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SOIL WATER CONSERVATION, GROWTH, YIELD AND WATER USE EFFICIENCY OF SORGHUM AS AFFECTED BY LAND CONFIGURATION AND WOOD-SHAVINGS MULCH IN SEMI-ARID NORTHEAST NIGERIA

By A. M. CHIROMA†, O. A. FOLORUNSO‡ *and* A. B. ALHASSAN

Department of Soil Science, University of Maiduguri, P.M.B. 1069, Maiduguri, Nigeria

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SUMMARY

Water is perhaps the most important single factor that limits crop production in the semi-arid northeast of Nigeria. A four-year field experiment was therefore initiated in 1999 to evaluate the influence of land configuration practices with or without wood-shavings mulch on water conservation, yield and water use efficiency (WUE) of sorghum. The experimental treatments consisted of flat bed (FB), open ridging (OR), tied ridging (TR), FB + mulch (FBM), OR + mulch (ORM), and TR + mulch (TRM). Ridge heights were 15 to 20 cm and furrows were left open (for OR and ORM) or tied (for TR and TRM). Wood-shavings mulch was used at the rate of 5 t ha^{-1} in 1999, but this was increased to 10 t ha^{-1} in subsequent years to ensure adequate soil coverage. Differences in soil water storage at various sampling dates were significant only in some cases in each year, but trends were towards greater soil water storage in the mulched treatments than in the non-mulched treatments, irrespective of tillage method. Growth parameters (plant height and leaf area index) indicated significant differences between treatments on only some measurement dates in each year. Sorghum water use varied significantly between years and treatments. Seasonal water use was greater with FBM, ORM and TRM than with the FB treatment in all cropping seasons. Averaged over the four-year period, mean increases in grain yield relative to the FB treatment were 16 % for OR, 25 % for TR, 77 % for FBM, 50 % for ORM and 57 % for TRM. Pooled across the experimental years, the WUE (ET) of FB, OR, TR, FBM, ORM and TRM were 1.95, 2.12, 2.13, 2.74, 2.36 and 2.48 kg ha^{-1} mm^{-1} respectively. The corresponding WUE(R) values for these treatments were 1.26, 1.46, 1.56, 2.22, 1.88 and 1.97 kg ha^{-1} mm^{-1} respectively. It is concluded that combining the practice of flat bed cultivation with mulching may eliminate the need for ridging in increasing the productivity of sorghum grain in semi-arid northeast Nigeria.

INTRODUCTION

Sorghum (*Sorghum bicolor*) is one of the most important food crops for smallholder farmers in semi-arid northeast Nigeria. However, in the last few decades, local farmers in the savanna region of Nigeria, where the bulk of the crop is grown, have observed a steady decline in its productivity due mainly to soil and climatic constraints. The majority of the soils on which sorghum is grown in northeast Nigeria are sandy, low in organic matter, and contain little silt and clay thereby rendering them structurally unstable (Chiroma, 1996; Chiroma *et al.*, 2002). These soils have the tendency to slake and form surface seals under intense rainstorms causing considerable runoff and soil erosion (Ekwue, 1994). In this area, water availability to crop plants is further limited

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† Corresponding author: Email amchiroma@yahoo.co.uk
‡ Deceased

by the occurrence of frequent drought and high evaporative demand occasioned by supra-optimal temperatures. In the above circumstances, management practices that optimize water conservation and efficient use of precipitation are needed.

In general, the physiological index, known as crop water use efficiency (WUE) (the ratio of grain yield to crop water use) provides a simple means of assessing whether yield is limited by water supply or other factors (Angus and van Herwaarden, 2001). Since, well over 90 % of the water taken up by plants in the field is normally transpired, crop water use efficiency is in effect the reciprocal of what has long been known as the transpiration ratio, defined as the 'ratio of the amount of water transpired to the amount of dry matter produced' (FAO, 1997). In general, the overall concept of agronomic efficiency of water use, F_{ag} can be represented in single equation as:

$$F_{ag} = P/U \tag{1}$$

where P is crop production (total dry matter or the marketable product as the case may be) and U is the volume of water applied through rainfall or irrigation (FAO, 1997).

Studies have shown that evapotranspiration (water removed from soils by evaporation and plant transpiration) is directly related to yield in cereals (Angus and van Herwaarden, 2001; Wang *et al.*, 2004). There is growing evidence that in a given climate, the growth of cereal crops like millet and sorghum is directly related to the amount of water they transpire (Maman *et al.*, 2003). Therefore, for these and other crops, practices that minimize evaporation while at the same time optimizing transpiration are likely to increase the efficiency of water utilization by the crop.

Conservation practices such as ridge tillage (RT) that capture run off water from the field and optimize infiltration have been shown to increase rain water utilization by crop plants in many dryland cropping systems in Africa (Hullugalle, 1990; Kronen, 1994; Nicou and Charreau, 1985; Omer and Elamin, 1997) and elsewhere in the world (Baumhardt *et al.*, 1993; Sow *et al.*, 1997; Unger, 1992*)*. Since the development of animal-drawn implements for ridging, the practice of RT is fast gaining popularity among farmers in semi-arid northeast Nigeria, even without being previously recommended (Chiroma, 1996). Whereas the changes in physical (Chiroma *et al.*, 2004a; Chiroma *et al.*, 2005a) and chemical (Chiroma *et al.*, 2005b) properties of the soil due to this tillage system have been documented, information regarding its efficacy for improving rainwater harvesting and crop yields has not been reported.

Previous studies conducted in northeast Nigeria showed that conservation tillage practices that involve the retention of surface crop residues were effective in reducing evaporation losses and increasing water storage and water use efficiency (Alhassan *et al.*, 1998; Chiroma *et al.*, 2004b). However, these and most other studies utilized small grain straws such as crop residues, and very few evaluated the value of organic wastes other than crop residues as mulch material. Chipped wood from certain tree or shrub species is becoming an increasingly important source of organic amendment in agricultural soils (Lalande *et al.*, 1998). Application of wood chips has been shown to improve soil fertility and maintain soil organic matter (Chiroma *et al.*, 2005b; Hendrickson, 1987), improve soil physical properties (Chiroma *et al.*, 2004c; 2005a),

Table 1. Monthly distribution of rainfall (mm) totals at the experimental site during the study period.

	1999	2000	2001	2002	Mean[†]
April	0	0	0	3	10
May	8	13	37	6	27
June	20	99	119	5	71
July	329	201	110	184	159
August	256	243	244	169	197
September	164	62	217	180	95
October	26	32	TR[‡]	29	9
November	0	0	0	0	0
Total	801	650	613	587	

[†] Long-term (1961–2003) average monthly rainfall.
[‡] TR = trace.

as well as biological properties (Lalande *et al.*, 1998). Wood-shavings are generated in huge amounts by furniture factories and timber sheds spread all over northeast Nigeria. In Maiduguri where the present study was carried out, it is estimated that at least 105 t of timber are brought in daily from the western part of the country (Chiroma *et al.*, 2005b). It is estimated that at least one-sixth of this (about 17.5 t) goes into the production of wood-shavings from the numerous workshops and timber sheds daily. Currently, these organic materials are either used as renewable energy sources, poultry litter or simply dumped as waste with possible adverse effects on the environment (Chiroma, 2004). At present, no other research has evaluated the effectiveness of wood-shavings as a mulch material, although its potential for mitigating the effects of weeds has been demonstrated (Edwards *et al.*, 1994).

A four-year field experiment was therefore initiated in Maiduguri (northeast Nigeria) with a view to assessing the relative efficacy of no-tillage and ridge tillage systems with and without wood-shavings mulch for improving rainwater harvesting, growth, yield and water use efficiency of sorghum under rainfed condition.

MATERIALS AND METHODS

Site and soil characteristics

The experiment was conducted at the University of Maiduguri Research Farm (11°54′N, 13°5′E, alt. 352 m amsl) in northeast Nigeria, during the 1999–2002 rainy seasons. Average annual rainfall (1961–1990) in Maiduguri is 553 mm and the distribution is unimodal, starting on average, in mid-June and lasting until the end of September (Grema and Hess, 1994). The monthly rainfall during the study period for Maiduguri is given in Table 1.

The soil has been classified as a Typic Ustipsamment (Rayar, 1984), loosely aggregated with a sandy loam texture (Chiroma *et al.*, 2004c). The surface 15 cm layer has 69.7 % sand, 18.2 % silt and 12.0 % clay. The slope of the study area was less than 2 %.

Treatments and crop husbandry

The experiment was established as a randomized complete block design with six treatments and four replicates. The treatments consisted of flat bed (FB); open-ridge (OR); tied-ridge (TR); FB + mulch (FBM); OR + mulch (ORM); and TR + mulch (TRM). The FB treatment did not receive any land configuration practice and is the conventional seedbed preparation method for this region. Ridges were made manually using a hoe at 0.75 m apart and about 0.15 to 0.20 m high for the OR and TR treatments. For the OR treatment, furrows were left untied. This method of seedbed preparation is gaining popularity, particularly among farmers who own draught animals (donkey, ox or camel) or who can afford to hire one (Chiroma, 1996). The TR treatment was similar to OR except that furrows were tied at 2 m intervals to create series of microbasins. Ridges and ties were established in July each year prior to seeding when the soil water content was below field capacity. Ridges and ties about 0.3 m high were made using a hand hoe. The layout and configuration of the treatments were maintained throughout the period of the study. All plots were kept free from weeds using a hand hoe; no herbicides were used. The FB and FBM treatments were established each year without prior tillage. The FBM treatment was established by applying wood-shavings uniformly on the surface of a flat bed. The only soil disturbance in the FB and FBM treatments occurred during seeding and occasional weeding. Wood-shavings in ORM and TRM were surface applied in the furrow positions. In all treatments, wood-shavings were added about two weeks after planting (WAP) each year. During the 1999 cropping season, a mulch rate of 5 t ha^{-1} was used, but this was increased to 10 t ha^{-1} during subsequent years to ensure adequate soil coverage. The individual plot size was 10 m × 5 m with 1m margins on both sides to curtail run-on to adjacent plots. Recommended rates of NPK (64:32:30) (FPDD, 1989) were applied to all the treatment plots just prior to planting each year with the N applied in two split doses, half at planting and the remaining half at 4 WAP each year through urea (46 % N). All the P and K was applied as compound fertilizer in the seed row and covered with soil at seeding. Sorghum (variety Paul Biya), native to the area was sown manually on 2 August 1999, 25 July 2000, 11 July 2001 and 28 July 2002. Seeding was done in the furrow positions because the furrow is wetter and cooler compared with the ridge top (Vogel, 1994). Planting was done each year at a spacing of 0.75 m between and 0.45 m within rows. Sorghum plants were thinned to two per stand at 2–3 WAP each year. The crop was harvested on 26 November 1999, 27 October 2000, 2 November 2001 and 3 November 2002.

Water balance calculations

The water balance equation may be expressed as:

$$\triangle S = R + C - ET - D - R_o \tag{2}$$

where $\triangle S$ is the change in soil water storage in the measured profile, R is the rainfall, C is the contribution to the profile by capillary rise from the water table, ET is the evapotranspiration, D is the drainage below the maximum rooting depth and R_o is the runoff (−) or runon (+) over a given time interval. Since the water table was at a depth greater than 10 m (Grema and Hess, 1994), capillary rise can be ignored. Runoff and runon (R_o) was reduced to zero by dikes built around each individual plot. Thus the ET may be estimated from:

$$ET = R - \triangle S - D \tag{3}$$

Drainage (D) losses below the maximum rooting depth were estimated as:

$$D = (\triangle Z)(\triangle \theta)(1000) \tag{4}$$

where $\triangle Z$ is the vertical distance between the maximum rooting depth (m) and the maximum wetting front (m), and $\triangle \theta$ is the difference between the moisture content of this soil layer between grain sowing and harvest ($m^3 m^{-3}$). A maximum rooting depth of 1.9 m was assumed based on earlier work by Zaongo *et al*. (1994).

Three replicates of each treatment were monitored for soil moisture storage. Soil moisture content at 0–2.2 m depth was measured weekly with a calibrated neutron probe at 10 cm depth intervals. A manual rain gauge was installed at the site before the commencement of the trial in 1999.

Crop measurements

Growth parameters (plant height and leaf area index [LAI]) were determined each year on 15 randomly selected plants per plot (60 plants per treatment) at 45, 65 and 80 days after sowing, corresponding to the vegetative, booting and physiological maturity stages of growth respectively. Leaf area index was determined using the method of Pal and Murari (1985). At maturity, a net plot (3 m × 8 m) consisting of the central four rows from each treatment were harvested for determination of yield and yield components. Evapotranspirational water use efficiency (WUE [ET]) was determined as the ratio of grain yield in kg ha^{-1} and evapotranspiration (ET) in mm. However, in the Sahel where rainfall is scarce and is the only source of water supply for crops, the use of evapotranspirational or transpirational water use, as currently cited in the literature, has been criticized for not adequately defining the use efficiency of this scarce resource and/or hiding its inefficient use (Zaongo *et al*., 1994). These workers recommended the use of rainfall use efficiency (WUE [R]) that closely relates efficiency to water supply and crop yield expressed as the ratio of yield to seasonal rainfall.

Data collected were subjected to analysis of variance and means were separated by least significant differences ($p < 0.05$) where appropriate. Growth parameters were related to yield by regression. Partial budgeting was used to assess the costs of production and economic returns to management under different management practices (CIMMYT, 1988).

RESULTS

Soil moisture storage

Soil profile water contents were measured during the growing seasons for comparison of treatment effects on water use. Since measurements were made in

Table 2. Soil profile (0–2.2 m) water storage under different treatments measured at different growth stages during the 2000, 2001 and 2002 growing seasons.

	Moisture storage (mm)								
	2000			2001			2002		
Treatments[†]	Vegetative	Booting	Maturity	Vegetative	Booting	Maturity	Vegetative	Booting	Maturity
FB	187	164	143	91	183	100	78	178	185
OR	204	166	158	108	197	107	90	185	189
TR	195	172	151	107	202	104	98	186	188
FBM	202	168	155	112	205	100	105	183	187
ORM	201	186	173	119	218	106	115	187	185
TRM	194	175	162	122	228	108	123	190	191
s.e.	7.5	11.7	13.9	1.3	8.6	2.8	3.0	1.7	2.8

[†] FB = flat bed, OR = open ridge, TR = tied ridge, FBM = flat bed + mulch, ORM = open ridge + mulch, TRM = tied ridge + mulch.

only one replicate in 1999, only the results for 2000, 2001 and 2002 are shown in Table 2. The major differences between land configuration and mulch treatments can be attributed to the distribution of rainfall between the different phases of crop growth rather than to the total seasonal rainfall. Following high rainfall during the early growing season in 2000, soil water storage in the 2.2 m deep profile ranged from 187 to 202 mm compared with 91 to 122 mm in 2001 and 78 to 123 mm in 2002 with lower early (vegetative) season rainfall (Table 2). This trend reversed during the mid-growing (booting) season. In 2000, this was preceded by limited rainfall resulting in soil water ranges of 164 to 186 mm when compared to the ranges of 183 to 228 mm for 2001 and 178 to 190 mm for 2002 when relatively higher mid-season rainfall was recorded.

The ridge tillage systems with or without mulch and the flat bed with mulch increased the soil profile water storage (though not significantly in some cases) at almost all stages of growth except at harvest over all the three years (Table 2). Averaged across growth stages, the OR, TR, FBM, ORM and TRM treatments stored about 6, 5, 6, 14 and 8 % more soil water respectively than FB in 2000. In 2001, the corresponding increases were 10, 11, 12, 19 and 26 %, and in 2002, 5.5, 7.6, 7.8, 10.6 and 14.4 %. Differences in soil water storage due to OR and TR treatments were significant only on one out of the nine measurement dates.

Seasonal water balance and water utilization

The components of the water balance for each of the three experimental years are presented in Table 3. Seasonal rainfall totals in 2000, 2001 and 2002 were 650, 612 and 587 mm respectively. Irrespective of differences in rainfall, soil profile water contents determined at the beginning of the rainy season were always higher than those determined at harvest time. Over the three years, soil profile water contents determined at the beginning of the rainy season ranged from 104 to 178 mm compared to 44 to 91 mm at harvest. Treatment differences in moisture profiles at planting time

Table 3. Components of water balance (mm) in the top 2.2 m of soil as affected by land configuration and wood-shavings mulch for the three experimental years.

Treatments[†]	Initial	Final	Drainage	Evapotranspiration (ET)
		2000		
FB	141	91	227	474
OR	143	82	213	498
TR	174	81	232	511
FBM	176	56	192	578
ORM	162	59	185	568
TRM	160	57	183	570
s.e.	20.00	0.54	9.00	15.60
		2001		
FB	105	71	151	495
OR	104	57	158	501
TR	104	54	148	514
FBM	104	44	78	594
ORM	104	47	93	576
TRM	104	45	84	587
s.e.	0.33	1.09	10.40	14.10
		2002		
FB	122	70	239	400
OR	132	67	230	422
TR	132	68	234	417
FBM	146	58	178	497
ORM	166	60	203	490
TRM	178	62	207	496
s.e.	4.30	1.42	10.20	14.70

[†] FB = flat bed, OR = open ridge, TR = tied ridge, FBM = flat bed + mulch, ORM = open ridge + mulch, TRM = tied ridge + mulch.

were similar in all years except for 2002 when the water contents were significantly ($p < 0.05$) greater for the mulched (FBM, ORM, TRM) treatments than for the bare soil (FB, OR, TR) treatments. On the other hand, residual moisture at the end of the growing season was significantly ($p < 0.05$) higher in the bare plots than in the mulched plots in all the years studied. Similarly, drainage losses below the maximum rooting depth of 1.9 m were significantly ($p < 0.05$) higher in the bare than in the mulched plots in all years. Drainage losses in the bare plots were 14–22 % higher than the average for the mulched plots in 2000, 74–86 % in 2001 and 17–22 % in 2002. Sorghum water extraction varied significantly ($p < 0.05$) among treatments in all years. Crops in mulched plots utilized more water than their counterparts on bare plots in all the three years. Sorghum on FBM plots utilized the highest amount of water, followed closely by TRM and ORM treatments respectively. Averaged over the three experimental years, water use in the FBM, ORM and TRM treatments respectively were about 18, 16 and 17 % greater than the average for the FB, OR or TR treatments. The FB, OR and TR treatments took up similar amounts of water in all years except in 2000 when TR plants took up about 8 % more water than FB plants.

Plant growth attributes

Plant height. Plant heights are presented in Table 4. Treatment differences at the early (vegetative) phase of growth were significant ($p < 0.05$) only in 2002 when plants grown in all the mulched plots were taller than those in the bare plots. However, with the advancement in growth, i.e. at booting (mid) and physiological maturity (late) development stages, mulching often resulted in taller plants. At both booting and physiological maturity, plants grown in the FBM, ORM and TRM plots were significantly ($p < 0.05$) taller than those grown in the FB plots during the four-year study period. Plants were tallest in the FBM plots at both booting and physiological maturity stages of growth in any given year. Averaged across growth stages, the height of plants under the mulched treatments exceeded those in the FB treatment by 31–43 % in 1999, 14–26 % in 2000, 15–24 % in 2001 and 11–30 % in 2002.

Leaf area index. Differences in LAI among treatments at the early (vegetative) stage of growth were significant ($p < 0.05$) only in 1999 and 2002 (Table 4). However, treatment differences became greater with the advancement in growth in each year. Irrespective of rainfall, LAIs during both booting and mature stages of growth were higher in FBM, ORM and TRM than in FB, OR or TR plots. Averaged across growth stages, LAIs in the mulched treatments were 33–35 % more than in the control (FB) in 1999, 19–53 % more in 2000, 27–42 % more in 2001 and 8–19 % more in 2002.

Grain yield. The analysis of variance (Table 5) indicated that there were highly significant ($p < 0.01$) differences in grain yield as a result of year (YR), mulch (M) and land configuration and mulch (LC × M) interactions. Sorghum grain yields varied considerably both between years and between treatments within a year (Table 6). Flat bed with wood-shavings mulch significantly ($p < 0.05$) increased grain yield when the annual rainfall was above average in 1999, 2000 and 2001, and when it was near average in 2002 (Table 6). The FBM treatment out yielded FB by 584 kg ha^{-1} (97 %) in 1999, 551 kg ha^{-1} (55 %) in 2000, 816 kg ha^{-1} (104 %) in 2001 and 544 kg ha^{-1} (63 %) in 2002. The response of grain yield to open and tied ridging with wood-shavings mulch (ORM and TRM respectively) was also significant ($p < 0.05$) in all four cropping seasons. Grain yields in ORM exceeded those in FB by 69 % in 1999, 33 % in 2000, 77 % in 2001 and 32 % in 2002. The increases due to TRM were 67 % in 1999, 44 % in 2000, 86 % in 2001 and 40 % in 2002. Grain yield differences between FBM, ORM and TRM were only significant in 2002 when ORM was significantly less than FBM by 19 %.

Grain water use efficiency

Significantly ($p < 0.05$) different WUE (ET) and WUE (R) were measured in all the years studied (Table 7). These two parameters also varied between years. Both WUE (ET) and WUE (R) for FBM, ORM and TRM were significantly ($p < 0.05$) higher than for FB in each year. Overall, the highest values of both parameters were recorded in FBM plots in all the years studied. Averaged over three experimental years, WUE (ET) with FBM, ORM and TRM exceeded that of FB by 41, 21 and 27 % respectively. The mean increases in WUE (R) due to these treatments were 76,

Table 4. Mean plant height and leaf area index (LAI) of sorghum as affected by land configuration and wood-shavings mulch.

	1999				2000				2001				2002			
Treatments[†]	Veg[‡].	Boot.	Mat.	Mean	Veg.	Boot.	Mat.	Mean	Veg.	Boot.	Mat.	Mean	Veg.	Boot.	Mat.	Mean
								Plant height (cm)								
FB	39	70	138	82.	40	134	148	107	37	172	184	131	28	162	181	124
OR	40	98	159	99	42	149	160	117	47	180	193	140	37	165	183	129
TR	39	68	156	86	44	152	165	120	47	182	196	142	40	171	187	133
FBM	42	134	178	118	57	164	186	136	54	211	222	162	65	198	220	161
ORM	42	107	174	108	47	151	168	122	48	189	214	150	48	174	191	138
TRM	41	119	172	111	53	154	179	129	51	194	219	55	55	178	199	144
s.e.	4.6	10.7	1.4	4.8	6.4	2.3	2.9	2.4	4.3	5.4	2.5	2.8	5.9	2.4	4.4	2.4
								LAI								
FB	0.32	0.65	0.75	0.57	0.34	0.68	0.73	0.58	0.21	0.71	0.88	0.60	0.28	0.97	1.08	0.78
OR	0.32	0.70	0.80	0.60	0.36	0.72	0.75	0.61	0.27	0.81	1.04	0.71	0.31	1.05	1.14	0.83
TR	0.40	0.71	0.88	0.63	0.37	0.78	0.80	0.65	0.25	0.84	1.05	0.72	0.32	1.02	1.14	0.83
FBM	0.42	0.93	0.97	0.77	0.43	1.01	1.23	0.89	0.31	0.98	1.25	0.85	0.37	1.12	1.28	0.93
ORM	0.42	0.91	0.96	0.77	0.40	0.81	0.87	0.69	0.28	0.86	1.12	0.76	0.32	1.03	1.15	0.84
TRM	0.42	0.91	0.95	0.76	0.41	0.90	0.93	0.75	0.31	0.97	1.23	0.84	0.34	1.06	1.16	0.85
s.e.	0.026	0.006	0.007	0.015	0.043	0.016	0.022	0.024	0.049	0.056	0.074	0.036	0.007	0.027	0.036	0.014

[†] FB = flat bed, OR = open ridge, TR = tied ridge, FBM = flat bed + mulch, ORM = open ridge + mulch, TRM = tied ridge + mulch.

[‡] Veg. = Vegetative, Boot. = Booting, Mat. = Maturity.

Table 5. Analysis of variance table for grain yield.

Source of variation	DF	MS	$p > F$
Block	3	4178	
Year (YR)	3	570051	0.0000
Land configuration (LC)	2	37140	0.2780
Mulch (M)	1	3566261	0.0000
YR × LC	6	37494	0.2615
YR × M	3	42597	0.2234
LC × M	2	340750	0.0000
YR × LC × M	6	42518	0.1935
Error	69	28478	

Table 6. Effects of land configuration and wood-shavings mulch on grain yield of sorghum.

	Grain yield (kg ha^{-1})				
Treatments[†]	1999	2000	2001	2002	Mean
FB	599	1007	782	858	812
OR	758	920	1186	904	942
TR	997	980	1212	884	1018
FBM	1183	1558	1598	1402	1389
ORM	1015	1338	1383	1134	1217
TRM	1000	1448	1456	1199	1321
Mean[‡]	925	1208	1269	1063	
s.e.	69.4	81.0	108.2	75.9	42.2

[†] FB = flat bed, OR = open ridge, TR = tied ridge, FBM = flat bed + mulch, ORM = open ridge + mulch, TRM = tied ridge + mulch.

[‡] Standard error of difference between means of treatments across years = 34.45.

49 and 56 % respectively. Differences in both WUE (ET) and WUE (R) between FB, OR and TR did not show any consistent yearly pattern. For example, WUE (ET) was greater with OR and TR than with FB in 2001 but showed the opposite trend in 2000 and 2002. Similarly, WUE (R) with OR and TR were greater than with FB in 1999, 2001 and 2002, but this difference was reversed in 2000. The regression equation between the four-year average grain yield and the four-year average rainfall water use efficiency is:

$$\mathrm{GY} = -1.5 + 648[\mathrm{WUE(R)}]\ (n = 6; r = 0.99^{**}) \tag{5}$$

where GY is grain yield (kg ha^{-1}) and WUE(R) is rainfall water use efficiency (kg ha^{-1} mm^{-1}).

Economic benefits

The results of the economic analysis show that only the FB and FBM treatments are expected to yield monetary benefits to farmers when the cost and returns from the soil treatments are compared (Table 8). The FBM treatment is expected to increase considerably the financial benefits to farmers (238 %) compared to the FB. High production costs associated with the OR, TR, ORM and TRM resulted in net economic losses of about 1, 0.5, 11 and 12 % respectively. The cost of production with

Table 7. Effects of land configuration and wood-shavings mulch on grain water use efficiency of sorghum.

	Grain water use efficiency (kg $ha^{-1}mm^{-1}$)								
	WUE (ET)				WUE (R)				
Treatments[†]	2000	2001	2002	Mean	1999	2000	2001	2002	Mean
FB	2.12	1.58	2.15	1.95	0.75	1.55	1.28	1.46	1.26
OR	1.85	2.37	2.14	2.12	0.95	1.42	1.94	1.54	1.46
TR	1.92	2.36	2.12	2.13	1.24	1.51	1.98	1.51	1.56
FBM	2.70	2.69	2.82	2.74	1.48	2.40	2.61	2.39	2.22
ORM	2.36	2.40	2.31	2.36	1.27	2.06	2.26	1.93	1.88
TRM	2.54	2.48	2.42	2.48	1.25	2.23	2.38	2.04	1.97
Mean[‡]	2.25	2.31	2.33		1.16	1.86	2.07	1.81	
s.e.	0.059	0.089	0.040	0.080	0.090	0.120	0.180	0.130	0.070

[†] FB = flat bed, OR = open ridge, TR = tied ridge, FBM = flat bed + mulch, ORM = open ridge + mulch, TRM = tied ridge + mulch.

[‡] Standard error of difference between means (across years) of WUE (ET) = 0.027 and WUE (R) = 0.050.

Table 8. Cost of production and economic return to six management practices for production of sorghum.

	Management practices					
Farm operation	FB[†]	OR	TR	FBM	ORM	TRM
[A] Production cost (N ha^{-1})						
Land preparation	1000	4000	4500	1000	4000	4500
Weeding	4000	6000	7000	4000	6000	7000
Other costs	14 334	14 699	14 911	26 080	25 469	25 634
Total variable cost of production	19 334	24 699	26 411	31 080	35 469	37 134
[B] Yield kg ha^{-1}						
i) Grain	812	942	1018	1435	1217	1276
ii) Straw	3160	3465	3675	4934	4393	4474
[C] Gross revenue[§]	21 058	24 338	26 270	26 907	31 405	32 861
[D] Return to management	1724	– 361	– 141	5827	– 4064	–4273
Benefit-Cost ratio	1.09	0.99	0.99	1.19	0.89	0.88

[†] FB = flat bed, OR open ridge, TR = tied ridge, FBM = flat bed + mulch, ORM = open ridge + mulch, TRM = tied ridge + mulch.

[‡] Four year average yield.

[§] Yield x Unit price of N2, 400 per 100 kg bag of grain and N5 per 10 kg bale of straw.

US $1 = N 145 official exchange rate.

these treatments exceeded that of FB by 28, 37, 83 and 92 % respectively. Although wood shavings are obtained free of charge, the costs associated with its handling alone accounted for between 28 and 34 % of the total cost of production with FBM, ORM and TRM.

DISCUSSION

Soil moisture storage

Mulching, irrespective of land configuration practice, resulted in significantly ($p < 0.05$) more soil profile water storage than the bare soil counterparts on most of the sampling dates in 2001 and 2002. Treatment differences in soil profile water storage were not significant during each crop development stage in 2002 except at harvest time where the bare soil treatments had more than the mulched treatments. An improvement in total soil water storage in the profile under the ORM and TRM treatments could be partly attributed to the surface modifying effects of ridging which tended to prevent runoff and increased the time of ponding for infiltration (Omer and Elamin, 1997), and partly to the reduction of evaporation losses due to the presence of a surface mulch and a larger leaf canopy. Similar results have been reported elsewhere in Nigeria (Maurya, 1986; Olasantan, 1999) and from the same experimental site (Alhassan *et al.*, 1998; Chiroma *et al.*, 2004b).

However, soil moisture conservation due to the FBM, OR and TR treatments were always similar except at harvest when soil profile moisture storage due to OR and TR was higher than for FBM. This lack of superiority of FBM over OR and TR does not necessarily imply the inefficacy of the FBM treatment for increasing water conservation on these coarse textured soils. A probable explanation is that, as a consequence of the better soil environment, as indicated by lower bulk density and penetration resistance (Chiroma *et al.*, 2005a), and higher total porosity (Chiroma *et al.*, 2004a) and nutrient availability (Chiroma *et al.*, 2005b) plants in the FBM plots utilized the profile water more efficiently than plants in the OR and TR treatments (Table 3). The crop in FBM plots utilized between 67–80 mm more soil water than the OR and TR crops in 2000, 80–93 mm more in 2001, and 75–80 mm more in 2002. More efficient utilization of water and nutrients by plants in mulched soil could be attributed to deeper and denser rooting (Gajri *et al.*, 1994; Sow *et al.*, 1997). Differences in soil water conservation due to OR and TR were not significant at any time during the study. This was probably due to similar evaporation losses from the open and tied-ridged plots (Baumhardt *et al.*, 1993).

Water balance

In all four seasons (1999–2002), rainfall was greater than the long-term average for the experimental site. Because planting was done about 24 hours following a ‘good’ rainfall, there was always enough water in the soil profile at the time of sowing, even in 2000, which had the least favourable rainfall distribution (Table 1). This observation explains why treatment differences in soil profile water content at the date of sowing were not significant except in 2002 when soil profile water content was greater ($p < 0.05$) for the mulched (FBM, ORM and FRM) than for the bare soil (FB, OR and TR) treatments. Residual soil moisture at the end of the growing season was higher in the bare than in the mulched plots in each year studied (Table 3). This was attributed to poor plant water utilization, and higher drainage losses in the bare plots, in the three years, than in the mulched plots. The range of drainage of 78–234 mm at 1.9 m depth observed compares well with the range of 76–234 mm recorded by Zaongo *et al.* (1994) at 1.6 m depth. Irrespective of differences in land configuration practice or rainfall, sorghum in mulched plots utilized more water than in bare plots (Table 3). The overall average water utilization (2000–2002) of

FBM, ORM and TRM plots was 21, 19 and 21 % greater than that of FB. Greater water extraction with the mulched treatments was partly the result of increased water holding capacity (between P_{-33} and P_{-1500} kPa) in the top 0.15 m depth (Chiroma *et al.*, 2004a). Greater availability of soil water in the root zone profile may have enhanced root proliferation and the availability of nutrients (Selvaraju *et al.*, 1999; Sow *et al.*, 1997). Deeper and denser rooting in mulched soil helps plants to use water and nutrients from the subsoil more efficiently (Arora *et al.*, 1991). On the other hand, the reduction in water use with the bare treatments, particularly with FB could have resulted predominantly from lack of available water as a result of the greater soil strength and smaller total porosity (Chiroma *et al.*, 2005a) This is consistent with the findings of previous studies that reductions of ET with no-tillage may be associated with higher levels of soil strength (López and Arrúe, 1997). Soil compaction can restrict root growth and hence the access to water and nutrients from deeper layers (Sow *et al.*, 1997). Although total rainfall in 2000 (650 mm) was greater than that in 2001 (612 mm) and 2002 (587 mm), the greatest seasonal ET over the three years was recorded in 2001. Seasonal ET in 2001 ranged from 495 to 594 mm compared with 474–578 mm in 2000 and 400–497 mm in 2002. These differences could have resulted from the variations in rainfall distribution. For example rainfall was better distributed in 2001 than in either 2000 or 2002 (Table 1). In 2001, rainfall was frequent (on average one event in five days) between July and September, leading to greater availability of soil water throughout most of the growing season. This accounted for the significant ($p < 0.05$) year to year variation in yield response (Table 6). Yields for 2001 were larger than for other years because the plants had more available water during vital stages of plant growth.

Plant growth attributes

Plant height and LAI during the vegetative growth phase were only influenced by land configuration and wood-shavings mulch in some years. This is probably due to drying of the soil in the vicinity of the small root system of the young plants, which might have resulted in decreased root growth. Because wood-shavings were applied about 2 WAP in each year, evaporation demand during the early growth phase when the soil was devoid of cover, may have been so great that adequate water was not moved to the limited root system or perhaps the roots did not expand rapidly enough into wet soil to meet plant water requirements (Jama and Ottman, 1993). However, with advancement in growth, i.e. at both booting (mid) and physiological maturity (late) crop development stages, mulching often produced evidence of better crop growth as measured by plant height and LAI which then translated into higher yields ($p < 0.05$). Leaf area index indirectly controls crop growth rate by influencing light interception and net assimilation rate (Carpenter and Board, 1997). The enhanced growth observed in the mulched treatments over the unmulched treatments could be due partly to the more favourable moisture regime in the root zone of the mulched treatments and partly to more efficient utilization of nutrients released from decomposition of the added wood-shavings mulch by the crop (Chiroma *et al.*, 2005b).

Grain yield

Grain yields varied considerably between both years and treatments (Tables 5 and 6). Differences in growing season rainfall distribution may have been responsible for the large year to year variations in yield. There was a substantial difference (215 mm) between the wettest (1999) and driest (2002) cropping season's rainfall. Grain yield (averaged across treatments) was highest in 2001, the year that had the most favourable rainfall distribution. Because planting in the wettest year (1999) was delayed up to 2 August, the sorghum matured late in November when the rains had essentially ceased. Hence the severe drought experienced during the critical grain filling stage affected yield that year. Supporting evidence can be found in the data collected on plant height. Earlier studies have also shown that delayed sowing is generally associated with yield decline in sorghum (Andrews, 1973). Sorghum grain yield was significantly ($p < 0.01$) influenced by M and LC × M interactions (Table 5). The FBM treatment increased grain yield when the annual rainfall was above average (1999–2001) and near average in 2002. The responses of grain yield to the ORM and TRM treatments were similar to that of the FBM treatment in all four cropping seasons. Mulching often produced evidence of better growth, as measured by plant height and LAI, which then translated into higher yields. The improved growth and yield of sorghum in the mulched treatments was attributed to a greater soil profile water content, higher nutrient availability in the 0–7.5 cm layer and more protection from erosion as compared with the bare treatments (Bielders *et al*., 2002; Chiroma *et al*., 2005b). These results confirm the findings of earlier experiments in northeast Nigeria (Alhassan *et al*., 1998; Chiroma *et al*., 2004b) that tillage practices involving retention of residues on the surface increase crop yields by improving the efficiency of use of that growing season's precipitation. These results also support data from semi-arid India (Selvaraju *et al*., 1999), which showed that combining tied ridging with coir dust increased soil water storage and grain yield of rainfed sorghum compared to flat bed cultivation on an Alfisol. Our results show that differences in sorghum grain yield as a result of LC, YR × LC, YR × M or YR × LC × M interactions were not significant on these coarse-textured soils (Table 5). The responses of sorghum grain yield as a result of OR and TR treatments were significant only in one and two years respectively out of the four cropping seasons. These treatments, however, recorded sorghum grain yield 9 and 3 % lower, respectively in 2000 than FB. This could be explained by the lack of rain at the flowering and grain filling stages of growth when only 94 mm of rain were received between flowering and harvest as compared to 190, 217 and 219 mm received during the same periods in 1999, 2001 and 2002 respectively. Lack of rain at flowering and grain filling had earlier been shown to decrease sorghum grain yields in a dry environment (Tewolde *et al*., 1993). Studies have shown that the potential of furrow diking (tied-ridging) for improving dryland yields depends on a number of factors such as rainfall amount, intensity and distribution (Gerard, 1987; McFarland *et al*., 1991), soil characteristics including slope, landscape position and soil texture (Wistrand, 1984). McFarland *et al*. (1991) found no effect of furrow diking on grain yield of maize (*Zea mays*) when the annual rainfall was below average with a tendency for there to be a negative effect when the annual rainfall was above average. Gerard

(1987) summarized the results of his seven-year study in the Rolling Plains of Texas and showed that the effectiveness of furrow diking in increasing grain yield of sorghum depended on the amount of rain during the growing season.

In an environment where rainfall is not only erratic but fluctuates every year, information on crop yield stability becomes much more relevant than annual yield increases (Omer and Elamin, 1997). Sorghum grain yields of <1000 kg ha^{-1} were not produced in any of the four years for FBM and ORM treatments, but occurred three times for FB, OR and TR treatments and once for TRM treatment (Table 6). A grain yield of >1500 kg ha^{-1} was obtained twice in four years for FBM treatment, but not at all in the other tillage systems.

Grain water use efficiency

Treatment effects on evapotranspiration water use efficiency, WUE (ET) and rainfall water use efficiency, WUE (R) showed a similar pattern to seasonal water use, where the mulched treatments responded better than their bare soil counterparts (Table 7). Both WUE (ET) and WUE (R) tended to be greater in FBM, ORM and TRM than in FB, OR or TR treatments in each year except in 2001 when the differences between the ORM, TRM, OR and TR treatments were not significant. Similar data on the beneficial effects of organic solid waste management on WUE have been reported in the study area (Alhassan *et al*., 1998; Chiroma *et al*., 2004b) and from elsewhere in a dry climate (López and Arrúe, 1997). These and other studies have shown that increasing the soil water available to crop and/or reducing evaporation from the soil are among the possible ways by which water use efficiency can be improved in dry land farming systems. The data on sequential monitoring of soil moisture profiles during the growing seasons (Table 2) appear to lend credence to this general conclusion. The root zone profiles in the mulched plots were frequently wetter than the bare plots. Similarly, the data on pore size distribution and soil water retention properties indicate that both the proportion of water retention micropores (diameter > 36 μm) and available water holding capacity (between P_{-33} and P_{-1500} kPa) in the top 0.15 m layer were higher in the mulched treatments than in the bare soil treatments (Chiroma *et al*., 2004a). The greater amount of water stored in the root profiles of the mulched treatments during the successive growing seasons resulted in higher yields and this, therefore, was a major factor contributing to the increase in WUE.

Both bulk density and penetration resistance in the top 0.15 m layer were greater in FB, OR and TR treatments than in FBM, ORM or TRM (Chiroma *et al*., 2005a). Hence the better WUEs under the mulched treatments are attributable to the cumulative effects of improved soil physical conditions and greater storage of rainwater in the profile, thereby creating a environment conducive to crop growth. On the other hand, the lower WUE (ET) and WUE (R) of the bare soil treatments could be attributed to soil compaction which probably reduced root growth and hence access to water and nutrients by crop roots (López and Arrúe, 1997). Our results show that neither OR nor TR consistently increased grain WUE indicating that ridging (open or tied) in the absence of a residue mulch may not be an improvement over a flat bed in increasing grain sorghum WUE in semi-arid northeast Nigeria. The values of sorghum WUE (ET) and WUE (R) reported in this study are within the range of values reported by Zaongo *et al*. (1994) in the Sahel. The trend in WUE (ET) mirrored that of WUE (R) thus indicating good agreement between the two methods.

Economic benefits

Although total costs of production with the FBM treatment were the third highest among the six management practices, the relatively higher grain and straw yield (data not shown) were responsible for the highest economic return. However, the increases in grain and straw yields due to the ORM and TRM treatments were unable to compensate for their higher production costs. Therefore, flat bed in conjunction with mulching was found to be superior to flat bed without mulch or ridge tillage with or without mulch in the production of grain sorghum.

CONCLUSIONS

This study indicates that capturing rainfall for increased soil water storage is a critical factor to increasing yield and WUE of rainfed sorghum. The FBM treatment increased soil water storage, yield and WUE of sorghum, irrespective of rainfall category. The ORM and TRM treatments were in this respect superior to the FB, OR and TR treatments in all the years studied but were not as effective as the FBM treatment, particularly with respect to yield and WUE. Neither the OR nor the TR treatments consistently increased soil water storage, yield and WUE of sorghum, indicating that ridging (open or tied) in the absence of a residue mulch may not be an improvement over a flat bed in improving the productivity of rainfed sorghum in semi-arid northeast Nigeria. Based on these results, the FBM treatment appeared to be a viable alternative to the farmers' practice of planting sorghum on either ridge-tilled or flat bed without residue mulch. Although ridging (open or tied) in conjunction with mulching was found to be effective in increasing soil water storage, yield and WUE, higher production costs limited the profitable application of the ridge tillage systems. One possibility for enhancing the profitability of the ORM and TRM is to reduce the costs associated with constructing and/or maintaining new ridges which from our estimate accounts for about one-third of the total cost of production with these two treatments. Studies in Malawi have shown that for the smallholder farmers who may have difficulties in meeting their labour requirement, existing ridges can be used without affecting yield at least in the first two years after they were constructed (Materechera and Mloza-Banda, 1997). Since the effect of tillage and residue management is site specific, there is the need to verify the possibility or otherwise of utilizing ridges constructed the previous season for crop production under the climatic conditions of northeast Nigeria. Further studies are also needed to i) assess whether or not the additional water conserved from land configuration and mulching during the crop growing season will be adequate to support a crop like guna (cow melon) that relies on the residual moisture from the preceding seasons cropping, and ii) assess the effects of long term additions of wood-shavings on microbial population and activity.

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