV111. However, these cultivars had a smaller grain size. The late maturing cultivar Jigurti yielded as well as the two early maturing cultivars. The longer growing period (data not shown) coupled with better rainfall condition might have enabled Jigurti to intercept greater radiation which resulted in higher biomass and grain yield production than was realized by the early maturing cultivars. Differences in yield performance of cultivars across the two sites probably reflect genotype x environment interaction.

N concentration

Differences in stover N concentrations at both locations and grain N concentrations at Kobo were highly significant between cultivars (Table 8). The highest stover N concentrations were recorded in ICSV111 (0.38 and 0.67%) and 76 T1 #23 (0.41 and 0.69%) while the lowest was recorded for Jigurti (0.30 and 0.54%). Jigurti, which yielded the most biomass, had the lowest stover N concentrations, which could be due to dry matter dilution effect as suggested by Hons *et al*. (1986) for other sorghum cultivars. This observation highlights the ability of Jigurti to accumulate greater stover biomass at lower shoot N concentration, a characteristic highly desirable in low-N environments (Traore & Maranville, 1999).

Grain N concentration followed a similar trend where the highest concentrations of 2.27% and 2.17% were recorded in ICSV111 and 76 T1 #23 respectively, while the lowest grain N concentration of 2.04% was recorded in Jigurti. The higher grain N concentration in the high yielding cultivars could be due to increased N absorption resulting from increased reproductive sink demand. That cultivars did not differ in grain N concentration at Sirinka was probably due to the fact that cultivars at this location had similar reproductive sink demands. At Sirinka, differences in grain N concentration occurred between the moisture conservation x cultivar interactions where grain N concentration in Jigurti and ICSV111 increased from 1.33% and 1.32% with tied-ridging to 1.46% and 1.42% with flatbed planting (data not shown). A negative association between grain yield and grain N concentration has been reported (Kamoshita *et al.*, 1998) making the simultaneous improvement of these traits difficult. However, in the present study grain N concentration was not correlated with grain yield suggesting that cultivars exhibiting both high yield and high grain N concentration might be selected. Cultivars ICSV111 and 76 T1 #23 having both higher grain yield and high N concentration, for instance at Kobo, support this argument.

Table 8 Stover (SNC) and grain (GNC) N concentrations, N harvest index (NHI), grain protein concentration (GPC), NUE_b and NUE_g of sorghum cultivars at Sirinka and Kobo

Location	Cultivars	SNC (%)	GNC (%)	NHI	GPC (%)	NUE_b (kg kg^{-1}N)	NUE_g (kg kg^{-1}N)
Sirinka	Jigurti	0.30b	1.39a	0.57b	8.7a	188a	41b
	ICSV111	0.38a	1.37a	0.70a	8.5a	132b	52a
	76T1#23	0.41a	1.34a	0.72a	8.3a	125b	55a
Kobo	Jigurti	0.54b	2.04b	-	12.8b	131a	-
	ICSV111	0.67a	2.27a	-	14.2a	77b	-
	76T1#23	0.69a	2.17a	-	13.6a	79b	-

Means within columns for each location followed by the same letters are not significantly different at $P \leq 0.05$.

N uptake and N harvest index

In order to evaluate cultivar differences in N accumulation, the uptake (content) of N was calculated as N concentration in tissue x dry mass. This was used as an estimate of N removal from the soil. Nutrient uptake has been advocated as a valuable index of nutrient use efficiency since it is closely related to growth and nutrient concentration (Glass, 1989). Cultivars differed in stover N uptake at both locations (Figure 4). Jigurti with the largest stover yield absorbed a greater amount of N (31 and 50 kg ha^{-1}) in the stover than the early maturing cultivars ICSV111 (17 and 31 kg ha^{-1}) and 76 T1 #23 (17 and 30 kg ha^{-1}).

Grain N uptake differed only at Kobo where it differed between the interaction effects of moisture conservation and cultivars (Table 9). Under both tied-ridge and flatbed plantings, grain N uptake was higher for the early maturing and high yielding cultivars (ICSV111 and 76 T1 #23). The highest grain N uptake of 71 kg ha^{-1} was obtained from ICSV111 with tied-ridge planting while the lowest grain N uptake of 23 kg ha^{-1} was obtained from Jigurti, the lowest yielding cultivar, with flatbed planting. For all cultivars grain N uptake declined with flatbed planting compared to tied-ridge planting. The greater grain N uptake with tied-ridge planting could be due to the greater partitioning of N to the grain with greater availability of moisture. The higher grain N concentration and grain N uptake in ICSV111 and 76T1 #23 could be due to a greater NHI and greater grain yield production. The data indicates that cultivars with a high yield potential accumulated more N than the cultivar with a lower yield potential. Similar results were reported for wheat by Dhugga & Waines (1989). Grain N uptake (yield) is a function of grain yield and grain N concentration. Analysis of the log of grain N yield as a sum of the logs of grain yield and grain N concentration showed that grain yield accounted for 92% of the variation in grain N yield among cultivars, while grain N concentration explained only 8% of the variation. From the limited data presented here it is suggested that selection for grain N uptake (yield) should be based primarily on grain yield.

Total plant N uptake differed between the main effects of cultivars at Sirinka (Figure 4) and between the interaction effects of moisture conservation and cultivars at Kobo (Table 9). At Sirinka, the highest total plant N uptake of 74 kg ha^{-1} was recorded for Jigurti, which could be attributed to its greater biomass production. At Kobo, under tied-ridge planting all the cultivars had similar total N uptake values, but under flatbed planting ICSV111 and 76 T1 #23 had greater total N uptake compared to Jigurti. The highest and lowest total N uptakes of 101 and 76 kg ha^{-1} were recorded for Jigurti with tied-ridge and flatbed planting, respectively. Analysis of total plant N as a sum of grain N yield and stover N yield revealed that grain N yield was the component that accounted for 67% of the variation in total plant N among cultivars. Cultivar differences in N uptake could be due to differences in resource capture system. Cultivars with an extensive root system will maintain nutrient uptake until maturity. Thus, the greater N uptake in the late maturing cultivar Jigurti could be due to the fact that it has more time to take up N and perhaps has better rooting depth and root distribution. Lafitte & Edmeades (1994) noted that cultivar traits such as maximum rooting depth and the capacity of the roots to absorb nutrients, enable plants to take up N from different soil layers.

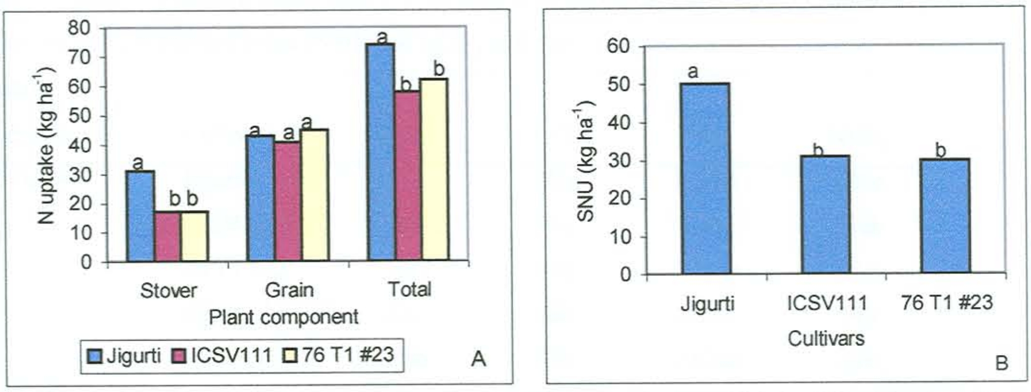

Figure 4 Stover, grain and total plant N uptake of sorghum cultivars at Sirinka (A) and stover N uptake (SNU) at Kobo (B). Bars with the same letters for each parameter are not significantly different at $P \leq 0.05$.

To obtain a high seed protein content and good quality, most of the absorbed N would have to be translocated to the grain before maturity. In this study, NHI differed between cultivar main effects at Sirinka (Table 8) and between the interaction effects of moisture conservation and cultivars at Kobo (Table 9). At Sirinka, ICSV111 and 76 T1 #23 had higher NHI compared to Jigurti. At Kobo, NHI under both tied-ridge and flatbed plantings was also higher for ICSV111 and 76 T1 #23. The highest NHI value of 74% was recorded for ICSV111 with tied-ridge planting while the lowest NHI value of 28% was recorded for Jigurti with flatbed planting. In all cultivars NHI was higher with tied-ridge planting compared to flatbed planting. The lower NHI in Jigurti suggests that its lower NHI canceled out the advantage of greater N uptake. NHI was tightly and significantly correlated (r = 0.99) with dry matter harvest index at both locations, indicating the association of N partitioning with that of dry matter partitioning to the grain. This association is clearly demonstrated by ICSV111 and 76 T1 #23, which had both higher NHI and HI. NHI also had a significant negative association with days to maturity (r = -0.99) and plant height at maturity (r = -0.99) at Sirinka. The observed negative association implies that taller cultivars, which are usually late maturing, tend to partition less N to the grain than early maturing short stature cultivars. In the present study, a lower NHI was obtained in the taller (281-294 cm) and late maturing (1459-1465 GDD) cultivar Jigurti compared to the shorter (143-174 cm) and early maturing (1250-1289 GDD) cultivars ICSV111 and 76 T1 #23.

Table 9 Effect of moisture conservation x cultivar interaction on grain (GNU) and total plant (TNU) N uptake (kg ha^{-1}), N harvest index (NHI) and NUE$_g$ at Kobo

Moisture conservation	Cultivars	GNU	TNU	NHI	NUE$_g$
Tied-ridge	Jigurti	54b	101a	0.55d	28bc
	ICSV111	71a	96a	0.74a	33ab
	76 T1 #23	70a	98a	0.71ab	35a
Flat	Jigurti	23c	76b	0.28e	14d
	ICSV111	60ab	98a	0.62cd	27c
	76 T1 #23	56b	88ab	0.65bc	30bc

Means within columns followed by the same letters are not significantly different at $P \leq 0.05$.

Nitrogen use efficiency

Cultivars that absorb N more efficiently and use it more efficiently to produce grain would improve productivity and maximize return from N fertilization (Le Gouis *et al.*, 2000). Cultivar differences in N use efficiency for biomass (NUE$_b$) production were significant at both locations (Table 8). The late maturing cultivar Jigurti had greater NUE$_b$ values (131 and 188 kg dry mass kg^{-1}N) compared to ICSV111 (77 and 132 kg dry mass kg^{-1}N) and 76 T1 #23 (79 and 125 kg dry mass kg^{-1}N). Jigurti derived its greater NUE$_b$ values from a more vegetative growth and lower N concentration in the shoot than ICSV111 and 76 T1 #23. The two improved cultivars ICSV111 and 76 T1 #23 did not significantly differ in NUE$_b$. NUE$_b$ also varied between the N fertilizer x cultivar interaction effects at Kobo where all cultivars produced the highest biomass per unit absorbed N with no fertilizer application. NUE_b with no N fertilization ranged from 78 to 152 kg dry matter kg^{-1} N, while with the application of 80 kg N ha^{-1} it ranged from 71 to 107 kg dry matter kg^{-1} N (data not shown).

Nitrogen use efficiency for grain production (NUE_g) differed between cultivar main effects at Sirinka (Table 8) and between the interaction effects of moisture conservation and cultivars at Kobo (Table 9). At Sirinka, the two improved cultivars ICSV111 and 76 T1 #23 had higher NUE_g compared to Jigurti. The highest NUE_g of 55 kg grain kg^{-1} N was recorded for 76 T1 #23 while the lowest NUE_g of 41 kg grain kg^{-1} N was recorded for Jigurti. At Kobo, ICSV111 and 76 T1 #23 under both tied-ridge and flatbed planting had the highest NUE_g. The highest NUE_g of 35 kg grain kg^{-1} N was recorded for 76 T1 #23 with tied-ridge planting while the lowest NUE_g of 14 kg grain kg^{-1} N was recorded for Jigurti with flatbed planting. For all cultivars NUE_g was higher with tied-ridge planting compared to flatbed planting. The higher NUE_g values for ICSV111 and 76 T1 #23 may relate to the high grain yield potential of these cultivars, which leads to a high reproductive sink demand for N. Buah *et al.* (1998) indicated that the physiological processes of carbohydrate partitioning and N metabolism are associated, thus genotypes with differences in grain yield potential may have differences in N accumulation and nitrogen use efficiency. Cultivars which had the highest grain yield generally had the highest NUE_g values, an indication of a positive relationship between N use efficiency and grain yield. This observation agrees with the results of Buah *et al.* (1998). The higher NUE_g in ICSV111 and 76 T1 #23 could also be due to their higher NHI.

Analysis of the log of NUE_g, as sum of the logs of grain yield per unit grain N (Gw/Ng), and NHI (Ng/Nt) revealed differences between locations in the magnitude of the contribution of each component to the variation of NUE_g among cultivars. At Sirinka, Gw/Ng and Ng/Nt accounted for 57 and 43% of the variation in NUE_g between cultivars, while at Kobo the two component traits accounted for 26 and 74% of the variation. In terms of NUE_g, a 34 and 52% difference between the most and the least nitrogen efficient cultivars were found at Sirinka and Kobo, respectively. This indicates that success in increasing sorghum yield on N poor soils could be achieved by screening genotypes for

NUE_g. Considerable evidence of genotypic differences in NUE has been reported for sorghum (Buah *et al*., 1998; Kamoshita *et al*., 1998; Traore & Maranville, 1999). Generally, it was observed that the high NUE_b cultivar had a significant response to N for aboveground biomass production and the high NUE_g cultivars had a significant response to N for grain yield. NUE_b and NUE_g values were greater at Sirinka than at Kobo reflecting the overall higher productivity at Sirinka.

Grain protein concentration and protein yield

Grain protein concentration is an important quality component related to the N economy of cereals, and genotypic variation has been reported in sorghum (Kamoshita *et al*., 1991). Grain protein concentration differences were observed between the interaction effects of moisture conservation and cultivars at Sirinka and between the cultivar main effects at Kobo. At Sirinka, grain protein concentration in all cultivars (except 76 T1 #23) increased with flatbed planting. The highest grain protein concentration of 9.1% was recorded for Jigurti with flatbed planting while the lowest grain protein concentration of 8.2% was recorded for 76 T1 #23 with flatbed planting (data not shown). At Kobo, averaged over moisture conservation and N fertilizer treatments, the highest grain protein concentration of 14.2% was recorded for ICSV111 while the lowest grain protein concentration of 12.8% was recorded for Jigurti (Table 8). The greater protein concentration in ICSV111 and 76 T1 #23 could be due to the greater partitioning of N to the grain.

Differences in grain protein yield were observed only at Kobo where it differed between the interaction effects of moisture conservation and cultivars (Table 10). Under both tied-ridge and flatbed planting grain protein yield was higher in ICSV111 and 76 T1 #23. The highest grain protein yield of 438 kg ha^{-1} was produced by 76 T1 #23, with tied-ridge planting, while Jigurti, with flatbed planting, produced the lowest grain protein yield of 145 kg ha^{-1}. Generally, in all cultivars grain protein yield was higher with tied-ridge planting compared to flatbed planting. Grain protein yield is a function of grain yield and grain protein concentration. Analysis of the log of grain protein yield as a sum of the logs of grain yield and grain protein concentration showed that grain yield accounted for 92% of the variation in grain protein yield among cultivars, while grain protein concentration explained only 8% of the variation. This indicates that high grain yielding cultivars are associated with high grain protein yield.

Table 10 Effect of moisture conservation x cultivar interaction on grain protein yield (kg ha^{-1}) at Kobo

	Cultivars		
Moisture conservation	Jigurti	ICSV111	76 T1 #23
Tied-ridge	339b	442a	438a
Flat	145c	377ab	350b

Means within columns followed by the same letters are not significantly different at $P \leq 0.05$.

Conclusion

The use of tied-ridging as a rainwater harvesting technique clearly demonstrated that tied-ridging at Sirinka was not beneficial in an average or normal season. Under the prevailing rainfall conditions and on the clayey soils of Sirinka tied-ridging may suppress crop growth and yield due to water logging effect. Thus, recognizing the potential drawbacks of tied-ridging alternative techniques of on-farm rainwater harvesting need to be explored. The use of tied-ridging at Kobo has previously proved beneficial (Reddy & Georgis, 1993). The present results, however, indicate that the benefits from tied-ridging, even at Kobo (a drier site), were not large. Despite the positive effects of tied-ridging reported in earlier results at Kobo, the non- significant effect of tied-ridging in this study seems clearly a seasonal effect suggesting that the benefit of tied-ridging is season dependent. It is, therefore, worth examining further the effects of tied-ridging using methodologies that can integrate soil texture and rainfall variability.

Nitrogen fertilization improved the grain yield and grain quality. Thus, farmers in NE Ethiopia need to apply N fertilizer in order to increase the yield and quality of sorghum.

Cultivars with greater N utilization efficiency (NUE$_g$) coupled with greater economic yields are preferred, on soils with limited available N, to cultivars with greater N uptake efficiency (Youngquist, Bramel-Cox & Maranville, 1992). In this regard, ICSV111 and 76 T1 #23 with their higher NUE$_g$, grain yield and protein yield are ideal cultivars for the N poor soils of NE Ethiopia, where farmers cannot afford to apply large amounts of inorganic fertilizers, as they can produce high yields with very little N. The difference in NUE_g between efficient and inefficient cultivars was large enough to postulate that success in increasing sorghum yield on N poor soils could be achieved by screening genotypes for NUE_g. NUE_g did not show significant cultivar x N fertilizer interaction effect and may be a useful character in developing new cultivars adapted to low soil fertility conditions.

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CHAPTER 5

Prepared according to the guidelines of the Journal of Plant Nutrition

EFFECT OF FARMYARD MANURE AND INORGANIC FERTILIZER ON SORGHUM GROWTH AND YIELD AND SOIL PROPERTIES IN A SEMI-ARID AREA IN ETHIOPIA. I. SORGHUM GROWTH, YIELD AND N USE

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ABSTRACT

A field experiment was conducted to assess the effect of the combined use of farmyard manure (FYM) and inorganic fertilizer on the growth and yield of sorghum and on soil chemical properties in a semi-arid area in NE Ethiopia. Twelve treatments comprising factorial combinations of four levels of FYM (0, 5, 10 and 15 t ha^{-1} $annum^{-1}$) and three levels of inorganic fertilizers (0, 50 and 100% of the recommended rate) were compared in a randomised complete block design with three replications over a period of six years. The results revealed significant improvements in the growth and yield of sorghum due to the main and interaction effects of FYM and inorganic fertilizer application. Application of FYM, inorganic fertilizers and their different combinations increased aboveground biomass and grain yield significantly. Grain yields were greater from combinations of FYM and inorganic fertilizer than either applied alone. Combined application of FYM and inorganic fertilizer also increased post-anthesis dry matter production. FYM application produced the highest N uptake, N concentration, N use efficiency and grain protein concentration and grain protein yield. Application of FYM in combination with 50% of the recommended inorganic fertilizer rate resulted in a grain yield equivalent to, or greater than, that for 100% of the recommended inorganic fertilizer rate, thus effecting a 50% saving of inorganic N and P fertilizer. Application of 5, 10 and 15 t FYM ha^{-1} in combination with 100% of the recommended fertilizer rate and 5, 10 and 15 t FYM ha^{-1} in combination with 50% of the recommended fertilizer rate can be recommended for farmers who can and can not afford to buy inorganic fertilizers, respectively.

INTRODUCTION

Sorghum (*Sorghum bicolor* L. Moench) is an important crop in the semi-arid areas of NE Ethiopia (1). However, its productivity is very low (approximately 1.2 t grain ha^{-1}) and variable due partly to poor fertility status of soils (2). As in many semi-arid environments where the management of organic residues is poor and the rate of organic matter decomposition is fast, the organic matter content and the fertility status of the soils in NE Ethiopia is low. These soils can no longer sustain production with the existing fertility status. The maintenance of the fertility status of the soils is essential for optimum and sustained productivity. Inorganic fertilizers can be used to replenish soil nutrients and increase crop yields but are too costly for the resource poor farmers of NE Ethiopia. Furthermore, concerns on soil exhaustion and nutritional imbalances, arising from increased and indiscriminate use of inorganic fertilizers, necessitates research on organic manure (Gaur *et al.*, 1984 as cited by 3). The use of organic manure alone may not, however, be enough to maintain the present level of crop production because of limited availability and relatively low nutrient content (4).

An integrated nutrient management program in which both organic manure and inorganic fertilizer are used has been suggested as a rational strategy (4). It is commonly believed that the combination of organic and inorganic fertilizer will increase synchrony and reduce nutrient losses (5). This is important not only in enhancing the efficiency of the fertilizers but also in reducing environmental problems that may arise from their use. The application of organic substances, including farmyard manure, apart from supplying nutrients, also provides growth regulating substances (Flaig, 1974 as cited by 6) and improves the physical (7), chemical (8) and microbial (9) properties of the soil. Unlike mineral fertilizers, nutrients contained in organic manures are released more slowly and are stored for a longer time in the soil, thereby ensuring a longer residual effect (3). The results of many studies conducted in different parts of the world on integrated nutrient management are variable, presumably due to the climatic, soil type and quality effects on the performance of the organic component of the system (10).

Farmyard manure is readily available in the crop-livestock farming systems of NE Ethiopia and it has potential for use in the fertilization schedule of sorghum in order to reduce dependence on inorganic fertilizers, while maintaining good soil health. However, information on the effect of the combined use of farmyard manure and inorganic fertilizers on the growth, development and yields of sorghum under the semi-arid environments of NE Ethiopia is not available. Research was conducted to study the effects of the integrated use of farmyard manure and inorganic N and P on the growth and yield and N use of rainfed sorghum and on soil chemical properties under semi-arid environments.

MATERIALS AND METHODS

Study Site

This experiment was conducted on the same plots for six years (1997-2002) on a Eutric fluvisol at Kobo research site of Sirinka Agricultural Research Centre in Ethiopia. The site is situated at 12^0 9'N, 39^0 38'E at an altitude of 1470 m above sea level, has a semi-arid climate with mean annual maximum and minimum air temperatures of 29^0 C and 15^0 C (1976-2002) and mean annual rainfall of 649 mm (1973-2002). The rainfall is characterized by an uneven and unpredictable distribution. The 0-23 cm horizon contains on average 34% clay, 52% silt and 14% sand, with a pH of 7.5 (1:2.5 in water), 1.20% organic C, 0.08% total N, 12.5 mg kg^{-1} available (Olsen) P, 2.3 meq 100 g^{-1} K, 34.23 meq 100 g^{-1} Ca, 11.41 meq 100 g^{-1} Mg, 1.58 meq 100 g^{-1} Na, and CEC of 50.6 meq 100 g^{-1}.

Experimental Design and Procedure

Treatments were annual application of factorial combinations of four rates of farmyard manure (0, 5, 10 and 15 t ha^{-1} annum^{-1} on dry weight basis) and three rates of inorganic fertilizer (0, 50 and 100% of the recommended rate). The locally recommended rate for a sorghum yield potential of 3 t ha^{-1} is 41 kg N ha^{-1} and 20 kg P ha^{-1}. For simplicity, the three inorganic fertilizer rates will hereafter be referred to as 0%, 50% and 100% fertilizer. The experimental design was a randomized complete block with three replications.

FYM was collected from neighbouring farmers' pens, mixed thoroughly, weighed for each plot, spread evenly, and incorporated into the soil a month before planting. The N, P and K contents of the FYM, determined before application are supplied in Table 1, varied year to year because of source and seasonal effects.

Table 1. N, P and K composition of FYM and resulting annual addition of N, P and K to the soil.

	N, P, K content of FYM (%)			Addition of N, P and K to the soil (kg ha^{-1})								
				5 t			10 t			15 t		
Year	N	P	K	N	P	K	N	P	K	N	P	K
1997	0.21	0.78	Nd	10.3	39.0	Nd	20.6	78.0	Nd	30.9	117.0	Nd
1998	0.21	0.44	Nd	10.4	22.2	Nd	20.8	44.4	Nd	31.2	66.6	Nd
1999	0.19	0.52	Nd	9.7	25.9	Nd	19.3	51.8	Nd	29.0	77.7	Nd
2000	0.19	0.14	Nd	9.5	6.9	Nd	18.9	13.7	Nd	28.4	20.6	Nd
2001	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd
2002	1.38	0.41	2.87	69	20.5	143.5	138	41.0	287.0	207	61.5	430.5

Nd = Not determined

Urea and diammonium phosphate (DAP) were used as inorganic fertilizer sources. Half of the urea and all the DAP were applied in the row prior to planting and incorporated into the soil. The remainder of the urea was side dressed at the six to eight leaf stages. Sorghum cultivar 76 T1 #23 was hand drilled in 75 cm rows and thinned to an interplant spacing of 15 cm to obtain a plant population of 88 888 plants ha^{-1}. Gross plot size was 5.25 m wide by 6 m long. Hand weeding and insect control were conducted on an as-needed basis. After discarding border rows two rows were hand harvested for the determination of grain yield at maturity. Grain yields were adjusted to 12.5% moisture content. Harvest index was calculated as the ratio of grain yield to aboveground biomass. Three plants visually judged as representative of the plot were harvested at anthesis (69 days after emergence) and maturity (111 days after emergence) stages of development for the determination of dry mass production. The net amount of biomass produced after anthesis was calculated as the difference between the biomass at anthesis and maturity (11). The amount of pre-anthesis biomass mobilized to grain was calculated as the difference between grain yield at maturity and the net biomass produced during grain filling (11).

Sorghum plant samples for determination of N uptake were collected at harvest. Plant samples were oven dried at 70^0 C to constant weight. Grain and stover samples were ground separately to pass through a 1 mm sieve. The N content of plant samples was determined by the micro-Kjeldahl method (12). The N uptake in the grain and stover was estimated by multiplying the concentrations with grain and stover yields. Whole plant N uptake was calculated by adding the uptake in the grain and stover. Grain protein content was calculated as %N in the grain x 6.25 (13) and grain protein yield as grain protein content x grain yield/100 (14). Nitrogen harvest index (NHI) was calculated as the ratio of grain N uptake to whole plant N uptake. Nitrogen use efficiency was calculated as (yield in fertilized plots – yield in control plots)/applied inorganic fertilizer N kg ha^{-1} (15).

Data from the 1997 season were not included, as a severe drought had resulted in crop failure. Post-anthesis dry matter production, pre-anthesis biomass mobilization and all N related traits, as well as grain protein concentration and grain protein yield, are based on data from the 2002 season after the treatments had been applied for six years.

Analyses of variance were performed using the SAS statistical program (SAS V8.2, SAS Institute Inc., Cary, NC, USA) for individual years and the pooled data. Analyses of variance for stover yield, panicle yield, grain yield, total aboveground biomass, thousand seed weight and harvest index were done after pooling data over years. Pooled data analyses were performed after testing the homogeneity of error variances using Bartlett's test (16). Whenever treatment differences were found to be significant, based on results of *F*-test, critical differences were calculated at 5% level of probability using Duncan's Multiple Range Test.

Regression model for yield stability (Y = a + be, where e is the environmental index) analysis followed the method previously used by Raun et al. (17) and Yamoah et al. (15). Stability analysis of yields of each individual treatment was computed using the mean of all treatments in each year as an environmental yield index. Performance of individual treatments was then regressed (fit to a linear model) against the environmental index. Systems for which the slope of the linear regression was smaller were considered as more stable or less responsive (18).

RESULTS AND DISCUSSION

Dry Matter Accumulation

Post-anthesis dry matter production and biomass mobilization

Post-anthesis dry matter production was affected by the interaction effects of FYM and inorganic fertilizer treatments (Table 2). The combined application of FYM and inorganic fertilizers considerably increased post-anthesis dry matter accumulation compared to the control. The highest post-anthesis dry matter accumulations of 475 and 458 g m^{-2} were recorded in the plots receiving 10 t FYM ha^{-1} along with 50% fertilizer and 15 t FYM ha^{-1} along with 100% fertilizer, respectively. The lowest post-anthesis dry matter accumulation of 97 g m^{-2} was recorded in the control plot. This could be explained by the postulated slow release and continuous supply of N from the FYM component, which might have increased leaf area duration and thus promoted higher rates of photosynthesis during grain filling.

Increased periods of leaf greenness and thus increased post-anthesis dry matter accumulation under the combined use of FYM and inorganic fertilizers could also be ascribed to increased soil water availability. It was observed that FYM applications increased the soil N and water holding capacity. Post-anthesis dry matter accumulation in plants that received no FYM was found to be significantly less.

Similar to post-anthesis dry matter accumulation, pre-anthesis biomass mobilization to the grain varied between the FYM x inorganic fertilizer interaction effects (Table 2). The amount of pre-anthesis biomass mobilized to the grain was significantly lower with the combined use of FYM and inorganic fertilizer than either alone. The least pre-anthesis biomass mobilization of 26 g m^{-2} was recorded for the highest fertility level (15 t FYM ha^{-1} plus 100% inorganic fertilizer) as compared to the highest biomass mobilization of 417 g m^{-2} in the control plot. Plants that did not receive FYM mobilized substantial amounts of pre-anthesis biomass to the grain.

The lower pre-anthesis biomass translocation with the combined application of FYM and inorganic fertilizers could be due to the continuation of photosynthesis and assimilate supply to the grain during the grain filling period as a result of increased N supply and soil water availability, thus reducing the need for translocation of pre-anthesis assimilates. This effect was confirmed by the higher post-anthesis biomass accumulation in the plots, which received the combined application of FYM and inorganic fertilizer. Muchow (11) indicated that large amounts of biomass translocation to the grain are especially evident under low soil fertility conditions, which supports the current observation that lower biomass was translocated under high soil fertility conditions.

Table 2. Effect of the combined use of FYM and inorganic fertilizers on post-anthesis dry matter accumulation (PADMA) and pre-anthesis biomass mobilization (PABM) in 2002.

	PADMA (g m^{-2})				PABM (g m^{-2})			
FYM	0 F^{++}	50 F	100 F	Mean	0 F^{++}	50 F	100 F	Mean
0 t ha^{-1}	97d	357abc	187cd	214B	417a	111bcd	392a	307A
5 t ha^{-1}	249bcd	397ab	299abc	315AB	256abc	171bcd	233a-d	220AB
10 t ha^{-1}	433ab	475a	314abc	407A	65cd	114bcd	247a-d	142B
15 t ha^{-1}	422ab	240bcd	458a	373A	77bcd	295ab	26d	133B
Mean	300A	367A	314A		203A	173A	224A	

$^{++}$ Indicates % of the recommended inorganic fertilizer rates. Means within columns and rows followed by the same lowercase letters; means within rows followed by the same uppercase letters; and means within columns followed by the same uppercase letters are not significantly different at P≤0.05.

Stover and aboveground biomass yield at harvest

Both FYM and inorganic fertilizer treatment main effects were significant for stover yield at harvest, whereas the FYM x inorganic fertilizer interactions were not significant. Averaged across inorganic fertilizer treatments, the application of 10 and 15 t FYM ha^{-1} gave significantly greater stover yields (4 274 and 4 648 kg ha^{-1}, respectively) compared to the FYM control (3 853 kg ha^{-1}) (Table 3). Application of 50 and 100% inorganic fertilizer, averaged across FYM treatments, also gave significantly greater stover yields (4 313 and 4 605 kg ha^{-1}, respectively) compared to the inorganic fertilizer control (3 793 kg ha^{-1}) (Table 3). Responses of stover yield to FYM and inorganic fertilizers, along with grain yield increases, have implications for agriculture in NE Ethiopia, where stover is an important source of feed and fuel and is as economically important as the grain.

Aboveground biomass yield followed a similar trend as the stover yield (Table 3). Averaged across inorganic fertilizer treatments, application of FYM increased aboveground biomass yield over the FYM control. The highest aboveground biomass yield of 9 750 kg ha^{-1}was produced on plots where 15 t FYM ha^{-1}were applied. Aboveground biomass yield with the application of 50 and 100% inorganic fertilizer, averaged across FYM treatments, were greater (9 177 and 9 567 kg ha^{-1}, respectively) than the inorganic fertilizer control (8 158 kg ha^{-1}). The FYM x inorganic fertilizer interaction effects were not, however, significant.

Table 3. Effects of FYM and inorganic fertilizers on stover and aboveground biomass yield at harvest (data pooled over five growing seasons).

FYM	Stover yield (kg ha^{-1})				Aboveground biomass yield (kg ha^{-1})			
	0 F^{++}	50 F	100 F	Mean	0 F^{++}	50 F	100 F	Mean
0 t ha^{-1}	3295a	4101a	4162a	3853C	7524a	8384a	8781a	8230C
5 t ha^{-1}	3881a	4003a	4631a	4172BC	8235a	8849a	9637a	8907B
10 t ha^{-1}	3966a	4422a	4435a	4274AB	8240a	9502a	9206a	8983B
15 t ha^{-1}	4029a	4725a	5189a	4648A	8634a	9972a	10643a	9750A
Mean	3793B	4313A	4605A		8158B	9177A	9567A	

$^{++}$ As in Table 2. Means within columns and rows followed by the same lowercase letters; means within rows followed by the same uppercase letters; and means within columns followed by the same uppercase letters are not significantly different at $P \leq 0.05$ for each comparison.

Grain Yield

Data presented in Tables 4, 5 and 6 indicate the main and interaction effects of FYM and inorganic fertilizer treatments on grain yield in individual years and yield pooled across years. In all years (except in 1998), grain yield significantly differed between the FYM x inorganic fertilizer interaction effects. Similar grain yield response trends to treatment effects were observed each year and only the pooled grain yield data is discussed.

The main and interaction effects of FYM and inorganic fertilizer treatments on grain yield averaged over years (pooled data) are illustrated in Table 6. Greater grain yields were obtained with the combination of FYM and inorganic fertilizer than with either manure or inorganic fertilizer alone. The combined application of 5, 10 and 15 t FYM ha^{-1} with 50 and 100% of the recommended inorganic fertilizer rate significantly increased grain yield over the control (Table 6). The highest grain yield of 4 535 kg ha^{-1} was obtained from the plots receiving the highest fertility level (15 t FYM ha^{-1} plus 100% of the recommended inorganic fertilizer rate) and the lowest yield of 3 340 kg ha^{-1} was obtained from the control.

Increases in grain yield with the combined applications of FYM and inorganic fertilizers are ascribed to the addition of NPK and other essential nutrients from the FYM component and its favourable effect on the physical, chemical and microbial properties of the soil (19, 20). Satyanarayana et al. (21) indicated that FYM plays an important role in improving soil permeability to air and water and water stable aggregates, thus improving soil properties and nutrient uptake, which results in greater growth and yield. Similar long term studies on different crops have shown increased yields due to the application of FYM and these effects were largely attributed to improved soil organic matter, and soil physical, chemical and microbial properties with the application of FYM (9, 21). Application of FYM also influences plant growth physiologically by providing growth regulating substances (Flaig, 1974 as cited by 6).

The combined use of FYM and inorganic fertilizers, in addition to the additive effect on nutrient supply and improvement of soil physical conditions, checks nitrogen losses and conserves soil N by forming organic-mineral complexes thereby ensuring continuous N availability and greater yields (21). The increased grain yields, from the combined application of FYM and inorganic fertilizers, are in agreement with the results of other studies on sorghum (22), rice (3, 23, 24), soybean (25), maize (26), and wheat (23, 24).

Application of 5 t FYM ha^{-1} in combination with 50% of the recommended inorganic fertilizer rate resulted in a grain yield comparable with that obtained from applying 100% of the recommended inorganic fertilizer rate. Further increases in the FYM rate to 10 and 15 t ha^{-1} and combining with 50% of the recommended inorganic fertilizer rate also resulted in statistically better yields than applying 100% of the recommended inorganic fertilizer rate alone. This suggests that, by applying FYM along with 50% of the recommended inorganic fertilizer rate a cost saving on inorganic fertilizers worth of 20 kg N ha^{-1} and 10 kg P ha^{-1} can be made, with the additional benefit of improving the physical and chemical conditions of the soil. Thus, application of FYM has potential of not only improving crop yield and soil fertility, but also of reducing dependence on inorganic fertilizers. Although soil organic matter and total N improvements observed in this study were cumulative for FYM treated plots, the time variable was not related to the sorghum yield, suggesting that there were no long term cumulative effects of annual application of FYM on productivity of sorghum.

Table 4. Effect of the combined use of FYM and inorganic fertilizers on sorghum grain yield (kg ha^{-1}) in 1998 and 1999.

	1998				1999			
FYM	0 F^{++}	50 F	100 F	Mean	0 F^{++}	50 F	100 F	Mean
0 t ha^{-1}	3079a	3201a	3610a	3297B	3422de	3257e	4568bc	3749B
5 t ha^{-1}	3332a	3526a	3843a	3567AB	3501de	4314bc	5003ab	4273A
10 t ha^{-1}	3185a	3646a	3904a	3578AB	3415de	4020cd	5331a	4255A
15 t ha^{-1}	3263a	4262a	4210a	3912A	3994cd	4659abc	4482bc	4378A
Mean	3215B	3659A	3892A	3589	3583C	4063B	4846A	4164

$^{++}$ As in Table 2. Means within columns and rows followed by the same lowercase letters; means within rows followed by the same uppercase letters; and means within columns followed by the same uppercase letters are not significantly different at P≤0.05.

Table 5. Effect of the combined use of FYM and inorganic fertilizers on sorghum grain yield (kg ha^{-1}) in 2000 and 2001.

	2000				2001			
FYM	0 F^{++}	50 F	100 F	Mean	0 F^{++}	50 F	100 F	Mean
0 t ha^{-1}	3435cde	3217e	3319de	3324C	2982d	3323b-d	3000d	3102C
5 t ha^{-1}	3491cde	3623b-e	3504cde	3539B	3493b	3286b-d	3428bc	3402B
10 t ha^{-1}	3677bcd	3982b	3488cde	3716B	3274b-d	3097cd	3315b-d	3228BC
15 t ha^{-1}	3910b	3805bc	4470a	4062A	3101cd	3389bc	4291a	3594A
Mean	3628A	3657A	3695A	3660	3212B	3274B	3509A	3332

$^{++}$ As in Table 2. Means within columns and rows followed by the same lowercase letters; means within rows followed by the same uppercase letters; and means within columns followed by the same uppercase letters are not significantly different at P≤0.05.

Table 6. Effect of the combined use of FYM and inorganic fertilizers on sorghum grain yield (kg ha^{-1}) in 2002 and grain yield (kg ha^{-1}) pooled over five growing seasons.

	2002				Pooled grain yield			
FYM	0 F^{++}	50 F	100 F	Mean	0 F^{++}	50 F	100 F	Mean
0 t ha^{-1}	3785de	3813de	4131cde	3910B	3340g	3362fg	3726de	3476C
5 t ha^{-1}	3929de	4362bcd	4597bc	4296A	3549efg	3822cd	4075b	3816B
10 t ha^{-1}	3736de	5240a	4299b-e	4425A	3457fg	3997bc	4067b	3841B
15 t ha^{-1}	3683e	4856ab	5220a	4586A	3590def	4194b	4535a	4106A
Mean	3783B	4568A	4562A	4304	3484C	3844B	4101A	

$^{++}$ As in Table 2. Means within columns and rows followed by the same lowercase letters; means within rows followed by the same uppercase letters; and means within columns followed by the same uppercase letters are not significantly different at P≤0.05.

Significant differences in fresh panicle yield were observed between the main effects of FYM and inorganic fertilizer treatments (Appendix Table 5.1). Fresh panicle yields increased from 4 377 kg ha^{-1} to 5 102 kg ha^{-1} with the application of 15 t FYM ha^{-1}. They were also increased from 4 366 kg ha^{-1} to 4962 kg ha^{-1} with the application of 100% of the recommended inorganic fertilizer rate.

Improvements in 1000-seed weight from the combined use of FYM and inorganic fertilizer were small, ranging between 3 to 6% (Appendix Table 5.1). The harvest index was in the range of 0.41 to 0.45 and was not affected by any of the treatment or interaction effects.

Yield Stability

The results of the regression analysis to assess the yield stability of treatments across a range of environments demonstrated variability between treatments (Table 7). A stable system has been defined as one that changes least in response to changes in environment (17). In this study, treatments marked with "+" are more stable as indicated by their smaller slope (*b*<1.0). This indicates that these treatments can produce reasonable consistent yield both in low yielding years and in good years, as they are less responsive to environmental changes. On the other hand treatments marked with "++" are less stable having steeper slopes (*b*>1.0). These treatments are responsive to environmental changes and may yield reasonably good in low yielding years and high in good years. These treatments are, thus, adapted to high-yielding environments. Generally, yield stability decreased with the applications of FYM and higher rates of inorganic fertilizer. However, although relatively less stable farmers would benefit from building up their soil fertility through the combined use of FYM and inorganic fertilizer as yield increases, even in bad years, are still better than the more stable treatments. Thus, building up the soil fertility would improve yield in any case although the benefit will be greater in good years.

Table 7. Stability analyses for the combined use of FYM and inorganic fertilizers.

Treatments	*a*	*b*	se	*p*-value	R^2	Categorical mark
0 t ha^{-1} FYM + 0F[$]	7030	0.69	0.21	0.046	0.78	+
0 t ha^{-1} FYM + 50F	1874	0.39	0.28	0.261	0.39	+
0 t ha^{-1} FYM + 100F	-1574	1.39	0.37	0.034	0.82	++
5 t ha^{-1} FYM + 0F	2104	0.38	0.22	0.193	0.48	+
5 t ha^{-1} FYM + 50F	-684	1.18	0.07	0.0004	0.98	++
5 t ha^{-1} FYM + 100F	-1799	1.54	0.41	0.033	0.82	++
10 t ha^{-1} FYM + 0F	2105	0.35	0.27	0.285	0.36	+
10 t ha^{-1} FYM + 50F	-2450	1.69	0.52	0.049	0.77	++
10 t ha^{-1} FYM + 100F	-1873	1.56	0.68	0.108	0.63	++
15 t ha^{-1} FYM + 0F	1044	0.67	0.40	0.193	0.48	+
15 t ha^{-1} FYM + 50F	-1038	1.37	0.31	0.021	0.86	++
15 t ha^{-1} FYM + 100F	1587	0.77	0.34	0.111	0.62	+

[$] Indicates % of the recommended inorganic fertilizer rates. + and ++ indicate stable and unstable treatments, respectively.

Nitrogen Concentration and Uptake

Stover and grain N concentrations were influenced by the main effects of FYM and inorganic fertilizer treatments, with the exception of stover N concentration with inorganic fertilizer treatments (Fig. 1). Averaged across inorganic fertilizer treatments, applications of 5, 10 and 15 t FYM ha^{-1} resulted in increased grain N concentrations over the FYM control, but differences between the FYM rates were not significant. Differences in grain N concentration between inorganic fertilizer treatments showed no consistent trend and were difficult to explain. Generally, grain N concentration values reported in this study, were within the range (1.23-2.44%) reported for sorghum by Muchow (11). Stover N concentrations tended to increase with increasing rates of FYM, although a significant difference was obtained only with the application of 15 t FYM ha^{-1}. The increase in stover N concentration with FYM applications indicates the availability of adequate levels of soil N and/or lower N translocation from the stover to the grain. With applications of FYM, translocation of N would not be great enough as there will be continued absorption until maturity. In agreement with this explanation Roy & Wright (27) indicated that the extent of translocation of N from the vegetative parts in fertilised plants would be low in comparison with that in unfertilised plants. According to Ruttunde et al. (28) the nitrogen content of the stover is an indicator of the stover feed quality. Thus, the increase in the nitrogen content of the stover with FYM applications, as in this study, would mean an improvement in the nutritive value of the stover, which would have major implications for resource poor farmers for whom sorghum stover is a major feed resource in the dry season.

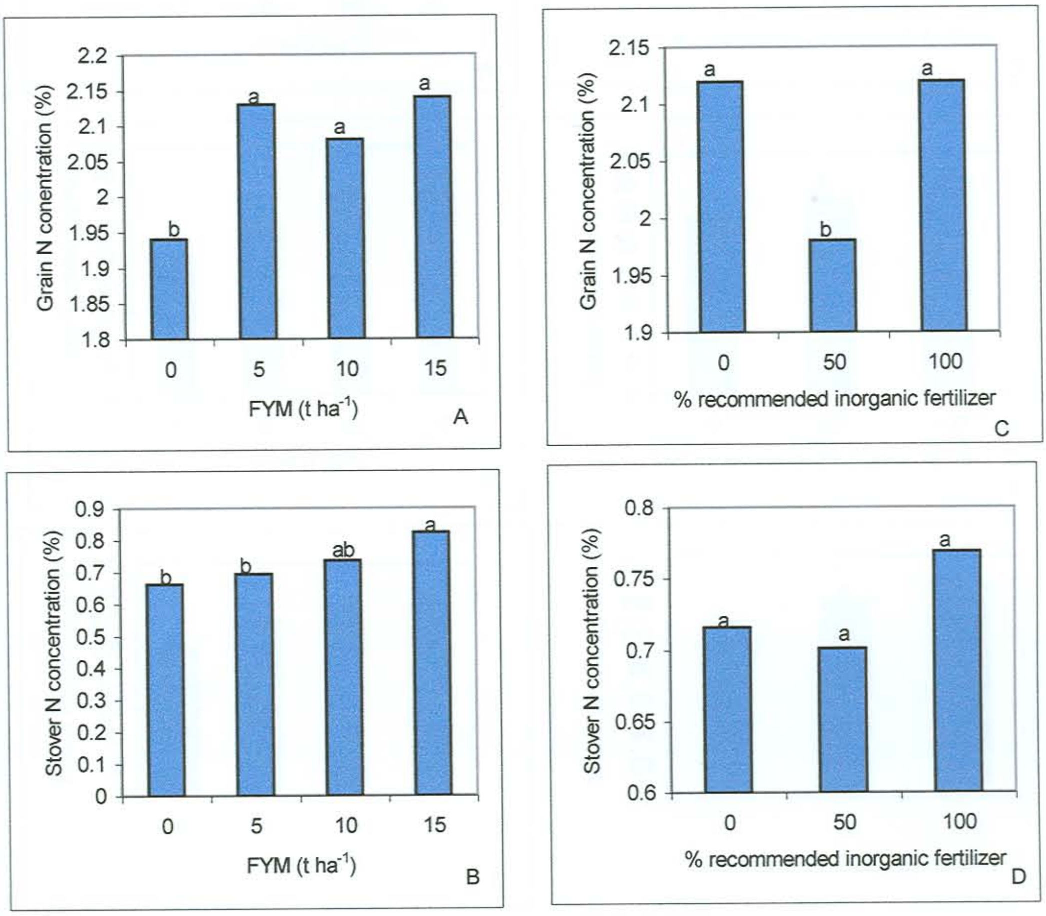

Figure 1. Effects of FYM and inorganic fertilizers on grain and stover N concentration. Values in A, and B are means across inorganic fertilizer rates; values in C and D are means across FYM rates. Bars with the same letter are not significantly different at $P \leq 0.05$.

N uptake in the grain, stover and whole plant (grain plus stover) was enhanced by increasing levels of FYM application (Fig. 2). Averaged over all inorganic fertilizer treatments, FYM applied at 5, 10 and 15 t ha^{-1} increased N uptake by 20, 20 and 29% in the grain, by 23, 43 and 57% in the stover and by 21, 26 and 36% in the whole plant compared to the FYM control.

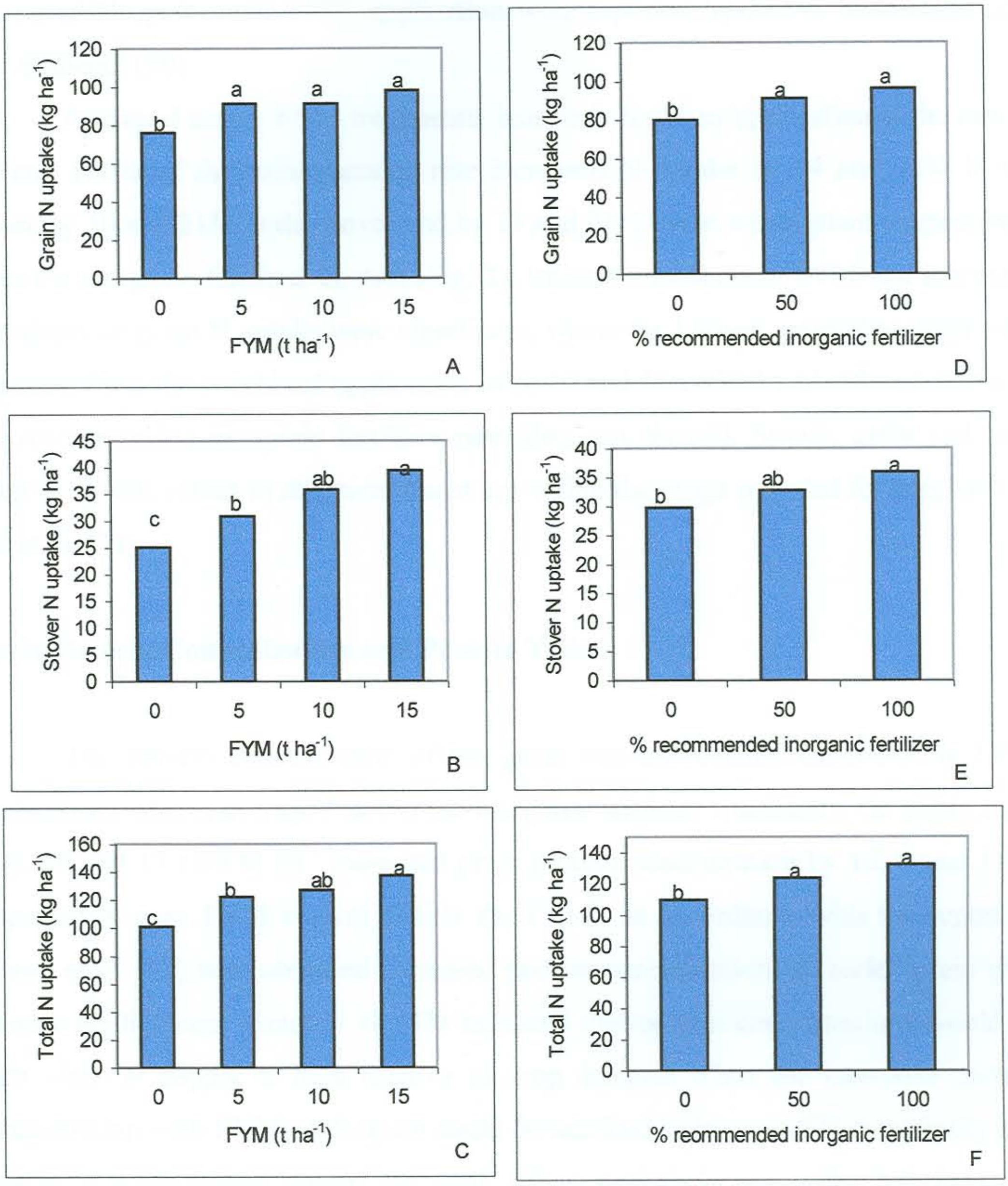

Figure 2. Effects of FYM and inorganic fertilizers on grain, stover and total plant N uptake. Values in A, B, and C are means across inorganic fertilizer rates; values in D, E, and F are means across FYM rates. Bars with the same letter are not significantly different at P≤0.05.

Increased N uptake with increased FYM applications could be ascribed to increased dry matter production and also to increased N concentration in plant tissue. N uptake increased with FYM application due to the build-up of organic N in the soil, from six successive annual applications, and its slow release throughout the growing period. As suggested by Yadav (24), it could also be due to the development of a higher root density, associated with the improved physical conditions of the soil, which in turn enhanced nutrient absorption capacity of the crop. Similar results of increased N uptake with FYM application were reported by Xie & Mackenzie (29) and Schlegel (30).

Averaged across FYM treatments, inorganic fertilizer application at the rate of 50 and 100% of the recommended rate increased N uptake by 14 and 20% in the grain, by 10 and 21% in the stover and by 13 and 21% in the whole plant, respectively over the inorganic fertilizer control (Fig. 2). Interaction effects of FYM and inorganic fertilizers on grain N uptake were significant, where the highest grain N uptakes were obtained from the combined application of 5, 10 and 15 t FYM with 50 and 100% of the recommended inorganic fertilizer rate (data not shown). Stover, grain and total plant N uptake values in this experiment are within the range reported for sorghum by Pal et al. (31).

Grain Protein Concentration and Protein Yield

The protein concentration of the grain was appreciably enhanced by FYM applications where, averaged across the inorganic fertilizer treatments, the application of 5, 10 and 15 t FYM ha^{-1} increased grain protein concentration by 10, 8 and 11%, respectively over FYM control (Table 8). This is in accordance with the report of Chang et al. (32) who observed increased protein concentrations in barley grain with manure applications. Grant et al. (33) indicated that protein concentrations would be high when N supply is high relative to crop demand. Thus the increased protein concentration with FYM application could be ascribed to improved N availability and greater N consumption during the grain filling period. In areas like NE Ethiopia, where cereal grains are a major source of proteins, any increase in grain protein content from improved fertility management would be a cost effective approach to the improvement of the nutrition of the people.

Similarly, FYM and inorganic fertilizer treatments affected grain protein yield. FYM, averaged over inorganic fertilizer treatments, increased grain protein yield by 20, 20 and 29% with the application of 5, 10 and 15 t ha^{-1}, respectively over the FYM control. Grain protein yield was also increased by 14 and 20% with the application of 50 and 100% of the recommended inorganic fertilizer rate (Table 8). Grain protein yield increased more when FYM and inorganic fertilizer were used in combination than when either was used alone. The combined application of 5, 10 and 15 t FYM ha^{-1} with 50 and 100% of the recommended inorganic fertilizer rate increased grain protein yield by 22 to 46% over the control (data not shown). Metho et al. (34) also reported increased grain protein yield in wheat with the application of NPK fertilizers alone and in combination with manure. Nitrogen harvest index was not significantly affected by any of the treatments (Table 8), indicating that the observed difference in grain N content is due to the difference in N absorption rather than in partitioning the absorbed N into the grain.

Table 8. Effects of FYM and inorganic fertilizers on grain protein content, grain protein yield and N harvest index in 2002.

FYM (t ha^{-1})	GPC (%)	GPY (kg ha^{-1})	NHI
0	12.10b	475.4b	0.746a
5	13.30a (10)	571.2a (20)	0.748a
10	13.01a (8)	570.6a (20)	0.719a
15	13.39a (11)	612.4a (29)	0.707a
Fertilizer			
0F	13.24a	500.1b	0.729a
50F	12.36b	569.5a (14)	0.730a
100F	13.25a	602.6a (20)	0.730a
CV (%)	7.1	10.9	6.7

GPC, grain protein concentration; GPY, grain protein yield; NHI, nitrogen harvest index. 0F, 50F, and 100F represent 0, 50%, and 100% of the recommended inorganic fertilizer rate. Numbers in parenthesis indicate percent increases above the control. Means in a column accompanied by different letters are significantly different at P≤ 0.05 for each comparison.

Nitrogen Use Efficiency

FYM applications significantly improved the efficiency of applied inorganic N (Fig. 3). Nitrogen use efficiency with the combined application of 50% of the recommended inorganic fertilizer rate together with 5, 10 and 15 t FYM ha^{-1} was increased by 21, 73 and 57 kg kg^{-1} respectively, compared with 1.4 kg kg^{-1} when 50% of the recommended inorganic fertilizer rate was applied alone. Similarly, nitrogen use efficiency in the combined application of 100% of the recommended inorganic fertilizer rate together with 5, 10 and 15 t FYM ha^{-1} was increased to 16, 14 and 38 kg kg^{-1} respectively, compared with 8 kg kg^{-1} when 100% of the recommended inorganic fertilizer rate was applied alone. Significantly higher nitrogen use efficiency values were obtained with the application of 50% of the recommended inorganic fertilizer rate with 10 and 15 t FYM ha^{-1}. This observation agrees with the results of Yamoah et al. (15) who reported increased fertilizer use efficiency when crop residues and inorganic fertilizers were combined than when fertilizer was applied alone. The improved efficiency of inorganic fertilizer N, when used in conjunction with FYM, could be due to the fact that high root density, due to improved physical conditions of the soil and greater water availability, might have enhanced nutrient absorption capacity of the crop, thereby improving biological yield at a given level of fertilizer application (35). These results demonstrate that greater yields are attainable with a limited amount of inorganic fertilizer, if FYM is integrated in the nutrient supply system.

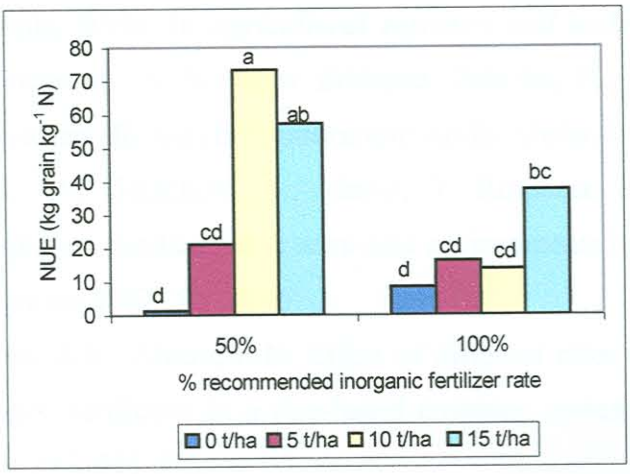

Figure 3. Effect of the combined use of FYM and inorganic fertilizer on nitrogen use efficiency (NUE). Bars with the same letter are not significantly different at $P \leq 0.05$.

CONCLUSION

An important finding of this study is that the combined use of FYM and inorganic fertilizer increased crop yield and quality at reduced inorganic fertilizer inputs, while maintaining and improving the soil resource. The results disprove farmers' concern that FYM can aggravate water stress under dry conditions and result in reduced yields. Results also demonstrated that 50% of the inorganic fertilizer recommended for sorghum production could be substituted by FYM without adverse effects on productivity, which implies a cost saving on inorganic fertilizers worth 20 kg N ha^{-1} and 10 kg P ha^{-1}. Application of 5, 10 and 15 t FYM ha^{-1} in combination with 100% of the recommended fertilizer rate and 5, 10 and 15 t FYM ha^{-1} in combination with 50% of the recommended fertilizer rate can be recommended for farmers who can and can not afford to buy inorganic fertilizers, respectively. However, the trial should be continued to assess the long-term effects of integrated use of FYM and inorganic fertilizers on soil physical and chemical properties, soil microbial activities, and interactions with other macro and micronutrient availability. Information on the economic feasibility and profitability of the integrated nutrient management systems in small-scale farming systems of NE Ethiopia also still needs to be addressed.

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CHAPTER 6

Prepared according to the guidelines of the Journal of Plant Nutrition

EFFECT OF FARMYARD MANURE AND INORGANIC FERTILIZER ON SORGHUM GROWTH AND YIELD AND SOIL PROPERTIES IN A SEMI-ARID AREA IN ETHIOPIA. II. SOIL PROPERTIES

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ABSTRACT

A field experiment was conducted to assess the effect of the integrated use of farmyard manure and inorganic fertilizers on the growth and yield of sorghum and on soil chemical properties in a semi-arid area in NE Ethiopia. Twelve treatments comprising the factorial combinations of four levels of FYM (0, 5, 10 and 15 t ha^{-1} annum^{-1}) and three levels of inorganic fertilizers (0, 50 and 100% of the recommended fertilizer rates) were compared for six years in a randomised complete block trial with three replications. The results revealed substantial increases in total N, available P, exchangeable K, organic carbon (OC) and organic matter (OM) contents of the soil with the application of 5 to 15 t FYM ha^{-1}. Increase in these soil parameters increased with the level of FYM application. The inorganic fertilizer treatments made no impact on fertility build up. The application of FYM and inorganic fertilizer did not affect exchangeable Na^{+}, Ca^{2+}, Mg^{2+}, cation exchange capacity, base saturation or soil pH. Significant increases in soil N balance and soil water holding capacity were observed with FYM application. It can be concluded that with the application FYM at 5, 10 and 15 t ha^{-1} soil degradation under continuous cultivation can be reversed within a relatively short period of time.

INTRODUCTION

The soils in the semi-arid sorghum growing areas of NE Ethiopia are predominantly shallow, low in organic matter content and poor in water holding capacity and plant nutrients (1, 2). Soil organic matter and nutrients have been severely depleted owing to continuous cultivation without nutrient inputs, absence of fallowing and prevalence of severe erosion (1, 3). The productivity of these soils has consequently declined (4). The enhancement of the soil organic matter status by regular addition of organic material is essential if adequate soil productivity is to be maintained. Farmyard manure is readily available in NE Ethiopia as a source of multiple nutrients and to improve soil characteristics.

Exclusive dependence on mineral fertilizers is often criticized because of the potential damage it causes to soil quality and soil life. It has been suggested that good soil fertility management needs to include organic material, which can improve the chemical and physical conditions of the soil (5). FYM is a valuable fertilizer and soil amendment in crop production. The addition of FYM is known to change the physical and chemical properties of soils. It increases soil pH in acidic soils, organic matter content, water holding capacity, infiltration rate, and the availability of N, P and K (6, 7).

Little or no research concerning the effect of FYM application on soil chemical properties has been conducted in NE Ethiopia. This paper reports on the effect of the combined application of FYM and inorganic fertilizer (N and P) on selected soil properties.

MATERIALS AND METHODS

Study Site

This experiment was conducted on the same plots for six years (1997-2002) on a Eutric fluvisol at Kobo research site of the Sirinka Agricultural Research Centre in Ethiopia. The site is situated at 12^0 9'N, 39^0 38'E at an altitude of 1470 m above sea level, has a semi-arid climate with mean annual maximum and minimum air temperatures of 29^0 C and 15^0 C (1976-2002) and mean annual rainfall of 649 mm (1973-2002). The rainfall is characterized by an uneven and unpredictable distribution. The soil in the 0-23 cm horizon contains on average 34% clay, 52% silt and 14% sand, with a pH of 7.5 (1:2.5 in water), 1.20% organic C, 0.08% total N, 12.5 mg kg^{-1} available P (Olsen), 2.3 meq 100 g^{-1} K, 34.2 meq 100 g^{-1} Ca, 11.4 meq 100 g^{-1} Mg, 1.58 meq 100 g^{-1} Na, and has a CEC of 50.6 meq 100 g^{-1}.

Experimental Design and Procedure

Treatments comprised factorial combinations of four rates of farmyard manure (0, 5, 10 and 15 t ha^{-1} annum^{-1} on dry weight basis) and three rates of inorganic fertilizers (0, 50 and 100% of the recommended rate). The locally recommended rate for a sorghum yield potential of 3 t ha^{-1} is 41 kg N ha^{-1} and 20 kg P ha^{-1}. The experimental layout was a randomised complete block design with three replications. Treatments were applied to the same plot every year. Crop residues were removed from the plots after harvest. FYM was collected from neighbouring farmers' kraals, mixed thoroughly, weighed for each plot, spread evenly, and incorporated into the soil a month before planting. The N, P and K contents of the FYM determined before application are presented in Table 1.

Table 1. Total N, P and K composition of FYM and resulting annual addition of N, P and K to the soil.

	N, P, K content of FYM (%)			Addition of N, P, and K to the soil (kg ha^{-1})								
				5 t			10 t			15 t		
Year	N	P	K	N	P	K	N	P	K	N	P	K
1997	0.21	0.78	Nd	10.3	39.0	Nd	20.6	78.0	Nd	30.9	117.0	Nd
1998	0.21	0.44	Nd	10.4	22.2	Nd	20.8	44.4	Nd	31.2	66.6	Nd
1999	0.19	0.52	Nd	9.7	25.9	Nd	19.3	51.8	Nd	29.0	77.7	Nd
2000	0.19	0.14	Nd	9.5	6.9	Nd	18.9	13.7	Nd	28.4	20.6	Nd
2001	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd
2002	1.38	0.41	2.87	69	20.5	143.5	138	41.0	287.0	207	61.5	430.5

Nd = Not determined

Urea and diammonium phosphate (DAP) were used as inorganic fertilizer sources. Half of the urea and all the DAP were applied in rows prior to planting and incorporated into the soil. The remainder of the urea was side dressed at the six to eight leaf stage. Sorghum cultivar 76 T1 #23 was hand drilled in 75 cm rows and thinned to an interplant spacing of 15 cm to obtain a plant population of 88 888 plants ha^{-1}. Gross plot size was 5.25 m wide by 6 m long. In each plot soil samples from nine random positions were taken from the 0-15 cm depth prior to planting and again after harvest in the sixth year. The samples were mixed, homogenised, air dried in shade, ground and passed through a 2 mm sieve. Soil samples were analysed for total N, available P, exchangeable cations (Na^+, K^+, Ca^{2+}, Mg^{2+}), organic C, cation exchange capacity, base saturation and pH. Organic carbon was determined by the rapid titration method (8). Total N and Olsen P were determined according to the procedures outlined by Page et al. (9). Soil pH was measured in 1:2.5 soil:water suspension. Exchangeable cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) were determined in an ammonium acetate extract at pH 7 using an atomic absorption spectrophotometer. Soil N balance was computed, according to Hegde (10), as the difference between N added (FYM and fertilizer) and N removed by plants (uptake). Soil water holding capacity was determined by the gravimetric method at crop harvest.

Analyses of variance for all data were performed using the SAS statistical program (SAS V8.2, SAS Institute Inc., Cary, NC, USA). Whenever treatment differences were found to be significant, based on results of the *F*-test, critical differences were calculated at 5% level of probability using Duncan's Multiple Range Test.

RESULTS AND DISCUSSION

Changes in Soil Chemical Properties

FYM applications substantially increased total N, available P, and exchangeable K contents of the soil after five and six years of application. FYM application was the major source of variation for all elements (Table 2). Variations, amounting to 90-98% in total N, 92% in P and 79% in exchangeable K, were largely accounted for by FYM applications (Table 2). Application of FYM increased the total N content of the soil by up to 59%, available P by up to 158%, and exchangeable K by up to 70% over the soil that received no FYM (Table 3).

Table 2. Analysis of variance of changes in total N, P, and K in soil resulting from the combined use of FYM and inorganic fertilizers (Fert).

Sources of variation	Nitrogen				Phosphorus		Potassium	
	5 Year$^{\phi}$	%	6 Year$^{\delta}$	%	6 Year$^{\delta}$	%	6 Year$^{\delta}$	%
FYM	0.0036**	90.0	0.0017**	98.0	699.82**	91.7	1.083**	78.8
Fert	0.0001ns	2.5	0.00003ns	1.7	58.77**	7.7	0.068ns	4.9
FYM * Fert	0.0003ns	7.5	0.000004ns	0.2	4.38ns	0.6	0.224*	16.3

$^{\phi}$ & $^{\delta}$ Indicate residuals from five and six years of FYM application, respectively. % Indicates percentage of the total variation accounted for by treatments.

Table 3. Effect of FYM on soil total N, available P, K, and N balance after five and six years of application, averaged across inorganic fertilizer treatments.

FYM (t ha^{-1})	Total N (%)		Available P (mg kg^{-1})	Exchangeable K (meq/100g)	N balance (kg ha^{-1})
	5 Year$^{\phi}$	6 Year$^{\delta}$	6 Year$^{\delta}$	6 Year$^{\delta}$	
0	0.079d	0.074c	12.9d	1.2c	-80.7d
5	0.093c (18)	0.082c (11)	19.8c (53)	1.7b (44)	-15.7c
10	0.109b (38)	0.093b (26)	26.8b (107)	1.7ab (48)	65.5b
15	0.126a (59)	0.105a (42)	33.4a (158)	2.0a (70)	141.4a
CV (%)	11.1	12.5	14.1	18.0	38.5

$^{\phi}$ & $^{\delta}$ as in Table 2. Numbers in parenthesis indicate percent change over the control. Means in a column accompanied by different letters are significantly different at $P \leq 0.05$.

The improvement in the soil available P with FYM addition may be attributed to many factors, such as the addition of P through FYM, the improved availability of soil P as a result of the action of organic acids produced during FYM decomposition, and retardation of soil P fixation by organic anions formed during FYM decomposition (11). Increases in soil K may be attributed to the additional K applied through FYM and the solubilizing action of certain organic acids formed during FYM decomposition (11). The observed enhancement in total N, available P and K is in agreement with the reports of several researchers (6, 12, 13, 14, 15). A three fold increase in soil N and six-fold increase in soil P as a result of manure applications were reported by Powell (6) and Kaihura et al. (12), respectively. Zia et al. (16) reported a 12.7% increase in total N in the soil with the application of 5 t FYM ha^{-1}.

Inorganic fertilizer application did not affect the soil N and K content. However, application of 100% of the recommended inorganic fertilizer rate increased soil available P by 20% over the soil that did not receive inorganic fertilizer (data not shown). Exchangeable cations (Na^+, Ca^{2+} and Mg^{2+}), cation exchange capacity, base saturation and soil pH were affected neither by FYM main effects (Table 4) nor by inorganic fertilizer and interaction effects of FYM and inorganic fertilizer. The FYM x inorganic fertilizer interaction effects were not significant for any of the soil nutrients.

Table 4. Effect of FYM on exchangeable cations, base saturation, cation exchange capacity and pH, averaged across inorganic fertilizer treatments.

FYM ($t\ ha^{-1}$)	Exchangeable cations (meq/100g)			Base saturation (%)	Cation exchange capacity (meq/100g)	pH (1:2.5 H_2O)	
	Na^+	Ca^{2+}	Mg^{2+}			5 Year$^{\phi}$	6 Year$^{\delta}$
0	0.401a	19.023a	16.92a	76.662a	49.111a	7.5a	7.7a
5	0.372a	16.538a	16.442a	70.755a	49.462a	7.5a	7.6a
10	0.392a	16.921a	15.812a	73.973a	47.362a	7.5a	7.7a
15	0.399a	20.452a	16.342a	79.996a	48.864a	7.6a	7.7a
CV (%)	18.2	23.1	9.4	12.9	7.1	1.6	1.4

$^{\phi}$ & $^{\delta}$ as in Table 2. Means in a column accompanied by different letters are significantly different at $P \leq 0.05$.

Changes in Soil Organic Carbon

FYM application also influenced organic carbon (OC) and organic matter (OM) contents of the soil. Variations amounting to 75-94% in OC and 75-99% in OM were accounted for by FYM applications (Table 5). FYM application increased soil organic carbon content by up to 67% and organic matter content by up to 59% over the FYM control (Table 6). The inorganic fertilizer treatments and the interaction effects had no significant effect on the organic carbon and organic matter contents of the soil. The increase in organic carbon with FYM application can be attributed to its stable nature and slow degradability (17).

The observed increase in soil organic carbon and organic matter in this study is in agreement with the results of Shirani et al. (18) who reported a three fold increase in soil organic matter with the application of FYM at 3 and 6 $t\ ha^{-1}$. Mokwunye (19) reported a two-fold increase with the application of FYM at 5 and 20 $t\ ha^{-1}$. Many other studies (10, 20, 21, 22) have also reported increased soil organic matter content after the application of FYM.

Table 5. Analysis of variance of change in soil organic carbon and organic matter from the combined use of FYM and inorganic fertilizers (Fert).

Sources of variation	Organic Carbon				Organic Matter			
	5 Year$^{\phi}$	%	6 Year$^{\delta}$	%	5 Year$^{\phi}$	%	6 Year$^{\delta}$	%
FYM	0.461**	94.0	0.099**	75.0	1.093**	98.6	0.293**	74.7
Fert	0.014ns	2.9	0.016ns	12.1	0.0007ns	0.1	0.049ns	12.5
FYM * Fert	0.015ns	3.1	0.017*	12.9	0.0146ns	16.3	0.050*	12.8

$^{\phi}$ & $^{\delta}$ as in Table 2. % Indicates percentage of the total variation accounted for by treatments.

Table 6. Effect of FYM applications on soil organic carbon and organic matter content and water holding capacity (SWHC), averaged across inorganic fertilizer treatments.

FYM (t ha^{-1})	Organic carbon (%)		Organic matter (%)		SWHC (%)
	5 Year$^{\phi}$	6 Year$^{\delta}$	5 Year	6 Year	
0	0.784d	0.869c	1.349c	1.499c	45.8b
5	0.943c (20)	0.991b (14)	1.626b (21)	1.708b (14)	45.4b (-0.9)
10	1.129b (44)	1.007b (15)	1.939a (44)	1.737b (16)	46.4ab (1.3)
15	1.307a (67)	1.125a (29)	2.141a (59)	1.910a (27)	47.4a (3.5)
CV (%)	9.5	7.2	14.6	7.2	2.4

$^{\phi}$ & $^{\delta}$ as in Table 2. Numbers in parenthesis indicate percent change over the control. Means in a column accompanied by different letters are significantly different at P≤ 0.05.

Data in Fig. 1 illustrate the relationship between the change in soil organic matter content with the change in soil total N and available P content and soil water holding capacity. Changes in total soil N and available P were linearly and significantly ($P<0.01$) related to the change in soil organic matter content. Between 40 to 65% of the variability in total soil N and 37% of available P were explained by the variance in OM content. However, the change in exchangeable K explained by the change in OM was small and insignificant ($r^2 = 0.09$ns).

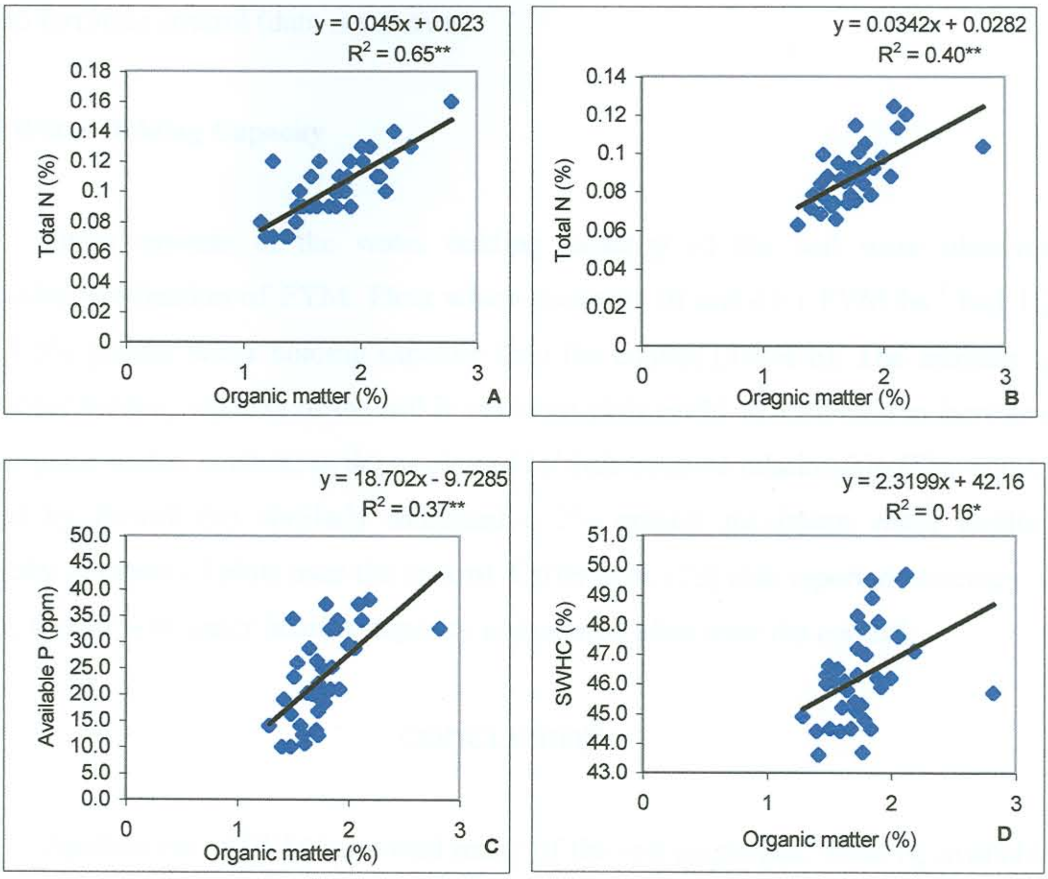

Figure 1. Relationship between soil organic matter and total nitrogen (A & B after 5 and 6 years, respectively), available P (C after 6 years) and soil water holding capacity (D after 6 years) as affected by the combined use of FYM and inorganic fertilizer. n=36.

Nitrogen Balance in Soil

The apparent N balance, computed as the difference between N addition (through fertilizer and FYM) and plant removal (uptake), was positively affected by the main effects of FYM and inorganic fertilizer applications. Cropping without addition of FYM and inorganic fertilizer resulted in a negative N balance amounting to –99 kg ha^{-1} (data not shown). Whereas FYM application at rates of 10 and 15 t ha^{-1}resulted in positive soil N balances amounting to 66 kg ha^{-1} and 141 kg ha^{-1} respectively (Table 3). Averaged across inorganic fertilizer treatments, plots that did not receive FYM had a negative N balance (–81 kg N ha^{-1}). Application of FYM at the lower rate (5 t ha^{-1}) led to a negative N balance (-16 kg ha^{-1}). This was still an improvement of 81% over the plot that received no FYM. Inorganic fertilizer application at 100% of the recommended rate increased soil N balance by 95% over the no fertilizer control (data not shown).

Soil Water Holding Capacity

Improvements in the water holding capacity of the soil were observed following application of FYM. Plots which received 10 and 15 t FYM ha^{-1} had 1.3 and 3.5% greater water holding capacity than the control (Table 6). The increase in the water holding capacity of the soil in manured plots could be attributed to increased soil organic matter content, as demonstrated by their positive relationship (Fig. 1D). A report by Powell (6) similarly indicated a 2% greater maximum water holding capacity in manured plots over the control. Carter et al. (23) also reported increases of 4, 19, and 27% in water holding capacity in manured plots over the control.

CONCLUSION

Application of FYM improved many of the soil properties. Total N, available P, exchangeable K, OC and OM contents of the soil and soil water holding capacity were substantially improved with FYM application compared to soil receiving no FYM. FYM applications also resulted in a positive soil N balance. The build-up of soil nutrients through repeated application of FYM was quite considerable for an area with a hot tropical climate like NE Ethiopia where organic matter decomposition and loss were expected to be high.

The results revealed that the integrated use of FYM with inorganic fertilizers, besides the immediate benefit of increasing crop yields could improve the chemical and physical properties of the soil within a reasonably short period of time. Thus, the possibility of sustaining the productivity of the soil through the addition of inexpensive organic amendments, such as FYM, may be an attractive strategy to the resource poor farmers. Sustainable soil management practices and the maintenance of soil quality are central to agricultural productivity.

The results of this study highlighted the positive effect of continual applications of FYM on soil organic matter content and soil physical conditions to improve the productivity of soils in NE Ethiopia.

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CHAPTER 7

Prepared according to the guidelines of South African Journal of Plant and Soil

The effect of plant population and nitrogen fertilization on the growth, yield and nitrogen use efficiency of sorghum in semi-arid areas in Ethiopia

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An experiment was conducted at two locations in NE Ethiopia to determine the effect of population density on the growth, yield and nitrogen use efficiency of sorghum under different levels of nitrogen fertilizer. Eight treatments, which consisted of factorial combinations of two N fertilizer levels (0 and 80 kg ha^{-1}) and four population densities (166 666, 88 888, 38 095 and 29 629 plants ha^{-1}), were evaluated in a randomised complete block design with three replications. The results indicated that nitrogen fertilizer significantly enhanced leaf area index, dry mass production, crop growth rate, and panicle and grain yields. Nitrogen fertilizer also positively affected yield components. Leaf area index, plant height and crop growth rate (at the early growth stages) as well as leaf, stem, panicle and total dry mass production increased as population density increased. Grain, panicle and stover yields at harvest increased in linear responses to increase in population density. Head and seed number per unit area accounted for most of the variation in grain yield at different plant densities. Stover and grain N concentrations and grain protein concentration increased with a reduction in population density, while N uptake increased with increasing population density. It can be concluded that the conventional planting density (88 888 plant ha^{-1}), being used in NE Ethiopia is not optimal for high grain yield, as increases in grain yield were linear up to a population density of 166 666 plants ha^{-1}. Thus, further study to determine the optimum planting density is recommended.

Keywords: grain yield, nitrogen fertilization, population density, sorghum

Introduction

A prerequisite for growing a successful sorghum crop is to obtain an adequate plant population density (Ismail & Ali, 1996). In areas where crop growth is constrained by limited precipitation optimising planting density is critical as high population densities may deplete most of the available moisture before the crop matures, while low densities may leave moisture unutilised (Reddy & Reddi, 1992).

Plant density strongly affects LAI, and therefore light interception and canopy photosynthesis (Gan *et al.*, 2002). In most crops planting density is a major management tool for increasing the capture of solar radiation. Van Averbeke & Marais (1992) and Cox (1996) indicated that higher LAI values, obtained by increasing planting density, resulted in higher crop growth rates during grain filling, and consequently, in higher grain yields. The influence of plant population density on grain sorghum canopy architecture, light interception and grain yields has been extensively recorded. Several scientists (Blum, 1970; Kudasomannavar, Kulkarni & Patil, 1980; Tetio-Kagho & Gardner, 1988; Amano & Salazar, 1989; Ogunlela & Okoh, 1989; M'Khaitir & Vanderlip, 1992) reported the development of higher leaf area indices and thus better radiation interception and radiation use efficiency with higher population densities. This ultimately results in higher yields under favourable growing conditions. In the absence of constraints from other environmental factors, crop productivity may be limited by the intercepted light (Ma, Dwyer & Costa, 2003).

There is a lack of recent research information on sorghum production practices in NE Ethiopia. Yield-density relationships for sorghum have not been studied in most of the sorghum growing areas. In areas where sorghum growth and yield is often constrained by limited and erratic rainfall, production strategies to use stored soil water and limited seasonal precipitation efficiently include, amongst others, the choice of plant population density. The objective of this study was, therefore, to determine the influence of plant population density on the growth, yield and nitrogen use efficiency of sorghum at different levels of nitrogen fertilization under the semi-arid conditions of NE Ethiopia.

Materials and Methods

Study sites

The experiment was conducted at Sirinka (11^0 45’ N latitude, 39^0 36’ E longitude; 1890 m. a. s. l. altitude) and Kobo (12^0 9’ N latitude, 39^0 38’ E longitude; 1470 m. a. s. l. altitude) research sites in NE Ethiopia under rainfed conditions during the 2002 growing season. The soil type at both locations was a Eutric vertisol. Details of the physicochemical characteristics of the soils are presented in Appendix Table 7.1. Climatic conditions in the growing season, at both locations, are presented in Table 1. Rainfall received in the growing season was similar to the long term average at Sirinka and above the long term average at Kobo. The relatively high total seasonal rainfall can be misleading, as great variability in distribution often exists. For instance, in this particular season about 78% and 76% of the rainfall at Sirinka and Kobo, respectively, was concentrated in July and August. The growing season at both experimental sites, and at Kobo in particular, is characterized by high temperatures, the maximum being above 25^0 C for most of the time (Table 1).

Table 1 Monthly precipitation and air temperatures during the growing season at the two locations

	Sirinka				Kobo			
	Precipitaion (mm)		Temperature (^{0}C)		Precipitaion (mm)		Temperature (^{0}C)	
Month	2002	Long term*	Max.$^{\varphi}$	Min.$^{\Re}$	2002	Long term*	Max.$^{\varphi}$	Min.$^{\Re}$
July	229.5	192.1	30.5	17.1	99.8	108.2	34.0	19.6
August	280.6	266.3	27.8	15.7	296.0	200.4	30.9	17.6
September	134.0	95.0	26.6	14.7	112.4	95.2	29.9	15.7
October	12.0	57.7	26.6	12.4	16.0	43.7	30.5	13.0
November	0.0	21.7	25.5	11.6	0	11.9	29.5	12.0
Total	656.1	632.8			524.2	459.4		

* Long term average rainfall (1980-2002 for Sirinka and 1973-2002 for Kobo). $^{\varphi}$Maximum. $^{\Re}$Minimum.

Experimental design and procedure

The experiment at both sites was conducted in a completely randomized block design with three replications. Treatments consisted of factorial combinations of two N fertilizer levels (0 and 80 kg ha^{-1}) and four plant population densities (166 666, 88 888, 38 095 and 29 629 plants ha^{-1}). Sorghum was planted on flatbeds at Sirinka and in tied-ridges at Kobo. Urea was used as the N source. All plots received P as triple super phosphate at the rate of 20 kg P ha^{-1}.

All the P, and half of the N, were applied in a band at planting. The remaining N was side dressed at the six to eight leaf stage. In all cases fertilizers were incorporated into the soil. The newly released sorghum cultivar ICSV111 was hand drilled in 75 cm rows and thinned to the appropriate population densities. Gross plot size was 6 m wide by 5 m long. Hand weeding and insect control were conducted on an as needed basis. Prior to planting, composite surface (0-15 cm) and subsurface (15-30 cm) soil samples from nine points across the experimental field were collected and analyzed for soil physicochemical properties following the procedure outlined by Page, Miller & Keeney (1982).

Panicle length and seed weight and seed number panicle^{-1} were determined on four tagged plants in each plot. Three plants, representative of the plot, were harvested at 42, 63, 84, 105 and 115 DAE at Sirinka and 48, 69, 90 and 101 DAE at Kobo. These were separated into leaf, stalk (plus leaf sheath) and panicle fractions including all senescent leaf material. The plant components were dried in a forced-air oven at 80^0 C until constant weight was achieved. The length and breadth of green leaf was measured from which leaf area was calculated as the product of leaf length, maximum leaf breadth, and a shape factor of 0.75 (Oosterom, Carberry & Muchow, 2001).

Mean crop growth rate (CGR) and leaf area indices were calculated according to Hunt (1990). Three rows, after discarding border rows, were hand harvested to determine stover, total aboveground biomass and grain yield at maturity. Stover yield included the leaf, stalk and chaff component of the plant. Total aboveground biomass yield was determined as the sum of stover and grain yields. Panicles were air-dried, hand threshed and grain yield determined at 12.5% moisture content. Grain and stover samples were ground separately to pass through a 1 mm sieve. N content in plant samples was determined by the micro-Kjeldahl method (Page *et al*., 1982). N uptake in the grain and stover was calculated by multiplying the concentration with grain and stover yields respectively. Whole plant N uptake was calculated by adding the uptake in grain and stover. Grain protein concentration was calculated as %N in the grain x 6.25 (Kudasomannavar *et al*., 1980) and grain protein yield as (grain protein concentration x grain yield)/100 (Ogunlela & Okoh, 1989). Nitrogen harvest index (NHI) was calculated as the ratio of grain N uptake to whole plant N uptake.

Analysis of variance for the measured parameters was performed using the MSTATC statistical program (MSTATC, 1989). Whenever treatment differences were found to be significant, based on results of the *F*-test, critical differences were calculated at the 5% level of probability using Duncan's Multiple Range Test.

Results and Discussion

Leaf area index

Increasing population density resulted in an increase in LAI at both sites (Figure 1A & B). The increased LAI at higher densities was because of the presence of more plants per unit area. This result agrees with the results of Amano & Salazar (1989) who reported increased LAIs with increasing population densities in sorghum. An increase in LAI with increasing population density is associated with effective light interception (Tollenaar, Aguilera & Nissanka, 1997) and may thus allow high plant densities to attain greater photosynthetic output per unit area and greater biomass production (Sangoi *et al*., 2002). Williams *et al*. (1968), as cited by Tetio-Kagho & Gardner (1988), reported a direct relationship between LAI and light interception and resulting photosynthesis.

The main effect of N fertility was significant for LAI at anthesis (63 DAE at Sirinka and 69 DAE Kobo). Nitrogen fertilization increased LAI by up to 27% at Sirinka and by 16% at Kobo (data not shown). The increase in LAI with N supply could be due to the effect of N on the rate of leaf expansion (Muchow, 1988) and reduced rate of leaf senescence (Van Keulen, Goudriaan & Seligman, 1989). The effect of the nitrogen x population density interaction effects on LAI was not large. Significant differences were observed only at 42 DAE at Sirinka and 69 DAE at Kobo where population densities of 166 666 and 88 888 plants ha^{-1} under both fertilized and unfertilized conditions provided higher LAIs (data not shown).

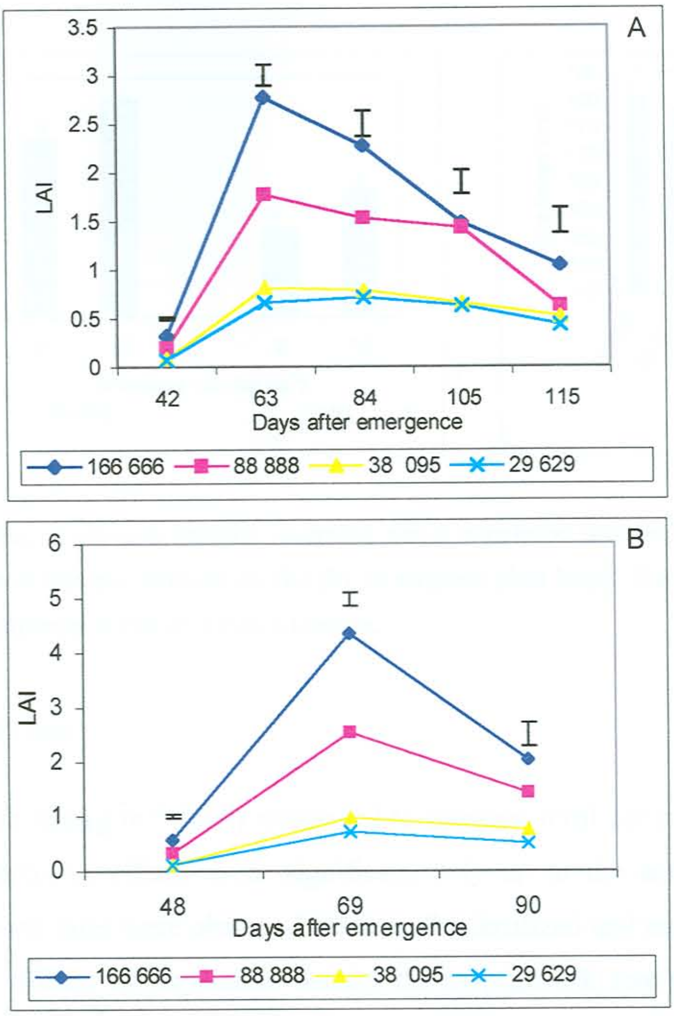

Figure 1 Effect of population density (averaged across nitrogen fertilizer levels) on leaf area index (LAI) at Sirinka (A) and Kobo (B). Vertical lines on each period of measurement indicate LSD values at $P \leq 0.05$.

Plant height

Nitrogen fertilization resulted in somewhat taller plants at both sites, but differences were not statistically significant (Figure 2A). Significant differences in plant height were observed only between the main effects of population density at both sites (Figure 2B), probably as a result of competition for light. The 166 666 population resulted in taller plants than the two lower plant densities at both sites. Although plants at the higher density were approximately 10% taller no clear effect on stem lodging was observed. Similar results were reported in sorghum by Blum (1970) and Martin & Kelleher (1984).

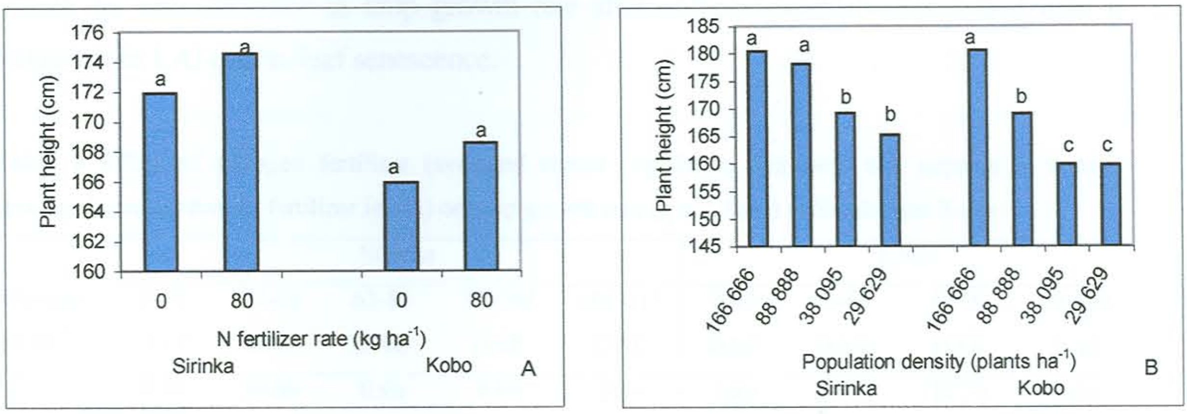

Figure 2 Effect of nitrogen fertilizer (averaged across population densities) (A) and population density (averaged across nitrogen fertilizer levels) (B) on sorghum plant height. Bars with the same letter are not significantly different at $P \leq 0.05$ for each location.

Crop growth rate

Crop growth rate (g m^{-2} day^{-1}) responded to nitrogen fertilizer treatments only at Sirinka. Nitrogen fertilizer effects were significant only up to the anthesis stage, after which similar growth rates were observed between the fertilized and unfertilized plots (Table 2). Significant effects of population density on crop growth rate were observed up to the anthesis stage at Sirinka. However, at Kobo it extended up to 90 DAE. Crop growth rate increased with the increase in population density. The highest density (166 666 plants ha^{-1}) had a significantly higher crop growth rate (Table 2). Differences in crop growth rate between densities in the early growth stages could be attributed to larger LAI and its influence on the amount of radiation intercepted. This is indicated by the close and positive relationship between crop growth rate and LAI (r^2 between 0.97* and 0.99** at Sirinka and r^2 between 0.96* and 0.99** at Kobo). Leaves in the high density treatments were narrow and less droopy and the plants themselves were taller. It has been reported that such features of the canopy are more favourable to light penetration per unit leaf area (Fischer & Wilson, 1975). Similarly, Van Averbeke & Marais (1992) reported that a higher LAI, obtained by increasing the planting density, resulted in a higher CGR in maize. Crop growth rates for all densities increased to a maximum around anthesis (42-63

DAE at Sirinka and 48-69 DAE at Kobo) and then declined during the grain filling period (Table 2). The reduction in crop growth rate after anthesis could be associated with a reduction in LAI due to leaf senescence.

Table 2 Effect of nitrogen fertilizer (averaged across population densities) and population density (averaged across nitrogen fertilizer levels) on crop growth rate (g m^{-2} day^{-1}) at Sirinka and Kobo

	Sirinka					Kobo			
Nitrogen (kg ha^{-1})	0-42 DAE	42-63 DAE	63-84 DAE	84-105 DAE	105-115 DAE	0-48 DAE	48-69 DAE	69-90 DAE	90-101 DAE
0	1.9b	30.6b	0.9a	8.9a	0.4a	3.8a	21.4a	11.3a	6.9a
80	2.5a	37.0a	4.0a	6.8a	4.6a	4.4a	22.6a	12.5a	18.9a
Population density (plants ha^{-1})									
166 666	4.0a	63.4a	-2.6a	10.01a	10.8a	8.3a	39.7a	20.1a	7.7a
88 888	2.7b	36.4b	5.3a	9.16a	-3.5a	4.8b	25.1b	14.1ab	14.5a
38 095	1.1c	20.8c	4.0a	5.81a	3.5a	1.9c	13.2c	6.4b	20.6a
29 629	1.1c	14.5c	3.3a	6.33a	-1.0a	1.4c	10.0c	7.1b	8.9a

DAE = days after emergence. Means within columns for each comparison followed by the same letters are not significantly different at $P \leq 0.05$.

Leaf, stem, panicle and total dry mass production

Leaf, stem, panicle and total dry mass production responded to nitrogen fertilizer and population density treatments. However, the responses of each parameter differed for each period of measurement and for each location. Leaf dry mass differed consistently between the main effects of nitrogen fertilizer (Table 3) and population density (Figure 3A & D), except the nitrogen effect at 105 DAE at Sirinka and 48 DAE at Kobo. Nitrogen application increased leaf dry mass by 16 to 25% at Sirinka and 23 to 30% at Kobo (Table 3). Leaf dry mass also increased with increasing population density at both locations (Figure 3A & D). The only significant differences observed between the interaction effects on leaf dry mass were at 42 DAE at Sirinka, where the highest population density, in combination with 80 kg N ha^{-1}, gave the highest leaf dry mass (Table 4).

The main effects of nitrogen fertilizer on stem dry mass were significant throughout the growth stage at Sirinka and only at 48 DAE at Kobo (Table 3). Nitrogen fertilization increased stem dry mass by up to 20 to 36% at Sirinka and 29% at Kobo. Stem dry mass increased significantly following the increase in population density (Figure 3 B & E). The nitrogen x population density interaction effects on stem dry mass were significant only at 42 DAE at Sirinka and at 48 and 90 DAE at Kobo (Table 4). Stem dry mass tended to increase with nitrogen fertilization in all densities. Statistically significant differences, however, were observed between the unfertilized and fertilized plots of the highest density (166 666 plants ha^{-1}) (Table 4).

Leaf and stem dry mass accumulation increased linearly with time until anthesis and decreased markedly during grain filling (Figure 3). Part of the loss in stem and leaf dry mass after anthesis represents mobilization of labile food reserves to the seeds (Papakosta & Gagianas, 1991).

Nitrogen fertilizer increased panicle dry mass per unit area at all measurement periods at Sirinka, but only at 101 DAE at Kobo (Table 3). Panicle dry mass was increased with nitrogen fertilization by up to 49% at Sirinka and 28% at Kobo. Panicle dry mass per unit area increased with increasing population density (Figure 3 C & F). The nitrogen x population density interaction effect was very infrequent with significant effects only being observed at 115 DAE at Sirinka (Table 4). Panicle dry mass tended to increase with nitrogen fertilization, however, statistically significant differences were observed between the unfertilized and fertilized plots of the highest density (166 666 plants ha^{-1}).

Table 3 Effect of nitrogen fertilizer (averaged across population densities) on leaf, stem, panicle and total dry mass (g m^{-2}) in sorghum

	Nitrogen	Sirinka					Kobo			
	(kg ha^{-1})	42 DAE	63 DAE	84 DAE	105 DAE	115 DAE	48 DAE	69 DAE	90 DAE	101 DAE
Leaf	0	46.1b	118.5b	78.9b	82.2a	80.0b	96.7a	118.2b	102.5b	92.6b
	80	56.8a	137.9a	98.5a	94.6a	97.0a	104.8a	144.9a	133.2a	114.3a
Stem	0	35.1b	304.8b	318.8b	281.3b	285.5a	83.5b	400.2a	357.0a	294.5a
	80	47.6a	388.4a	403.7a	338.3a	323.5a	108.0a	416.9a	340.7a	328.9a
Panicle	0	-	116.7b	161.9b	382.4b	383.7b	-	113.1a	410.7a	559.9b
	80	-	133.2a	242.0a	454.6a	512.7a	-	126.1a	477.6a	716.5a
Total	0	81.3b	540.2b	559.7b	745.9b	749.3b	180.2a	631.6a	870.3a	947.0b
	80	104.5a	659.5a	744.3a	887.6a	933.3a	212.9a	687.9a	951.5a	1159.8a

DAE = Days after emergence. Means within columns followed by the same letter for each parameter are not significantly different at $P \leq 0.05$.

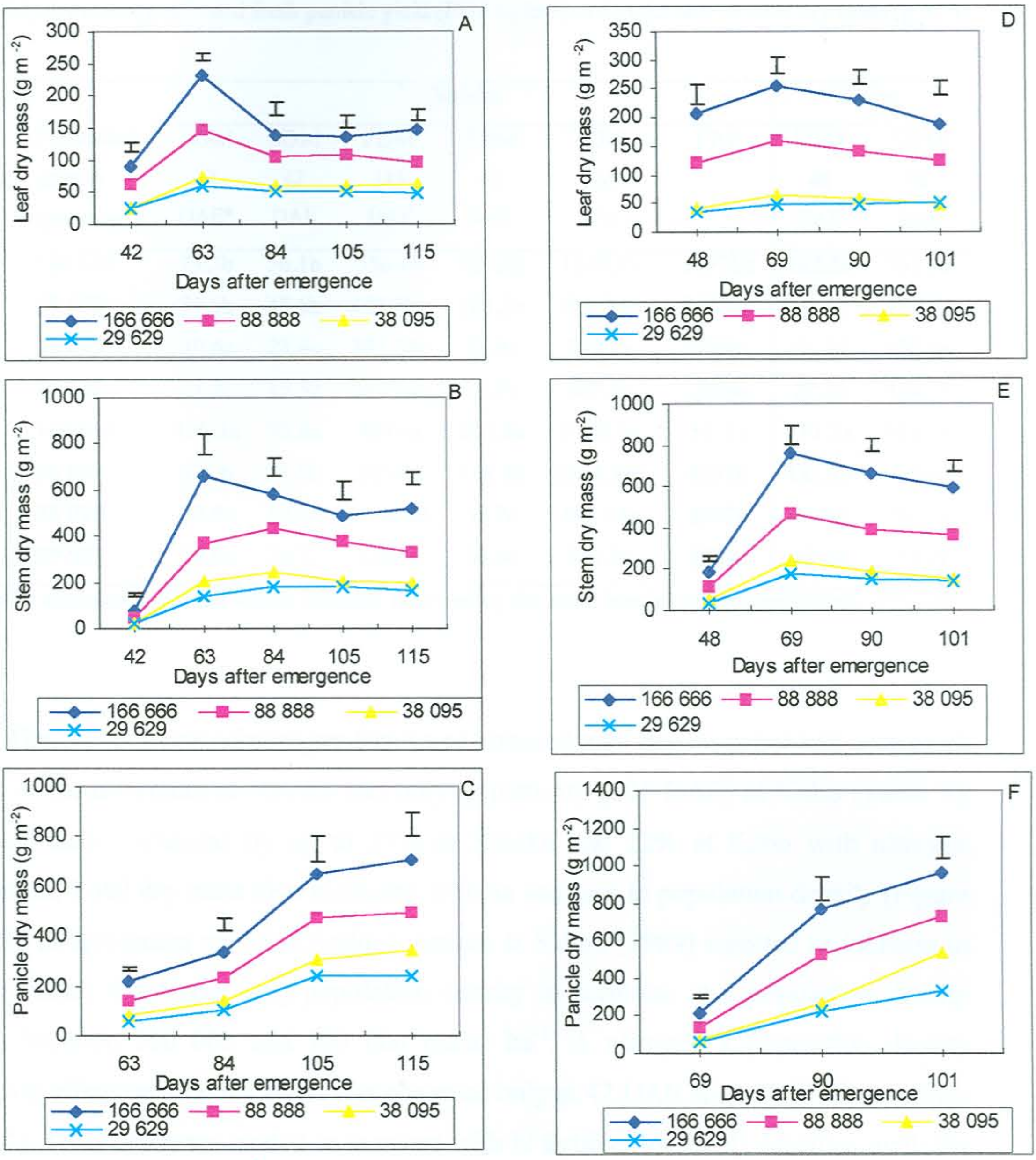

Figure 3 Effect of population density (averaged across nitrogen fertilizer levels) on leaf, stem and panicle dry mass at Sirinka (A-C) and Kobo (D-F). Vertical lines on each period of measurement indicate LSD values at P ≤0.05.

Table 4 Effect of nitrogen fertilizer x population density on leaf (LDM), stem (SDM), panicle (PDM) and total (TDM) dry mass (g m^{-2}) and fresh panicle yield (FPY kg ha^{-1}) at Sirinka and on stem dry mass (g m^{-2}) at Kobo

		Sirinka						Kobo	
Nitrogen (kg ha^{-1})	Population density (plants ha^{-1})	LDM 42 DAE*	SDM 42 DAE	PDM 115 DAE	TDM 42 DAE	TDM 115 DAE	FPY	SDM 48 DAE	SDM 90 DAE
0	166 666	73.3b	56.1b	556.1b	129.4b	1168.3b	3437bc	162.2b	763.3a
	88 888	59.5b	45.6b	428.1bc	105.2b	826.7cd	3437bc	90.4c	339.5d
	38 095	30.6c	23.4c	283.8de	53.9c	537.2e	2969c	54.3d	170.6e
	29 629	21.2c	15.5c	267.1de	36.7c	465.2e	2888c	27.2d	154.7e
80	166 666	108.3a	95.6a	865.6a	203.9a	1593.9a	5511a	217.2a	561.1b
	88 888	67.0b	51.9b	565.6b	118.8b	1024.3bc	4237b	132.1b	440.6c
	38 095	22.4c	16.4c	399.0cd	38.7c	663.7de	2993c	44.6d	207.1e
	29 629	29.8c	26.7c	220.7e	56.6c	451.3e	2933c	38.4d	154.2e

* Days after emergence. Means within columns followed by the same letters are not significantly different at $P \leq 0.05$.

The main effects of nitrogen fertilizer increased total dry mass per unit area at all periods of measurement at Sirinka and only at maturity (101 DAE) at Kobo (Table 3). Total dry mass increased by up to 33% at Sirinka and 22% at Kobo with nitrogen fertilization. Total dry mass also increased with an increase in population density (Figure 4A & B). In agreement with this finding, Amano & Salaza (1989) reported an increase in total dry mass with increasing population density in sorghum at a population density ranging between 100 000 and 300 000 plants ha^{-1}. A nitrogen x population density interaction effect on total dry mass was observed only at 42 DAE and 115 DAE at Sirinka (Table 4). Total dry mass tended to increase with N fertilization in all densities, with the exception of the lowest density (29 629 plants ha^{-1}). Statistically significant differences, however, were observed only between the fertilized and unfertilized plots of the highest population density (166 666 plants ha^{-1}).

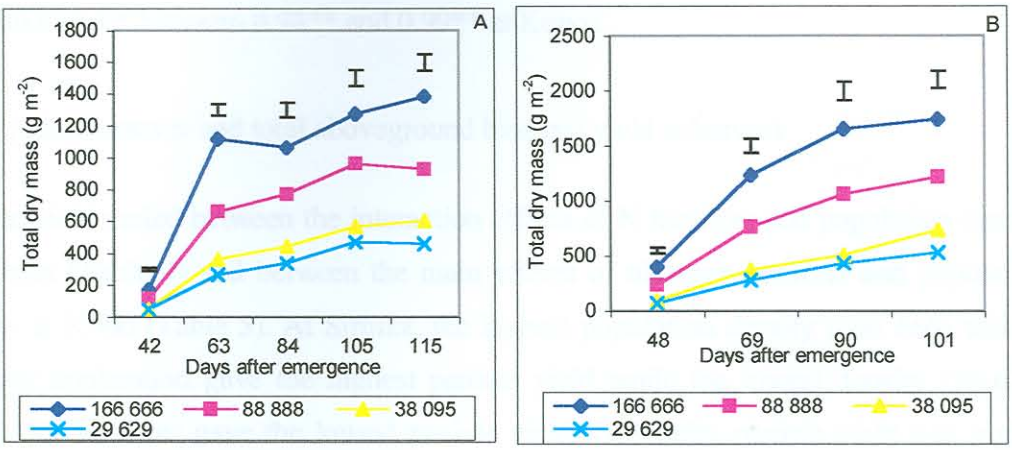

Figure 4 Effect of population density (averaged across nitrogen fertilizer levels) on total dry mass at Sirinka (A) and Kobo (B). Vertical lines on each period of measurement indicate LSD values at $P \leq 0.05$.

The higher leaf, stem and total dry mass with N fertilization could be due to the positive effect of N on canopy development as a result of alterations in leaf area development. Plants receiving N fertilization might have larger leaf area index which can have an effect on radiation interception and thus on photosynthetic activity of the canopy (Lugg & Sinclair, 1981 as cited by Muchow, 1988). Muchow & Davis (1988) also ascribed increased dry mass accumulation in sorghum and maize in response to N fertilization to higher radiation interception and radiation use efficiency.

Several researchers have reported increases in leaf, stem, panicle and total dry mass production with increasing plant density. Saiieb, Singh & Singh (1997) reported increased leaf, stem and total dry mass for sorghum with increasing density (80 000 to 120 000 plants ha^{-1}). Martin & Kelleher (1984) also reported increased leaf, stem and total dry mass production in sorghum as population density was increased from 80 000 to 160 000 plants ha^{-1}. Muchow & Davis (1988) reported that dry mass production was dependent on the interception of incident radiation by the crop canopy and the efficiency with which it is used to produce dry mass. Thus, the higher LAI of the highest plant density, indicative of much greater absorption of photosynthetically active radiation could be the reason for the higher dry mass (leaf, stem, panicle and total) production in the highest population density. This justification can be supported by the highly positive relationship between, for instance, total dry mass and LAI (r^2 between 0.89** and 0.99** at Sirinka and r^2 between 0.98** and 0.99** at Kobo).

Fresh panicle, stover and total aboveground biomass yield at harvest

Panicle yield varied between the interaction effects of N fertilizer and population density at Sirinka (Table 4) and between the main effects of nitrogen fertilizer and population density at Kobo (Table 5). At Sirinka, the highest population density (166 666) with N fertilizer application gave the highest panicle yield while the lowest density (29 629) without N fertilizer gave the lowest panicle yield. Generally, panicle yield was higher with N fertilizer application. At Kobo, nitrogen fertilization increased panicle yield by 28%. Averaged across nitrogen fertilizer treatments, panicle yield increased in linear response to increasing population density. Stover and total aboveground biomass yields increased by more than 30% with nitrogen fertilization at Sirinka (Table 5). At both sites, stover and total aboveground biomass yields increased linearly with increasing population density (Table 5).

Table 5 Effect of nitrogen fertilizer and population density on fresh panicle yield (FPY kg ha^{-1}), stover yield (SY kg ha^{-1}) and total aboveground biomass yield (TBY kg ha^{-1}) at Sirinka and Kobo

Nitrogen	Sirinka		Kobo		
(kg ha^{-1})	SY	TBY	FPY	SY	TBY
0	4127b	6816b	2993b	4104a	7722a
80	5444a	8910a	3822a	4052a	7999a
Population density (plants ha^{-1})					
166 666	5983a	9800a	4637a	5408a	9812a
88 888	5172ab	8449a	3941b	4498b	8606a
38 095	4307bc	7020b	2682c	3526c	6894b
29 629	3680c	6184b	2370c	2880c	6128b
Contrasts[§]					
Linear	**	**	**	**	**
Quadratic	NS	NS	NS	NS	NS

Means within columns for each comparison followed by the same letters are not significantly different at P<0.05. [§]Contrasts are for population density. ** Significant at $P\leq0.01$. NS = non-significant difference.

Grain yield and yield components

Grain yield responded to the interaction effects of nitrogen fertilizer and population density at Sirinka (Table 6). Grain yield tended to increase in all population densities with nitrogen fertilization. However significant differences were observed only between the fertilized and unfertilised plots of the two highest densities (166 666 and 88 888 plants ha^{-1}). Under no fertilized condition grain yield did not differ between the population density treatments, but with the application of 80 kg N ha^{-1} the two highest population densities gave significantly higher grain yields. At Kobo, grain yield responded only to the main effect of population density (Table 6). Averaged over nitrogen fertilizer treatments, grain yield increased in linear response to increasing population density. Grain yield with the highest density (166 666 plants ha^{-1}) was greater by 35% over the lowest population density (29 629 plants ha^{-1}) and by 7% over the conventionally recommended population density (88 888 plants ha^{-1}).

Table 6 Effect of nitrogen fertilizer and population density on sorghum grain yield (kg ha^{-1}) at Sirinka and Kobo

	Nitrogen	Population density (plants ha^{-1})				
Location	(kg ha^{-1})	166 666	88 888	38 095	29 629	Mean
Sirinka	0	2967c	2735c	2690c	2366c	2689B
	80	4667a	3818b	2737c	2642c	3466A
	Mean	3817A	3277AB	2714BC	2504C	
Kobo	0	4493a	3479a	3210a	3288a	3617A
	80	4315a	4739a	3526a	3209a	3947A
	Mean	4404A	4109AB	3368BC	3248C	
	Contrasts§	Sirinka	Kobo			
	Linear	**	**			
	Quadratic	NS	NS			

Means within columns and rows followed by the same lowercase letters; means within rows followed by the same uppercase letters; and means within columns followed by the same uppercase letters are not significantly different at $P \leq 0.05$. § Contrasts are for population density. ** Significant at $P<0.01$. NS = non-significant difference.

Grain yield, averaged across N fertilizer treatments, was negatively correlated to yield components (Table 7). However, it was positively correlated to head and seed number per unit area (Table 7). This correlation emphasizes that under high population densities, the yield components will be reduced possibly owing to competition for resources between plants. However, the higher number of heads per hectare compensated for the reduction in grain yield per plant due to reduction in yield components. The higher head and seed number per unit area were the major yield components contributing (r^2 = 0.97** and 0.99** at Sirinka and 0.92* and 0.95* at Kobo) to the yield increase under high population densities.

Variation in grain yields due to population density, were associated with variation in LAI (r^2 between 0.91** and 0.99** at Sirinka and between 0.92* and 0.97* at Kobo), which would affect the photosynthetic activity of the canopy (Cox, 1996). Similarly, variation in grain yield due to population density was related to variation in total dry mass production (r^2 between 97** and 0.99** at Sirinka and r^2 between 0.94* and 0.95* at Kobo) and crop growth rate (r^2 between 0.89* and 0.97** at Sirinka and r^2 between 0.94* and 0.95* at Kobo). Fischer & Wilson (1975) reported increased yields from high plant population densities in sorghum despite the reduced yield per individual plant. M'Khaitir & Vanderlip (1992) also observed increased sorghum grain yield following an increase in planting densities ranging between 15 000 to 135 000 plants ha^{-1}. Amano & Salazar (1989) reported yield increases of 9 and 21% as sorghum plant densities were increased from 100 000 to 200 000 and 300 000 plants ha^{-1}, respectively. Grimes & Musick (1960), as cited by Amano & Salazar (1989), indicated that sorghum is tolerant to varying plant population densities due to its ability to tiller and produce larger heads at low plant density and smaller heads at high density.

Table 7 Simple correlation coefficients between grain yield and yield components (averaged across N fertilizer treatments, n=4)

Yield components	Sirinka	Kobo
Panicle length (cm)	r = -0.99**	r = -0.98**
Panicle weight plant^{-1}	r = -0.99**	r = -0.98**
Seed weight panicle^{-1}	r = -0.99**	r = -0.97*
Seed number panicle^{-1}	r = -0.99**	r = -0.93NS
1000-seed weight (g)	r = -0.96*	r = -0.88NS
Head number m^{-2}	r = 0.98**	r = 0.96*
Seed number m^{-2}	r = 0.99**	r = 0.97*

*, ** denote significance at 0.05 and 0.01 probability level. NS = non-significant difference.

Yield components such as panicle length (PL), panicle weight plant^{-1} (PWP), seed weight panicle^{-1} (SWP), seed number panicle^{-1} (SNP) and 1000-seed weight (TKW) were affected by the main effects of nitrogen fertilizer and population density (Tables 8 and 9). Averaged over population density treatments, PL, PWP, SWP and SNP responded to nitrogen fertilization at both locations, except for PL and PWP at Kobo. TKW responded negatively to nitrogen fertilization at Sirinka (Table 8) and did not respond at Kobo (Table 9). Similar results were reported by Ogunlela & Okoh (1989).

Averaged over nitrogen fertilizer treatments, PL, PWP, SNP and TKW increased in linear response to decreasing population densities, while SWP had a quadratic response. The negative relationship between yield components and population density could be due to reduced competition for resources under low densities and thus better growth of individual plants. Increasing population density to 166 666 plants ha^{-1} reduced PL by 21 and 7%, PWP by 50 and 23%, SWP by 50 and 23% and SNP by 39 and 22% compared to the lowest (29 629 plants ha^{-1}) and conventional (88 888 plants ha^{-1}) densities at Sirinka (Table 8). The corresponding values at Kobo were 16 and 5% for PL, 46 and 25% for PWP, 47 and 25% for SWP and 35 and 19% for SNP (Table 9). These observations are in accordance with the results of several workers (Ogunlela & Okoh, 1989; M'Khaitir & Vanderlip, 1992; Berenguer & Faci, 2001). Goldsworthy & Tayler (1970) as cited by Ogunlela & Okoh (1989) indicated that differences in seed number might be due to variations in the number of flower initials formed, or to variations in the number which survive to produce grain.

The observed increase in yield components, with a decrease in population density, indicates the capacity of sorghum to adjust yield components through compensatory growth. Nevertheless, the yield compensatory mechanisms observed at lower densities were not capable of equilibrating grain yield to that obtained from the highest density. This is due to the fact that the significantly lower number of panicles per unit area offset yield compensation advantages in the lower population densities. This indicates that although considerable reductions occurred in yield components in densely populated crops, it is the number of heads that actually contribute to higher yield in closely planted sorghum (Kudasomannavar *et al*., 1980). This observation leads to the conclusion that data on growth and yield per plant may not be a satisfactory parameter for describing and `understanding the response of sorghum to population density.

Table 8 Effect of nitrogen fertilizer (averaged across population densities) and population density (averaged across nitrogen fertilizer levels) on yield components of sorghum at Sirinka

Nitrogen (kg ha^{-1})	Panicle length (cm)	Panicle weight (g panicle^{-1})	Seed weight (g panicle^{-1})	Seed number panicle^{-1}	1000-seed weight (g)	Head number m^{-2}	Seed number m^{-2}
0	24.7b	63.3b	51.6b	1966b	28.8a	7a	13860b
80	26.4a	78.1a	64.0a	2243a	26.7b	7a	15904a
Population density (plants ha^{-1})							
166 666	22.4c	46.5b	38.1b	1530c	25.1b	13a	25496a
88 888	24.2b	60.2b	49.2b	1953b	25.9b	8b	17360b
38 095	27.4a	82.5a	67.1a	2420a	29.3a	4c	9221c
29 629	28.4a	93.5a	76.7a	2515a	30.7a	3c	7451c
Contrasts§							
Linear	**	**	**	**	**	**	**
Quadratic	NS	NS	*	NS	NS	**	**

Means within columns for each comparison followed by the same letters are not significantly different at P≤0.05. § Contrasts are for population density. *, ** Significant at the 0.05 and 0.01 probability level, respectively. NS denotes non-significant difference.

Table 9 Effect of nitrogen fertilizer (averaged across population densities) and population density (averaged across nitrogen fertilizer levels) on yield components of sorghum at Kobo

Nitrogen (kg ha^{-1})	Panicle length (cm)	Panicle weight (g panicle^{-1})	Seed weight (g panicle^{-1})	Seed number panicle^{-1}	1000-seed weight (g)	Head number m^{-2}	Seed number m^{-2}
0	26.7a	81.1a	68.9b	2632b	27.8a	6b	19344a
80	26.9a	91.8a	82.9a	3049a	25.8a	7a	22144a
Population density (plants ha^{-1})							
166 666	24.5d	58.4b	48.6c	2233c	23.2c	12a	37212a
88 888	25.7c	78.0b	64.8b	2733b	25.8bc	8b	24294b
38 095	27.9b	101.5a	98.7a	2978ab	30.4a	4c	11344c
29 629	29.1a	107.9a	91.6a	3417a	27.7ab	4c	10124c
Contrasts[§]							
Linear	**	**	**	**	**	**	**
Quadratic	NS	NS	**	NS	NS	**	**

Means within columns for each comparison followed by the same letters are not significantly different at P≤0.05. § Contrasts are for population density. *, ** Significant at the 0.05 and 0.01 probability level, respectively. NS denotes non-significant difference.

Nitrogen uptake and concentration

Nitrogen fertilization increased stover N uptake by 51%, grain N uptake by 36%, total N uptake by 41% and stover N concentration by 17% at Sirinka (Table 10). Grain N concentration did not, however, respond to N fertilizer treatments at Sirinka. At Kobo, N fertilization markedly increased stover N uptake by 35%, total aboveground biomass N uptake by 14% and stover N concentration by 41% (Table 10). Grain N uptake and concentration did not, however, respond to N fertilizer treatments at Kobo. Significant differences in N uptake (stover, grain and total plant) between population density treatments were not observed at Sirinka. However, at Kobo population density significantly affected stover, grain and total aboveground biomass N uptake where these parameters increased with an increase in population density (Table 10). The higher N uptake at the higher densities could be due to a greater number of plants per unit area resulting in higher stover, grain and total dry matter production. This observation is in accordance with the results of Kudasomannavar *et al*. (1980).

Stover and grain N concentrations at Sirinka differed between population density treatments where the values of both parameters increased with a decrease in population density (Table 10). The lower stover and grain N concentrations in the higher densities could be due to greater competition between plants for soil N. Similar results were reported by Rosolem *et al.* (1993) who found reduced stover and grain N concentrations as sorghum population density increased. At Kobo, grain N concentration did not respond to population density while stover N concentration did not follow any trend (Table 10).

Nitrogen harvest index and nitrogen use efficiency

The effects of both nitrogen fertilizer and population density treatments on nitrogen harvest index (the proportion of absorbed N that is distributed to grain) were not great, but tended to increase with an increase in population density at Sirinka (Table 10).

Nitrogen use efficiency (utilization of absorbed N for grain production) was significantly affected by the main effects of nitrogen fertilizer and population density treatments only at Sirinka (Table 10). Nitrogen use efficiency was higher in plants which did not receive nitrogen fertilization. Nitrogen use efficiency increased following the increase in population density where about 53 kg grain by the highest density and 39 kg grain by the lowest density were produced for each kg of N taken up.

Grain protein concentration and protein yield

Grain protein concentration did not respond to nitrogen fertilizer treatment at Sirinka and to neither nitrogen nor population density treatments at Kobo (Table 10). However, at Sirinka grain protein concentration differed between population density treatments where grain protein concentration tend to increase as population density decreased (Table 10). Similar results were reported by Kudasomannavar *et al.* (1980) and Ogunlela & Okoh (1989). Grain protein yield responded to nitrogen fertilizer at Sirinka and to population density at Kobo (Table 10). Grain protein yield increased by 37% with nitrogen fertilization at Sirinka, while at Kobo it was found to respond to increasing population density but not to nitrogen fertilization. Ogunlela & Okoh (1989) also reported 52% increase in sorghum grain protein yield with the application of 60 kg N ha^{-1}.

Table 10 Effect of nitrogen fertilizer (averaged across population densities) and population density (averaged across nitrogen fertilizer levels) on nitrogen use efficiency attributes at Sirinka and Kobo

Location	Nitrogen (kg ha^{-1})	SNU (kg ha^{-1})	GNU (kg ha^{-1})	TNU (kg ha^{-1})	SNC (%)	GNC (%)	NHI	NUE (kg kg^{-1})	GPC (%)	GPY (kg ha^{-1})
Sirinka	0	19b	41b	60b	0.47b	1.53a	0.68a	46a	9.6a	257b
	80	29a	56a	85a	0.55a	1.63a	0.66a	41b	10.2a	351a
	Population density (plants ha^{-1})									
	166 666	22a	54a	76a	0.36c	1.38c	0.71a	53a	8.6c	337a
	88 888	25a	50a	74a	0.48b	1.49bc	0.66b	45b	9.3bc	310a
	38 095	25a	50a	75a	0.58a	1.83a	0.67b	36c	11.5a	310a
	29 629	24a	42a	65a	0.64a	1.64b	0.64b	39c	10.3b	259a
Kobo	0	12.0b	72.0a	84.0b	0.29b	2.01a	0.86a	43.0a	12.5a	450.1a
	80	16.2a	79.2a	95.4a	0.41a	2.00a	0.83a	41.9a	12.5a	495.0a
	Population density (plants ha^{-1})									
	166 666	18.8a	88.8a	107.6a	0.35ab	2.03a	0.83a	41.2a	12.7a	555.2a
	88 888	12.4b	83.47a	95.9a	0.28b	2.03a	0.87a	43.0a	12.7a	521.7a
	38 095	15.4ab	65.0b	80.4b	0.44a	1.94a	0.82a	42.3a	12.1a	406.4b
	29 629	9.8b	65.1b	74.9b	0.35ab	2.02a	0.87a	43.4a	12.6a	406.9b

SNU, GNU, TNU, SNC, GNC, NHI, GPC, GPY, and NUE represent stover N uptake, grain N uptake, total plant N uptake, stover N concentration, grain N concentration, N harvest index, grain nitrogen use efficiency, grain protein concentration and grain protein yield. Means within columns for each comparison followed by the same letters are not significantly different at $P \leq 0.05$.

Conclusion

Increasing plant density resulted in increased growth and yield of sorghum on a per unit area basis. Grain, stover and total aboveground biomass yields were generally greater for the higher plant densities. However, plant growth, yield and yield components on individual plant basis increased with decreasing density. Grain yield per plant at high population densities was lower owing to lower seed number and lower seed weight per panicle, smaller head size and lower 1000-seed weight. This indicates that important yield compensation processes have occurred as the population density declined. The observed yield compensation mechanisms could not, however, equilibrate the final yield as the yield compensation advantages were offset by the lower head and seed number per square meter.

Results indicated that differential CGR, TDM production and LAI per unit area were the major growth dynamic mechanisms responsible for yield differences across densities. Results also indicated that an increase in population density should be accompanied by the elimination of nitrogen stress, which slowed down leaf area development, dry mass production and crop growth rate, especially at Sirinka. Generally, under the present climatic conditions and the cultivar used, the conventional planting density (88 888 plant ha^{-1}) being used in NE Ethiopia is not the optimum density as increases in grain yield were found to be linear up to a population density of 166 666 plants ha^{-1}. These results also showed the ability of the newly released cultivar ICSV 111 to tolerate population stress as shown by its linear response in most parameters to increasing planting density. Increasing plant population was also associated with increased stover yield, which is an important consideration for small-scale farmers to whom stover has multiple uses.

Generally, sorghum yield-density relationships exhibited an asymptotic relationship in the present study, a relationship in which yield approaches a maximum as plant density increases and it is impossible to determine an optimum density. Thus, it can be recommended that further study should be conducted to determine the optimum planting density. Willey & Heath (1969) as cited by Shirtliffe & Johnston (2002) indicated that yield-density relationships in plants generally follow either an asymptotic or a parabolic pattern. A hyperbolic yield-density relationship occurs when there is a yield maximum at an optimum plant density and yield decreases at higher densities.

Farmland is a scarce resource in NE Ethiopia where the average land holding is approximately 0.1 ha per family. The results of this study, which revealed increasing productivity through increasing plant population, would be most welcome to the small-scale farmers to whom increasing productivity through increasing farm size is not possible.

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CHAPTER 8

General Discussion

Sorghum (*Sorghum bicolor* L. Moench) is an important crop in the drought prone lowland areas of NE Ethiopia. However, its productivity is constrained either separately or concurrently, by water deficit stress and poor soil fertility. Owing to low, often poorly distributed and highly variable rainfall, moisture deficit stress is an overriding environmental problem in the region, which often results in low and unstable crop yields. The soils are predominantly shallow, low in organic matter content and poor in fertility and water holding capacity. Recognizing the fundamental importance of water deficit stress and poor soil fertility in crop production in NE Ethiopia, this study has endeavoured to determine the effect of different agronomic practices (rainwater harvesting, nitrogen fertilizer, FYM application, planting density) and cultivars in improving the productivity of sorghum under semi-arid conditions.

Effect of water deficit stress on sorghum productivity

The lack of sufficient moisture in the seeding zone at planting adversely affects the germination and establishment of sorghum. The high temperature, high evaporative demand and the limited and erratic precipitation in NE Ethiopia mostly result in rapid drying of the soil surrounding the seeds, thus resulting in poor seed germination and seedling establishment. This problem necessitated assessing the effects of moisture deficit on seed germination and seedling establishment and also assessing the variability of tolerance between cultivars.

The overall effects of water deficit stress on seed germination and seedling growth have been demonstrated in two separate experiments reported in Chapter 2. From the results it was evident that water deficit negatively affected the rate and percentage of germination and seedling emergence. It was made clear that the rate of germination was more strongly affected than the percentage of germination with reductions as high as 50% being recorded.

A lower percentage of germination, as well as slower germination rate, have agronomic implications for the productivity of sorghum. Reductions in the percentage germination results in sub-optimal plant populations and uneven stands. From an agronomic point of view, rapid germination enhances seedling establishment as seedlings will develop secondary roots and access wet soil ahead of the drying front (Baalbaki *et al*., 1999). This indicates that the slower rate of germination and emergence observed at the higher water deficits (-0.85 MPa and 40% field capacity) in this study imply that seedlings would have a lower chance of survival if subsequent water deficits occurred. A slower rate of germination also mean that imbibed seeds in the soil are more prone to fungal and bacterial attacks, which might lead to reduced seedling emergence. The faster the seeds germinate and emerge the greater will be the likelihood of escaping pre-emergence fungal and bacterial attacks. Thus, it is suggested that the speed of germination, rather than the percentage of germination, is the more appropriate parameter to identify cultivars tolerant to water deficit at germination.

Water deficit at germination severely curtailed the elongation growth of the coleoptile, mesocotyl and radicle, resulting in seedlings with weak vigour. Severe water deficit (-0.85 MPa) reduced coleoptile length from 17 mm to 4 mm, mesocotyl length from 20 mm to 4 mm and radicle length from 94 mm to 46 mm (Chapter 2). Water stress after emergence also severely reduced the shoot and root length and root area of seedlings. The reduction in root length and root surface area under water deficit stress will have a detrimental effect on seedling establishment as water supply to the seedling depends on the ability of the root system to grow into the germination medium and the ability of the roots to absorb water. Such seedlings have less chance of survival and establishment under stress environments that may confront them in the forthcoming growing period. Cultivars exhibiting vigorous growth under water deficit at the establishment stage may better adapt to the stress environments which they might encounter during the growing period. Thus, seedling vigour parameters could be of importance in identifying cultivars tolerant of water deficit conditions.

One of the strategies to mitigate the challenges of water deficit stress in crop production is selecting cultivars which are relatively tolerant of such stress. The results reported in Chapter 2 demonstrated cultivar differences in terms of the rate and percentage of germination and seedling vigour under water deficit at germination. Gambella 1107, Meko and P9403 exhibited the highest rates and percentages of germination and emergence. These cultivars also required less time (72 hours) to reach final germination, while other cultivars required more time (96 hours). In semi-arid areas where water in the upper soil surface may be available for only a short period, rapidly germinating cultivars like Gambella 1107, Meko and P9403 may have an advantage in stand establishment. Gambella 1107 and P9403 also grew well under water deficit conditions. Thus, in seasons of expected water deficit at germination farmers may improve the establishment and then productivity of their sorghum if they grow tolerant cultivars like Gambella 1107, Meko and P9403. Jigurti and 76 T1 #23, although they had a low and slow germination and emergence, may establish better under water deficit conditions once the seeds have germinated as they are characterized by extensive root systems.

Apart from the germination stage, a sorghum plant may be confronted with moisture deficit during its vegetative growth. With this consideration, an experiment (reported in Chapter 3) was conducted to quantify the effect of water deficit stress on the growth and development of sorghum, to identify tolerance mechanisms and to evaluate genotypic variability in response to water deficit stress. The results indicated that plant growth attributes such as shoot height, leaf number and leaf area, dry matter (leaf, stem, total) production, root length, root to shoot ratio, and water use efficiency differed between the water deficit treatments. The results also showed that water deficit stress adversely affected leaf diffusive resistance, stomatal density and pore size, stomatal aperture and starch deposition in chloroplasts. The results suggest that these traits can be used in selecting sorghum cultivars tolerant to drought stress. It has been demonstrated that genotypes which maintain a relatively better shoot height, leaf area and dry matter production under water deficit conditions ultimately have better yields (Parameswara & Kirshnasastry, 1982; Fischer *et al*., 1983). Daie (1996) indicated that the effective dry mass production under water stress conditions is an indication of tolerance as it indicates the plant's ability to fix carbon, regardless of the stress. Relatively better dry mass production under water deficit conditions can, therefore, be suggested as a screening criterion in selecting tolerant cultivars.

It was also observed that sorghum plants grown under water deficit conditions deposited larger amounts of epicuticular wax on the leaf surfaces, which is presumed to be a tolerance mechanism. The deposition of epicuticular wax is known to serve as a barrier to water loss (Bondada *et al*., 1996; Cameron *et al*., 2002). A positive association between increased epicuticular wax deposition and drought tolerance was also noted by Cameron *et al*. (2002). Based on these results it is suggested that epicuticular wax deposition can be used as an important trait in selecting drought tolerant cultivars, as plants with greater epicuticular wax deposition exhibit a higher ability in retaining tissue water (Jordan *et al*., 1983).

The hypothesis that sorghum cultivars differ in their drought tolerance was proven. The results in Chapter 3 revealed cultivar differences in plant height, leaf area development, dry matter (leaf, stem, total) production, root length, root to shoot ratio and water use efficiency in response to water deficit stress. Among the cultivars, Jigurti, Gambella 1107 and Meko consistently showed tolerance based on the parameters studied. In addition, Gambella 1107 and Meko were also found to be tolerant at the germination stage (Chapter 2). Small-scale farmers can, therefore, reduce yield losses due to moisture deficit by growing relatively tolerant cultivars like Gambella 1107 and Meko. Jigurti, however, is a long duration cultivar that is not suitable for production in NE Ethiopia where terminal drought stress prevails, but could be useful in a breeding programme.

Effect of rainwater conservation, nitrogen fertilizer and cultivars on sorghum productivity

Considering the yield reduction occurring in sorghum as a result of water deficit stress and poor soil fertility, an experiment (reported in Chapter 4) was conducted to evaluate the effect of rainwater harvesting, nitrogen fertilization and cultivars on sorghum productivity. Based on the results of this investigation, it was assumed that the efficiency of rainwater harvesting technique is highly dependent on soil texture and rainfall condition of the particular season. On clayey soils and in seasons of heavy rainfall tied-ridging may even negatively affect crop growth and yield. This effect was clearly demonstrated at Sirinka where the soils are clayey and at Kobo where the rainfall was above average in the experimental season. This result suggests that the indiscriminate recommendation of tied-ridging as a rainwater harvesting technique in NE Ethiopia, without due consideration to the soil texture and rainfall characteristics, may lead to yield reductions. Thus, it is suggested that the effect of tied-ridging should be further studied using models that take into consideration differences in soil texture and climatic variability. For instance, Wiyo & Feyen (1999) in Malawi studied the expected maize yield gain due to tied-ridging, taking into account the probability of occurrence of drought, dry, normal and wet years (climatic uncertainty) and concluded that under the smallholder conditions and climate of Malawi, the expected yield gain in any year due to tied-ridging is likely to be minimal and uneconomic. Wiyo *et al.* (2000) also used a calibrated field capacity-based water balance model (TIEWBM) to assess the impact of tied-ridging on soil water status and found increases in soil water content in fine textured soils (clayey texture) but not in coarse-textured soils (sandy soils). These results from Malawi have clearly demonstrated the importance of rainfall variability and soil texture on the performance of tied-ridging.

Nitrogen fertilization is a major input in sorghum production, affecting both yield and quality. Results, reported in Chapters 4 and 7, indicated that increasing the soil N status increased leaf area development, biomass production, grain number, grain yield, nitrogen uptake, grain protein content and grain protein yield. N fertilization is known to have a greater impact on crop yield and quality than other production factors (Novoa & Loomis, 1981). Several workers have reported increased grain protein content and yield by applying N fertilizer (Kamoshita *et al.*, 1998; Metho *et al.*, 1999; Le Gouis *et al.*, 2000). Based on the results of this investigation, farmers in NE Ethiopia should be advised to apply 40 kg N ha^{-1} to increase the productivity and quality of sorghum.

Exploiting genetic differences in N utilization efficiency of cultivars should be a strategy on which to focus to improve the productivity of sorghum on the relatively infertile soils of NE Ethiopia. Sorghum cultivars with higher efficiency in uptake and utilization of the limited soil nutrients may play an important role in increasing the productivity and grain quality of sorghum. The results in Chapter 4 demonstrated cultivar differences in yield potential as well as in N uptake, N utilization, grain and stover N content, grain protein content and grain protein yield. Cultivars that were efficient in N utilization generally produced higher yields. For instance, ICSV111 and

76 T1 #23 had higher N utilization efficiency, higher grain yields and higher grain protein content, motivating further exploitation of the sorghum gene pool to develope cultivars with high N utilization efficiency. Given the fact that Ethiopia is the centre of origin of this crop, there may be ample potential for developing cultivars efficient in nutrient utilization.

The cultivars studied differed in several agronomic traits, like leaf area development, biomass and grain yields, stover yield, harvest index, dry matter partitioning and nitrogen harvest index (Chapter 4). The data indicated that HI is closely related (r = 0.99) to NHI, indicating that cultivars with high HI also had a high NHI. Those cultivars with higher HI also had higher nitrogen use efficiency and grain yield. Thus, HI may be an important trait in identifying cultivars efficient in N utilization. Nevertheless, one should bear in mind that the use of nutrient efficient genotypes cannot be a long lasting solution to increase productivity on infertile soils. To sustain the productivity of sorghum on such soils improving the general chemical and physical properties of the soils through integrated nutrient management strategies would be the only sustainable solution.

Effect of integrated nutrient management on sorghum productivity and soil properties

Soils in NE Ethiopia are generally shallow, low in organic matter content, poor in nutrients and have a poor water holding capacity (Georgis & Alemu, 1994). Furthermore, small-scale farmers cannot afford to apply inorganic fertilizers. Hence, the sustainable maintenance of the fertility status of these soils with relatively inexpensive inputs deserves investigation. In this regard, the effect of continuous applications of FYM and inorganic fertilizers on selected soil properties and on the growth, yield and quality of sorghum was determined. The hypothesis that the combined application of FYM and inorganic fertilizers, rather than applying each alone, improves soil chemical properties and sorghum productivity was proven. The benefits from the application of FYM were evident in improved soil N, P, K, organic matter content and water holding capacity as well as in improved sorghum biomass and grain yield, nitrogen uptake, grain protein content, grain protein yield and fertilizer use efficiency (Chapter 5 and Chapter 6). Increases in soil N, P, K, organic matter and water holding capacity were greater with increasing levels of FYM application. However, FYM application did not bring any appreciable changes in soil Na^+, Ca^{2+}, Mg^{2+}, CEC, base saturation or pH. The reasons for no change in these parameters were not clear and may need further study.

The increased sorghum growth, biomass and grain yields, N uptake, grain and stover N contents and grain protein content appear to be the result of increased nutrient and moisture availability, as well as increased microbial activity as a result of the FYM component. It is presumed that integrating FYM and inorganic fertilizers, beyond its effect on nutrient availability, might have increased synchrony of nutrient release, thus resulting in increased nutrient uptake and yield. It was also observed that application of FYM improved the efficiency of uptake of applied inorganic fertilizer. The results, reported in Chapter 5 demonstrated that by integrating FYM with inorganic fertilizers the need for inorganic fertilizers in achieving higher yields was reduced by the amount of 20 kg N ha^{-1} and 10 kg P ha^{-1}. This implies that with this nutrient management strategy greater yields can be attained with less amount of inorganic fertilizer.

Overall, the results showed that the integrated use of FYM and inorganic fertilizers increased crop yield and quality at reduced inorganic fertilizer input, while maintaining or improving the soil chemical and physical properties. Thus, these results warrant the adoption of an integrated soil nutrient management strategy by farmers, in order to improve the productivity of their soils on a sustainable basis. Consequently, resource poor farmers of NE Ethiopia may be able to reduce reliance on inorganic fertilizers and also reduce fertilizer costs. However, the effect of this nutrient management strategy on soil physical and microbial properties and its economic feasibility and profitability deserves further research focus.

Effect of planting density on the productivity and quality of sorghum

In dryland crop production where water and nutrient deficits limit crop productivity, plant population density was hypothesized to have a significant impact on the productivity and quality of sorghum, as the optimum plant population density should match the available moisture and nutrients. The effect of plant population densities, ranging from 29 629 to 166 666 plants ha^{-1}, under different nitrogen fertilizer regimes, on the growth, development and grain and stover quality of sorghum was studied in field experiments at two locations in NE Ethiopia, and reported in Chapter 7. It was found that plants under low population densities tend to grow vigorously with thicker stalks, larger canopy, bigger heads and higher grain yields on an individual plant basis owing to reduced competition for resources. Most of the yield component parameters (panicle length, panicle weight, seed weight per panicle, seed number per panicle and thousand seed weight) were greater at lower planning densities. The grain and biomass yields on unit area basis were, however, higher at higher population densities. The greater yields at higher densities were due to greater number of heads and seeds per unit area. Thus, it is the number of heads and seeds per unit area that determines the final yield rather than the other yield component parameters.

Overall, sorghum biomass yield, grain yield, and N uptake increased with increasing population densities across all nitrogen fertilizer regimes. Crop production is the practice of trapping solar energy. Thus, crop production strategies are usually designed to maximize light interception by achieving complete ground cover through manipulating plant density. Ma *et al*. (2003) noted that, with no other limitations, crop productivity might be limited by the amount of light intercepted. Thus, the observed increase in sorghum productivity under high population densities was presumed to be due to improved radiation interception and radiation use efficiency as a result of increased LAI development per unit area. Tollenaar *et al*. (1997) noted that increased LAI with increasing population density is associated with effective light interception and thus may allow high plant densities to attain greater photosynthetic rates and greater biomass production. In the present study, leaves at higher plant densities were narrow and more erect, and the plants themselves were taller. Fischer & Wilson (1975) noted that such features of the canopy are more favourable to light penetration per unit leaf area.

Under the condition of this study, grain yield increased linearly with increasing density up to a planting density of 166 666 plants ha^{-1} which is nearly double the conventional planting density (88 888 plant ha^{-1}) being used in NE Ethiopia. Thus, there is a potential for extending the optimum density beyond the current recommendation.

Conclusion

- This study has shown that there is potential for improving the productivity of sorghum in the drought prone areas of NE Ethiopia by selecting sorghum cultivars tolerant to water deficit stress both at germination and during the vegetative growth stages. The potential of developing drought tolerant cultivars would be immense due to the fact that Ethiopia is the centre of diversity for sorghum. The cultivation of Gambella 1107 and Meko can be recommended for NE Ethiopia as these cultivars exhibited tolerance to water deficit stress both at the germination and vegetative growth stages. The high rate and percentage of germination in P9403 and the extensive root growth in 76 T1 #23 and the overall unaffected growth of Jigurti under water deficit stress could be important traits to be exploited in the breeding programme.

- Tied-ridging as a rainwater harvesting technique did not contribute much towards improving the productivity of sorghum under the conditions experienced. The use of tied-ridging under the climate and soil conditions of NE Ethiopia needs further study using methodologies that can take soil texture differences and rainfall variability into account. Alternative on-farm rainwater harvesting techniques should also be investigated.

- The application of N fertilizer increased grain and stover yield and quality of sorghum. Thus, farmers in NE Ethiopia need to apply 40 kg N ha^{-1} in either organic or inorganic form to increase the productivity and quality of sorghum on their infertile soils.

- There is potential to improve the productivity of sorghum on the relatively infertile soils of NE Ethiopia through selecting cultivars efficient in nitrogen uptake and utilization. At Kobo, growing ICSV111 and 76 T1 #23 with tied-ridging could be recommended for improved yield, quality and greater nitrogen use efficiency. At Sirinka, ICSV111 and 76 T1 #23 gave similar yields and grain quality to Jigurti with lower N uptake thus their cultivation will give higher yields with lower N input. However, the use of nutrient efficient genotypes cannot be a panacea for increasing the productivity of sorghum on infertile soils. The improvement in the productivity of sorghum on infertile soils should, therefore, include improving the fertility status of the soils.

✧ The integrated application of FYM and inorganic fertilizers improved the nutrient and organic matter content and water holding capacity of the soil. This resulted in improved sorghum biomass and grain yields and grain and stover quality. Thus, to improve the productivity of these soils on a sustainable basis soils should be amended with organic fertilizer inputs like FYM. Because inorganic fertilizers are costly inputs for the small-scale farmers, soil fertility management strategies that involve relatively inexpensive inputs like FYM should be most attractive. Based on the results of the experiment reported in Chapters 5 and 6, application of 5, 10 and 15 t FYM ha^{-1} in combination with 100% of the recommended fertilizer rate and 5, 10 and 15 t FYM ha^{-1} in combination with 50% of the recommended fertilizer rate can be recommended for farmers who can and can not afford to buy inorganic fertilizers, respectively.

✧ Yield variations were observed between different levels of planting density. Under the conditions of the present experiment, extending planting density beyond the existing recommendation could increase sorghum grain and biomass yields. However, further study should be conducted to determine the optimum planting density, as the optimum planting density was not achieved in this experiment.

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Summary

The problems of water deficit stress and poor soil fertility have been identified as the major factors constraining crop production in the semi-arid areas of NE Ethiopia. Consequently, productivity of sorghum in this region still falls behind the national average yield of 1.2 t ha^{-1}. Currently, it is realized that crop productivity in such areas could be improved through integrating agronomic measures focusing on moisture conservation, soil fertility improvement, and selecting cultivars tolerant to moisture stress and are efficient in nutrient use. Hence, the overall goal of this study was to examine the effects of different agronomic practices (rainwater harvesting, nitrogen fertilizer, FYM application, planting density) and cultivars in improving the productivity of sorghum under moisture limited and infertile soil conditions of NE Ethiopia. The research questions that this study endeavoured to answer were:

a) Do sorghum cultivars differ in their tolerance to moisture deficit occurring at germination and in the vegetative stages?

b) What are the traits that are most affected by water deficit stress that can best be used to evaluate a cultivar tolerance?

c) What are the tolerance mechanisms that cultivars exhibit under moisture deficit stress?

d) Does tied-ridging, as a rainwater harvesting technique, improve sorghum productivity through improving moisture availability under conditions in NE Ethiopia?

e) Do sorghum cultivars differ in nitrogen use efficiency?

f) Does the combined use of FYM and inorganic fertilizers improve the fertility status of the soil, and thus the growth, yield and quality of sorghum under semi-arid conditions, more than using them separately?

g) Does planting density affect the productivity of sorghum under the prevailing soil moisture and fertility conditions?

To answer these questions experiments were conducted under field and laboratory conditions. Laboratory and growth chamber experiments were conducted to determine the effect of water stress on the germination and growth of sorghum and to evaluate cultivar differences in their tolerance to water deficit stress occurring at the germination and vegetative growth stages. Field experiments were also conducted at

two locations in NE Ethiopia to determine the effect of rainwater harvesting, nitrogen fertilizer and cultivars on the growth, yield, grain protein content, grain protein yield and nitrogen use efficiency of sorghum; to determine the combined use of FYM and inorganic fertilizers on soil properties and on the growth, yield, grain protein content, grain protein yield and nitrogen use efficiency of sorghum; and to determine the effect of planting density on the growth, yield, N uptake, grain N content, grain protein content and N use efficiency of sorghum under different nitrogen fertility regimes.

Water deficit stress at germination reduced the rate and percentage of germination and emergence. The effect of water deficit stress was more detrimental on the rate of germination and emergence than on the percentage. Water deficit stress reduced the elongation of the coleoptile, mesocotyl, radicle, shoot and roots and root surface area, thus resulting in seedlings with poor vigour. Cultivars differed in their response to water deficit stress at germination. Among the cultivars, Gambella 1107, Meko and P9403 exhibited the highest rate and percentage of germination and emergence while Gambella 1107 and P9403 also grew relatively vigorously.

Water deficit stress at the vegetative growth stage adversely affected plant growth attributes such as shoot height, leaf number, leaf area development, root length and biomass production. Electron microscopy observations showed that water stress also resulted in closed stomata, reduced starch deposition in the chloroplasts and more epicuticular wax on the leaf surfaces. Cultivars differed in agronomic, physiological and anatomical attributes in response to water deficit. Among the cultivars, Jigurti, Gambella 1107 and Meko consistently showed tolerance based on the parameters studied.

Tied-ridging, as a rainwater harvesting technique, has been successfully used in other areas. However, in the present study tied-ridging had either a negative effect or no effect on sorghum growth and yield. Nitrogen fertilizer application increased leaf area development, biomass production, grain number, grain yield, nitrogen uptake, grain protein content and grain protein yield, thus improving the productivity and quality of sorghum. Sorghum cultivars differed in leaf area development, biomass production, grain yields, harvest index, N uptake, grain protein content, N harvest index and N use efficiency. ICSV111 and 76 T1 #23 produced the highest grain yields, grain protein content and had higher N utilization efficiencies, indicating the potential for further exploiting the sorghum gene pool for developing more cultivars with high N utilization efficiency on infertile soils.

Since poor soil fertility adversely affects sorghum productivity, it is imperative to improve the productivity of these soils on sustainable basis through the combined use of organic inputs with inorganic fertilizers. Continuous application of FYM and inorganic fertilizers improved the N, P, K content, organic matter content, water holding capacity and N balance of the soil and thus improved sorghum biomass and grain yield, grain protein content and protein yield. FYM application also improved uptake of inorganic fertilizer. Overall, the integrated use of FYM and inorganic fertilizers increased crop yield and quality at reduced inorganic fertilizer inputs, while maintaining the soil chemical and physical properties.

One agronomic management approach to maximize crop productivity in environments with water deficit and infertile soil is to match plant population density to the level of available resources. Hence, field experiments were conducted at two locations to determine the effect of different planting densities on the growth, yield, N uptake, N use efficiency, grain N content and grain protein content of sorghum under the prevailing moisture and soil fertility conditions. Sorghum biomass yield, grain yield, N uptake per unit area and N use efficiency increased with increasing population density. But grain N content and grain protein concentration were higher at lower densities. Under the conditions of this study, there is a potential for extending the optimum planting density beyond the conventional planting density (88 888 plant ha^{-1}), being used in NE Ethiopia, as grain yield increased linearly up to a population density of 166 666 plants ha^{-1}.

Appendices

Appendix Table 4.1. Physicochemical properties of the soils on the experimental sites

	Sirinka		Kobo	
Properties	0-15 cm	15-30 cm	0-15 cm	15-30 cm
pH (1:1 H_2O)	6.64	6.61	7.38	7.31
Total N (%)	0.14	0.15	0.09	0.09
Available P (Olsen, ppm)	10.40	8.60	13.60	10.40
Organic C (%)	1.68	1.39	1.20	1.22
Clay (%)	57.5	60.0	47.5	45.0
Silt (%)	35.0	32.5	42.5	42.5
Sand (%)	7.5	7.5	10.0	12.5

Appendix Table 5.1. Effects of FYM and inorganic fertilizers on panicle yield at harvest and 1000-seed weight (data pooled over five growing seasons)

	Panicle yield (kg ha^{-1})				1000-seed weight (g)			
FYM	0 F^{++}	50 F	100 F	Mean	0 F^{++}	50 F	100 F	Mean
0 t ha^{-1}	4229a	4283a	4619a	4377C	23.6d	26.3a	25.0a-d	25.0A
5 t ha^{-1}	4354a	4846a	5005a	4735B	24.8bcd	24.8bcd	25.4abc	25.0A
10 t ha^{-1}	4274a	5080a	4770a	4708B	25.2abc	25.9ab	23.8d	25.0A
15 t ha^{-1}	4604a	5247a	5454a	5102A	24.1cd	26.1ab	25.6ab	25.2A
Mean	4366B	4864A	4962A		24.4B	25.8A	24.9B	

$^{++}$ Indicate % of the recommended inorganic fertilizer rates. Means within rows and columns followed by the same letters are not significantly different at P<0.05 for each comparison.

Appendix Table 7.1. Physicochemical properties of the soils on the two experimental sites

	Sirinka		Kobo	
Properties	0-15 cm	15-30 cm	0-15 cm	15-30 cm
pH (1:2.5 H_2O)	6.7	6.7	7.38	7.38
Total N (%)	0.14	0.13	0.10	0.11
Available P (Olsen, ppm)	8.20	8.00	13.60	10.20
Organic C (%)	1.53	1.51	1.28	1.28
Ca^{2+} (cmol kg^{-1})	22.03	19.93	15.95	19.33
Mg^{2+} (cmol kg-1)	2.95	3.93	10.7	7.93
Na^{+} (cmol kg^{-1})	0.61	0.61	0.27	0.29
K^{+} (cmol kg^{-1})	1.10	0.97	0.44	0.40
CEC (cmol kg^{-1})	57.16	33.32	54.86	43.2
Clay (%)	55.0	57.5	52.5	52.5
Silt (%)	35.0	35.0	37.5	35.0
Sand (%)	10.0	7.5	10.0	12.5