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}.