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

W. Bayu, N.F.G. Rethman and P.S. Hammes

Department of Plant Production and Soil Science, University of Pretoria, Pretoria 0002, South Africa

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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

	Sirinka				Kobo			
	Precipitaion (mm)		Temperature (^{O}C)		Precipitaion (mm)		Temperature (^{O}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	0.0	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 $P \leq 0.05$.

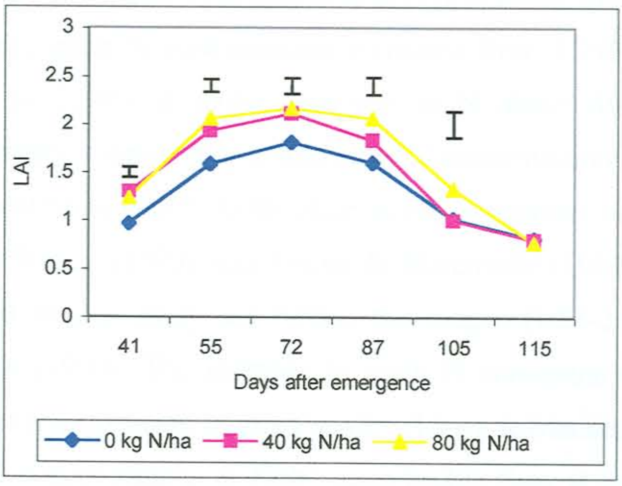

Figure 1 Effect of N fertilizer on leaf area index at Sirinka. Vertical lines on each period of measurement indicate LSD values at $P<0.05$.

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).

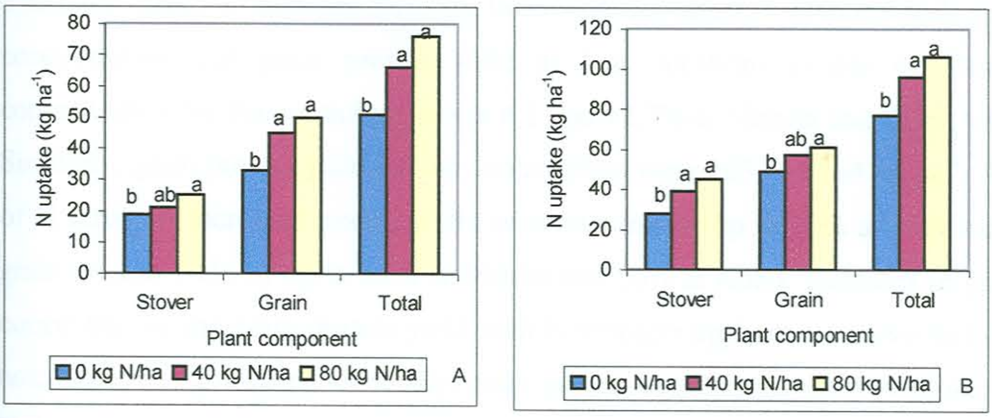

Figure 2 Effect of N fertilizer on stover, grain and total plant N uptake at Sirinka (A) and Kobo (B). Bars with the same letters for each parameter are not significantly different at $P \leq 0.05$.

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 $P \leq 0.05$.

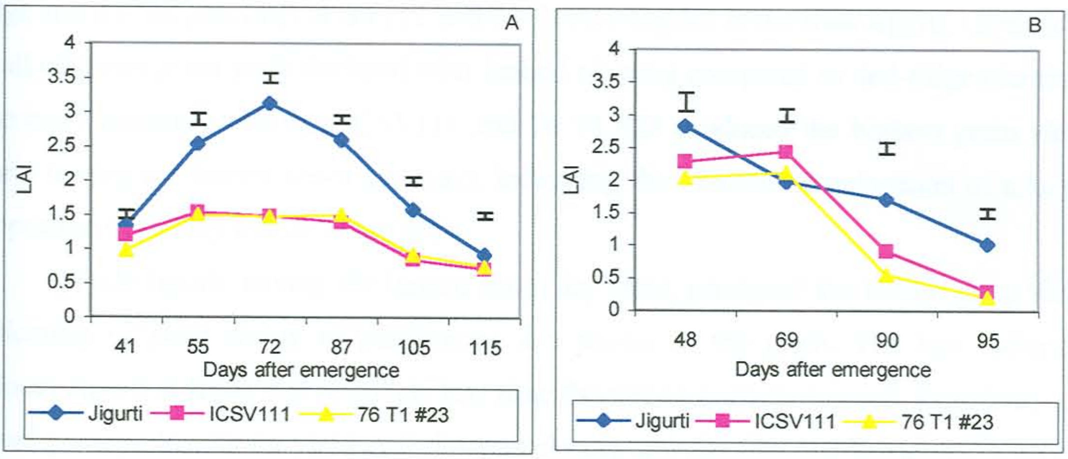

Figure 3 Leaf area index of sorghum cultivars at Sirinka (A) and Kobo (B). Vertical lines on each period of measurement indicate LSD values at $P<0.05$.

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≤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.

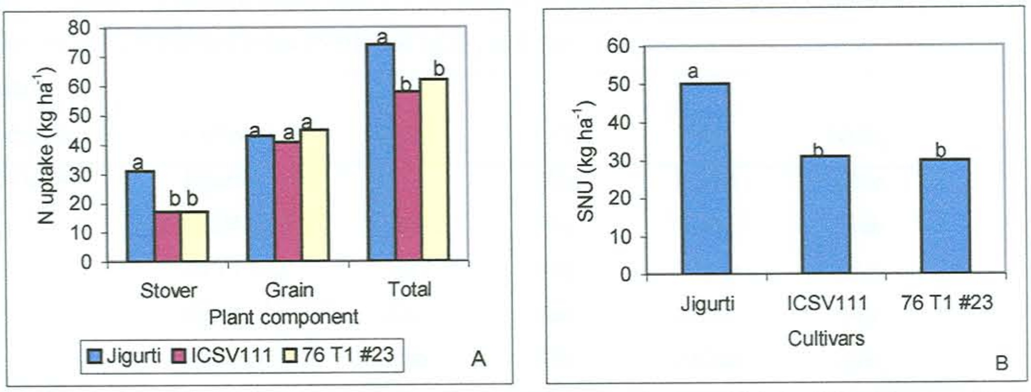

Figure 4 Stover, grain and total plant N uptake of sorghum cultivars at Sirinka (A) and stover N uptake (SNU) at Kobo (B). Bars with the same letters for each parameter are not significantly different at $P \leq 0.05$.

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≤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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