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.

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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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