CHAPTER 2

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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) = $RT\Sigma Cj$ 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}) = Σ [$(G_i-G_{i-1})/i$] 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).

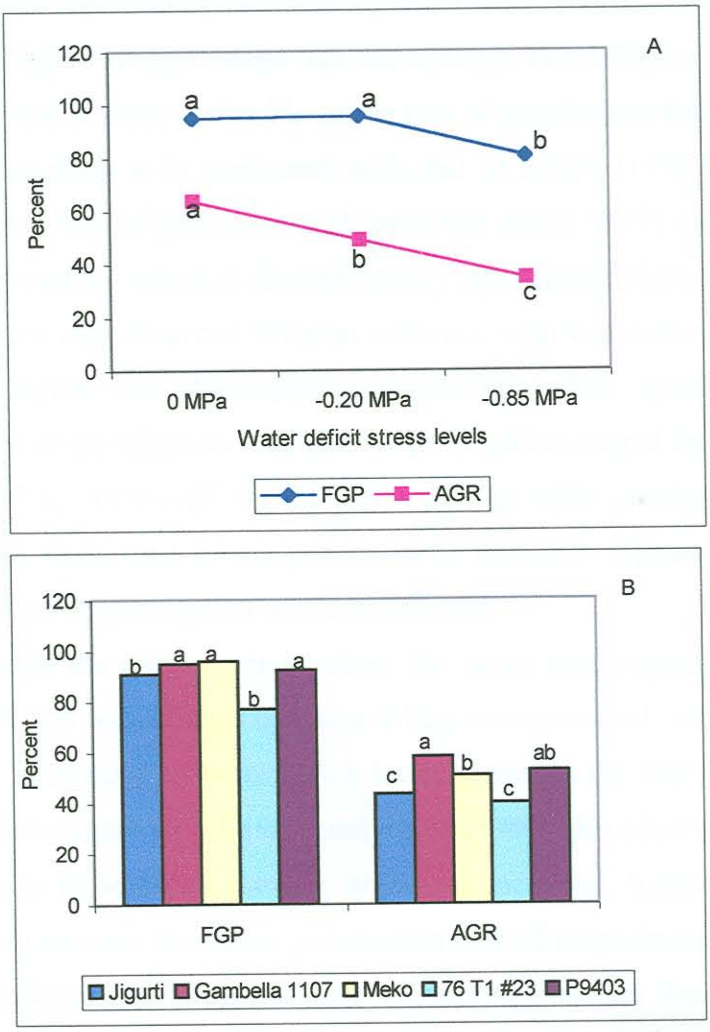

Figure 1. Effect of water deficit stress (A) and cultivar differences (B) on final germination percentage (FGP) and average germination rate (AGR). Means followed by the same letters for each parameter are not significantly different at P≤0.05.

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).

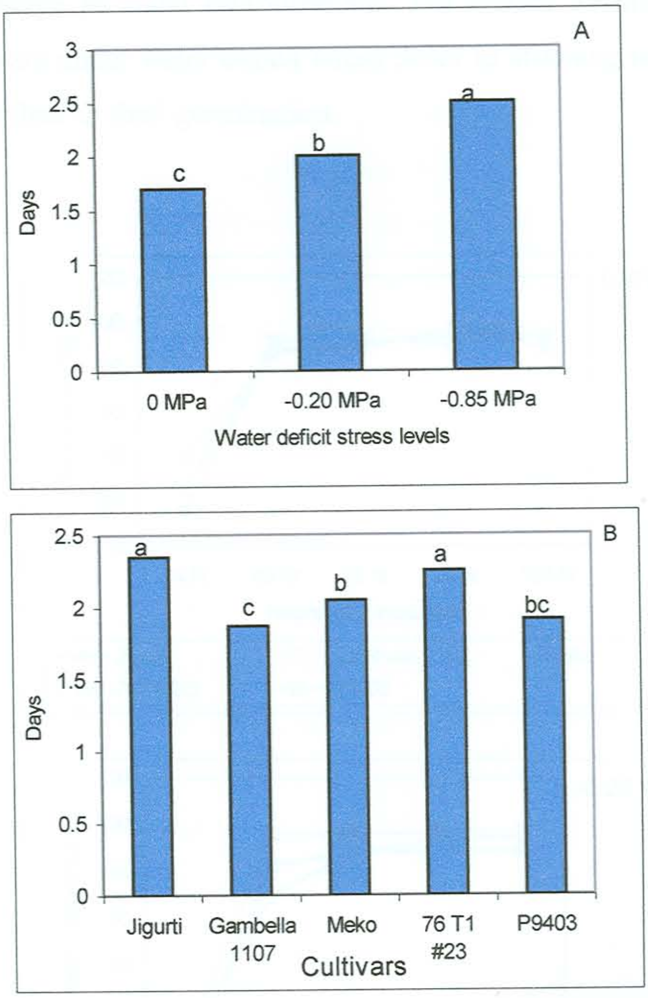

Figure 2. Effect of water deficit stress (A) and cultivar differences (B) on mean time to final germination. Bars with the same letters are not significantly different at P≤0.05.

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.

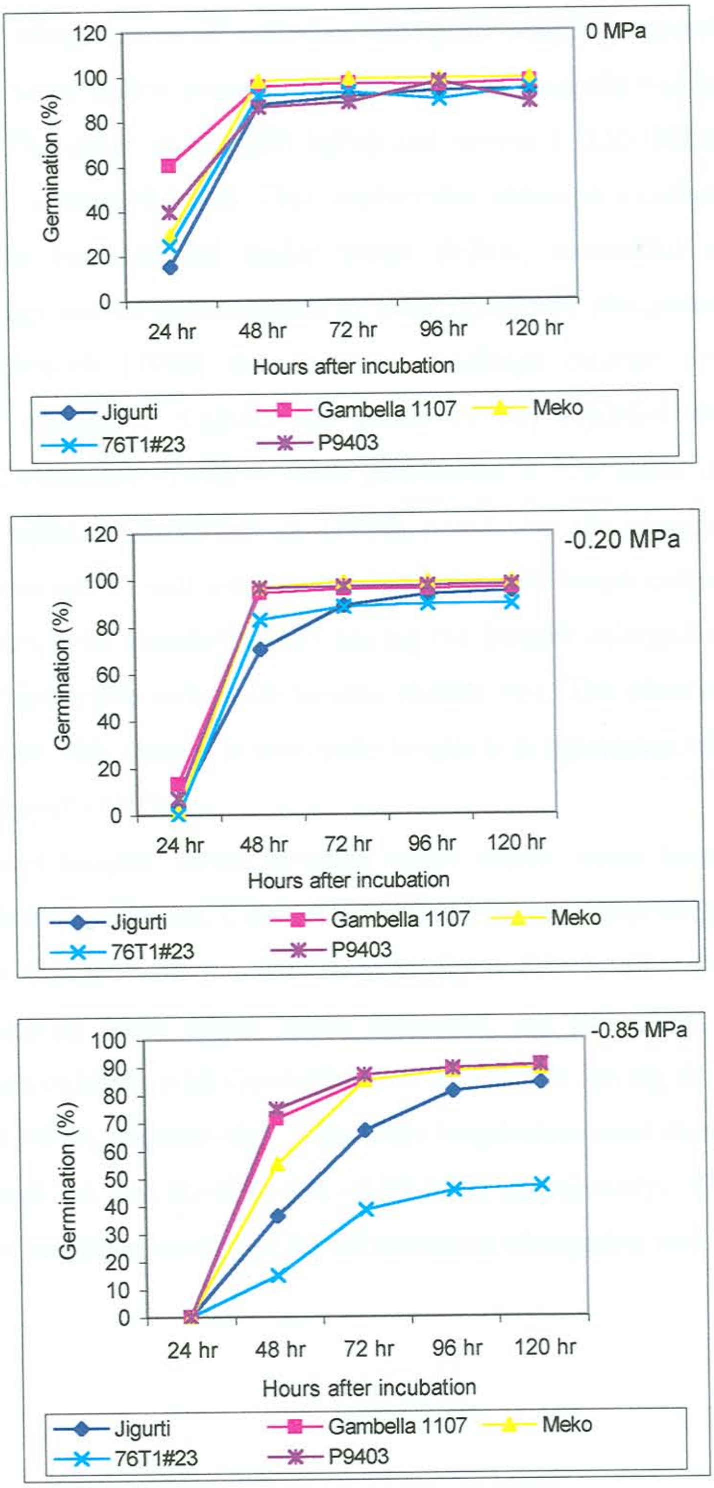

Figure 3. Effect of water deficit stress on the time course of germination of sorghum cultivars.

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.

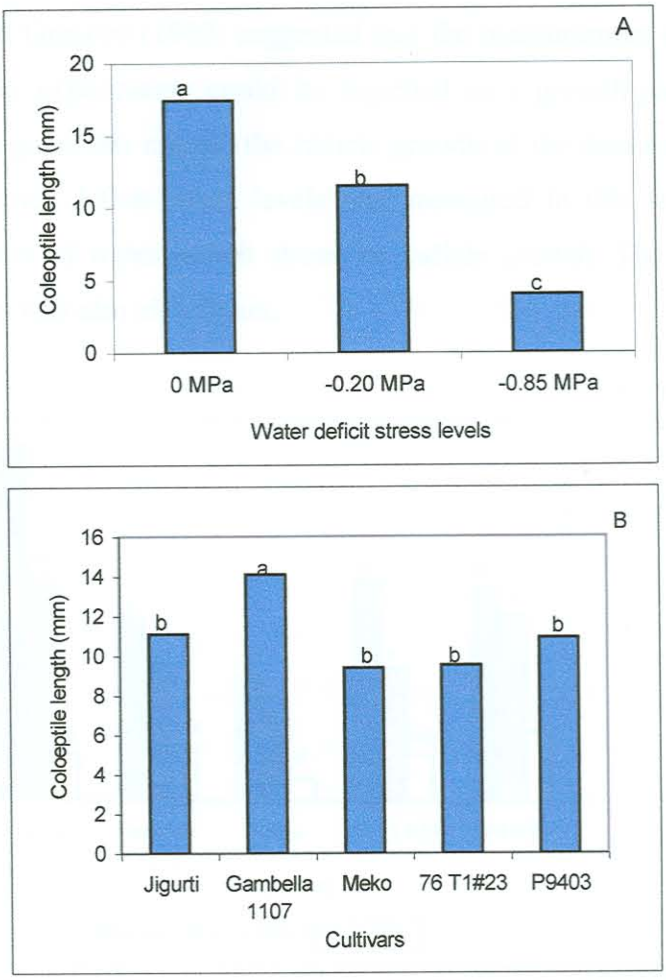

Figure 4. Effect of water deficit stress (A) and cultivar differences (B) on coleoptile length. Bars with the same letters are not significantly different at $P \leq 0.05$.

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.

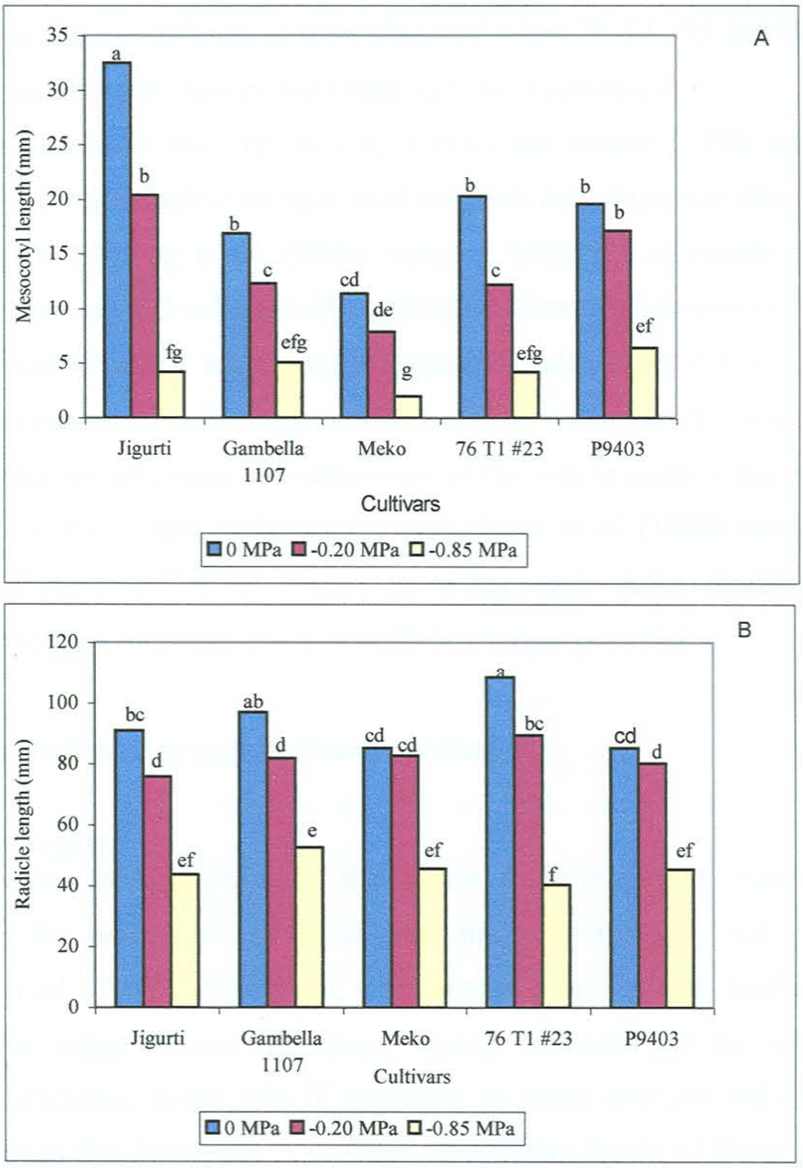

Figure 5. Effect of water deficit stress on the mesocotyl (A) and radicle (B) lengths of sorghum cultivars. Bars with the same letters are not significantly different at $P \leq 0.05$.

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.

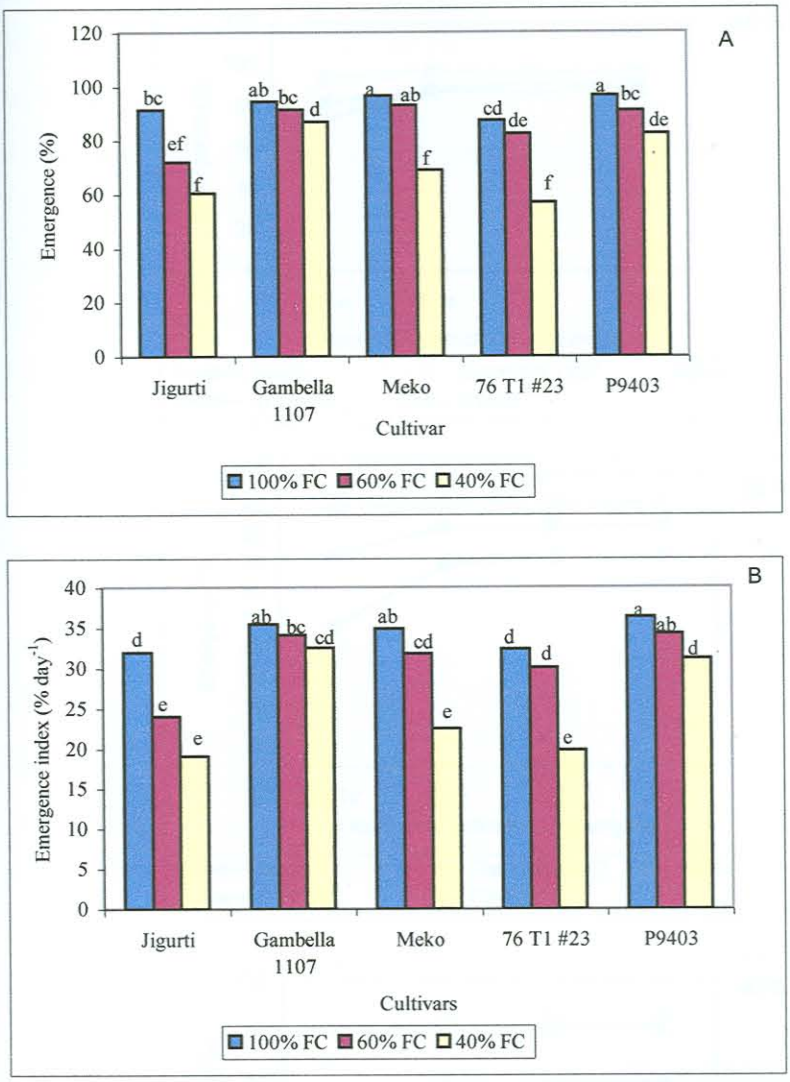

Figure 6. Effect of level of growing media water content on final seedling emergence (A) and emergence index (B). Bars with the same letters are not significantly different at P≤0.05.

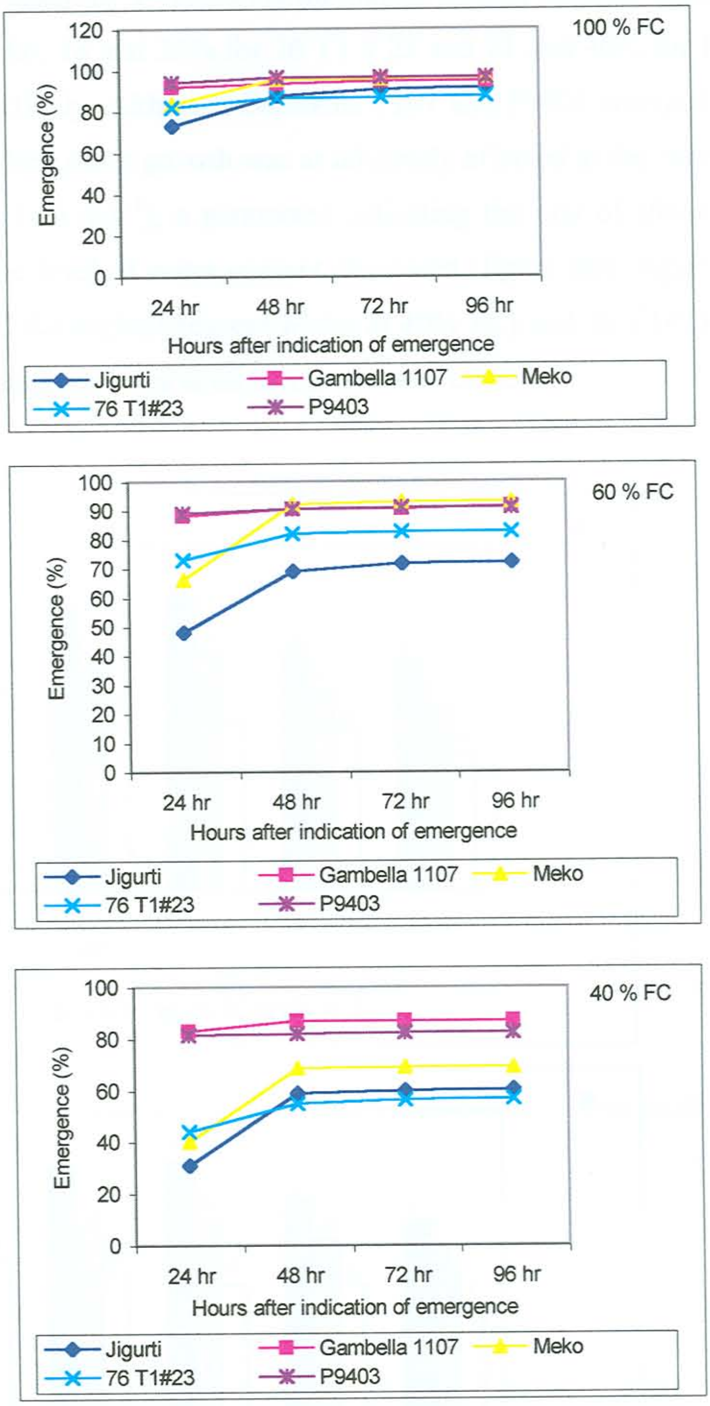

Figure 7. Effect of level of growing media water content on the time course of emergence of sorghum cultivars.

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.

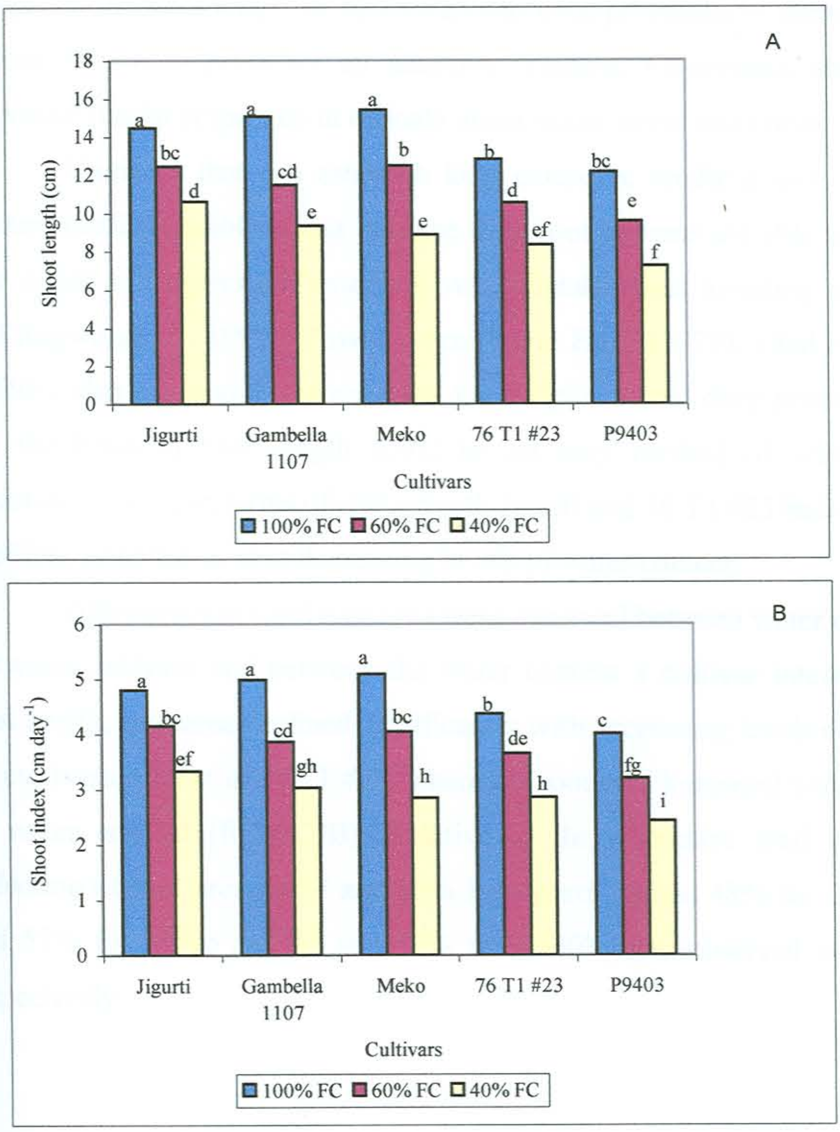

Figure 8. Effect of level of growing media water content on shoot length (A) and shoot index (B) of sorghum cultivars. Bars with the same letters are not significantly different at $P \leq 0.05$.

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.

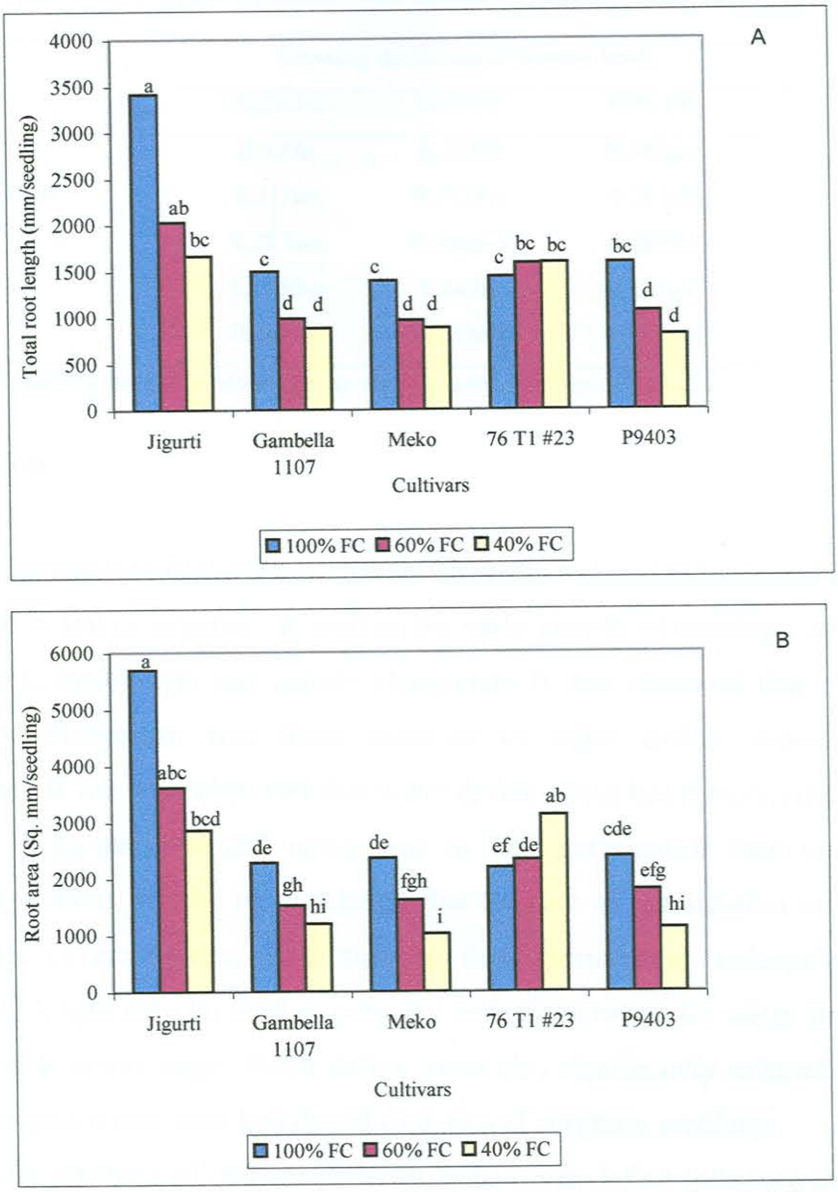

Figure 9. Effect of level of growing media water content on total root length (A) and area (B) of sorghum cultivars. Bars with the same letters are not significantly different at $P \leq 0.05$.

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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