Water Conservation Technologies for Sustainable Dryland Agriculture in Sub-Saharan Africa
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Technologies for Improving Green Water Use Efficiency in West Africa

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When a 'natural' landscape is transformed into a 'cultural' landscape this affects the field water balance: runoff and evaporation increase, while infiltration and transpiration decrease. This has direct and indirect effects on the fraction of the rainwater that is used for biomass production: the Green Water Use Efficiency (GWUE). Water Conservation (WC) practices reduce erosion, improve soil qualities and increase GWUE. In semi-arid Africa WC can easily double GWUE, can improve food security and can also provide the water needed for the 'regreening' of land use systems. Five WC practices are described that have locally successfully contributed to a higher GWUE in West Africa. (1) The runoff from mulched plots (6000 kg ha^{-1}) was 35 % of that from non-mulched plots, while runoff threshold values increased from 5.0 to 6.4 mm. (2) Stone rows makes that sorghum water demand (ET:ETc ratio) is satisfied more often than without this WC practice (3) Vegetation barriers, in particular with the perennial grass *Andropogon gayanus* proved to be very effective in reducing runoff to only 20 % of precipitation. (4) Water conservation tillage (braking the surface crust every 15 days) without an additional increase in external nutrient inputs only had a marginal effect. However, with a complete prevention of runoff (as seems possible with tied ridging) the vegetative period is prolonged and an increase in yield of no less than 40 % seems possible. (5) Termite 'management' reduces runoff significantly. Although WC seems beneficial two important lessens can be drawn from integrative studies. The first is that there is no efficient WC without improved nutrient management. This is proven by the fact that when semi-permeable barriers (stone rows or grass strips) are combined with compost application the synergetic effect is a tripled grain yield. The second lesson is that with WC easily too much water can infiltrate into the soil. In permeable soils this leads to nutrient leaching below the root zone and highering of the groundwater (in some case a much wanted effect). In soils with less impermeable deep layers this leads to saturation of the top soil, causing water logging and risk for saturation overland flow.

Keywords: *mulch, stone rows, vegetation barrier, water-nutrient synergy, field water balance*

Introduction

Rainfed agriculture is predominant in the world. Almost 80 % of the agricultural land is in use by rainfed production systems, providing for 60 % of the world food production. In semi-arid regions rainfed agriculture is coping with unreliable rainfall and recurrent droughts with subsequent production failures. Although irrigation plays an important role in food production, the possibilities of further extension seem to be limited since water resources of sufficient quality become scarce or too expensive to use. Since an increasing population requires an increased food production, more efficient use of rain in rainfed agriculture therefore deserves an increased (scientific) attention.

Precipitation Use Efficiency (PUE) is defined as the yield divided by the precipitation (eventually corrected for differences in stored water between subsequent years: ΔW). PUE is expressed in kg ha^{-1} mm^{-1} and ranges from 4 (low) – 10 (improved). PUE is particular useful in agricultural systems with a distinctive harvestable yield. However, in more general 'ecosystems' discussion and in relation to the issue of carbon sequestration in soils, it is the total amount of produced biomass that matters, (Stroosnijder and Hoogmoed, 2002). For given species and location there is a good relation between the amount of produced biomass and the amount of transpired water. Therefore, in terms of water use efficiency it is of more relevance to use the concept of 'Green Water'. Green Water is defined as 'the fraction of rain water that infiltrates into the rooted soil zone and that is used, through the process of transpiration, for biomass production' (Ringersma, 2003). Green Water Use Efficiency (GWUE), expressed as the fraction T/P, ranges in dryland systems in sub Saharan Africa from 5-15 %.

The goal of GWUE improvement is to maximize the productive flow of water as plant transpiration and to minimize the non-productive water flows, including soil evaporation, run-off and percolation beyond the rootzone.

In conditions where there is still a continuous cover of 'natural' vegetation, the land and the field water balance (Precipitation–Runoff = Infiltration = Transpiration + Evaporation + Drainage below the rootable depth) are in equilibrium. Erosion and hydrology have shaped the land into a landscape with its soils, topography and drainage system. In a 'cultural landscape' all the changes in physical, chemical and biological soil properties directly and indirectly affect the field water balance (Stroosnijder, 1996). Food crops, for instance, cover the soil for only part of the year and therefore this land use uses less water for transpiration than the 'natural' vegetation that covers the soil permanently. The surplus water flows through the soil down to the groundwater (higher water tables) or flows over the soil surface as overland flow in sheet flow or in rills. Rain that hits bare soil causes soil aggregates to break up. This further reduces the infiltration of rainwater through the soil surface, in turn creating more overland flow. In other words, in a complex combination of both direct and indirect processes, the proportion of the rain that is effectively used by vegetation decreases and the proportion that discharges increases. The result is that in current land use systems runoff and soil evaporation are often excessive, leaving little of the rainfall to be taken up by plants and transpired.

Mitigating the deterioration of soil qualities, Feller et al. (2001) wrote 'we need new land use alternatives at different scales with more organic matter restitutions and soil organic carbon retention'. According to the SSSA (2001) this can be achieved by applying currently recognised best management practices. In semi-arid regions this can be achieved in the form of parklands, live fences and hedges, boundary trees, etc. However, all this green material transpires water that is thought to be the factor limiting production in semi-arid regions. So, many people still believe that greening of current land use systems can only occur at the expense of the already insufficient food crop production.

However, WC reduces runoff and evaporation, thus leaving a greater share of the rainfall for green biomass. By enhancing GWUE, WC practices can easily provide more available water for both food crops as well as for the regreening of current land use systems.

This paper presents the scientific proof of a number of WC practices used successfully by farmers in West Africa.

Mulching

Introduction

Recently, mulching is becoming a general farmers' practice in the Sahel. Mulching reduces runoff (or in other words increase infiltration) and evaporation. Early measurements by Stroosnijder and Kone (1982) showed that cumulative actual soil evaporation (Σ E) between showers in the growing season can be described by:

$\Sigma E = f(LAI) * PEVAP + 3.5 * (t^{0.5} - 1)$, where f(LAI) is a correction term depending on the leaf area index of the cover, PEVAP is the potential evaporation (in Mali this could be approximated as 70 % of open pan evaporation), t is the number of days since the previous rain. The cover only affects evaporation on the day after the rainfall. Thereafter the cumulative evaporation is proportional to the square root of time. The proportionality factor of 3.5 was constant for a variety of soils, ranging from sand to clay, and was also found for sandy soils in Senegal (Hall and Dancette, 1978 in Stroosnijder and Hoogmoed, 1984). The seasonal evaporation for the south-Sahelian region calculated according to the above simple model showed that the average daily evaporation over the growing season decreases from 2.5 mm d^{-1} for bare soil to 1.5 mm d^{-1} for a soil with a vegetation cover characterised by LAI = 1.

Materials and methods

Experiments (Slingerland and Masdewel, 1996) have been conducted in Tagalla in the Sudano-sahelian zone of Burkina Faso. Mean annual rainfall (1962-1992) is 650 mm and rainfall was 625 mm in 1996 and 540 mm in 1997. The experiments were carried out on a Chromic Luvisol (pH(H_2O) 6.4 with 1.4 % SOC), between stone bunds that were installed to conserve soil and water. The experiment consisted of 6 blocks, each comprising 4 plots of 100 m^2 each. There were four treatments: (1) a control, (2) mulching (6000 kg ha^{-1} dry matter), (3) mulching (6000 kg ha^{-1}) + manure (2000 kg ha^{-1}) and (4) mulching (6000 kg ha^{-1}) + natural phosphate (200 kg ha^{-1}). *Loudetia togoensis* hay (0.23 % N, 0.002 % P and 0.08 % K) that could not be used for grazing anymore was cut on adjacent rangeland and transported to the experimental plots. Manure (1.66 % N, 0.4 % P and 1.14 % K) came from small ruminants. Rock phosphate (Burkina Phosphate; 0 % N, 11.20 % P and 0.19 % K) was applied in the form of powder. Runoff and soil evaporation were measured according to Stroosnijder and Koné (1982).

Results and discussion

The runoff from the mulched plots was on average only 35 % (the range was 8–51%) of the runoff from non-mulched plots. Threshold values (i.e. the shower size below which no runoff will occur) increased from 5.0 to 6.4 mm (Table 1). ANOVA showed that mulching significantly reduced runoff during the entire growing season. However, the effect decreased towards the end of the season as the mulch decomposed due to severe termite activity.

Table 1 *Threshold values (mm) for different periods of the rainy season for mulched and non-mulched fields in Tagala, Burkina Faso.*

Period	Without mulching	With mulching	No.of showers
Sowing to 1st weeding	1.0 (r = 0.95)	7.4 (r = 0.94)	9
Sowing to 2nd weeding	2.5 (r = 0.96)	5.9 (r = 0.96)	14
Sowing to 3rd weeding	5.3 (r = 0.95)	7.0 (r = 0.90)	34
1st w.- end of rainy season	5.2 (r = 0.97)	6.3 (r = 0.92)	32
Average rainy season	5.0 (r = 0.95)	6.4 (r = 0.90)	41

The weight loss of micro lysimeters, used to measure soil evaporation, on bare soil was 17.2 g (± 6.5) and 6.9 g (± 2.3) on mulched plots. ANOVA showed that these differences were significant at $p < 0.0001$. Daily soil evaporation expressed in mm appeared to be reduced by 53 % (from 2.6 mm d^{-1} to 1.2 mm d^{-1}).

Primary production of sorghum was greater on mulched fields (1340 to 2730 kg DM of stover and 395 to 1060 kg grain ha^{-1}) than on fields receiving no amendments at all (200 to 480 kg DM and 45 to 140 kg grain ha^{-1}), especially when mulching was associated with other organic inputs such as manure.

Applying 6000 kg ha^{-1} of mulch resulted in a deficiency in phosphorus (P). This deficiency can apparently be rectified by applying manure (2000 kg ha^{-1}) or rock phosphate (200 kg ha^{-1}). However, applying phosphorus increased the N uptake, and the outcome was a negative N balance. Thus, the treatment 'mulch only' has some risk of depleting the soil of phosphorus, while the combination of 'mulch + rock phosphate' might use up the nitrogen reserve in the soils more rapidly. The only treatment that increased production without depletion of soil nutrients was the application of both N and P with mulch.

The above data were used in a recent study by Stroosnijder et al. (2001): 2.0 mm d^{-1} soil evaporation under extensive cropping, 1.5 mm d^{-1} under mulch and 1.0 mm d^{-1} for more intensive production technologies.

Stone rows

Introduction

Various studies have demonstrated the benefits to the soil water balance of semi-permeable obstacles such as stone rows and live hedges (e.g. Perez et al., 1998). The technique is particularly efficient in reducing runoff and in improving rainwater infiltration; because of its filtering function it also reduces fine sediment transport (Mando et al., 2001).

Materials and methods

This study, conducted in the north of Burkina Faso (annual rainfall 800 mm, PET of 2000 mm y^{-1}) assessed the combined and interactive effects of two types of permeable barriers (stone rows and grass strips of *Andropogon gayanus Kunth cv. Bisquamulatus (Hochst.) Hack.*) and organic or mineral sources of nitrogen on erosion control and sorghum performance (Zougmore et al., 2003). The field experiment (Ferric Lixisol, 1.5 % slope) consisted of two replications of 9 treatments in which the barriers were put along contours and combined with compost (7000 kg ha^{-1}, equivalent to 50 kgN ha^{-1}), manure (5000 kg ha^{-1}, equivalent to 50 kgN ha^{-1}), and mineral nitrogen (50 kgN ha^{-1}).

Results and discussion

Stone rows induced more surface water storage and infiltration than the grass strips (Table 2). Compared to grass strips, the architecture of stone rows allowed the runoff velocity to be reduced more than was the case when the barriers were grass strips. Furthermore, because the grass strips take at least one month to regrow after the long, harsh, 6-month dry season, they are less effective at the start of the rainy season (Zougmoré et al., 2002).

This is confirmed by the data in Figure 1, which showed that sorghum water demand (ET:ETc ratio) was satisfied more in the plots with stone rows than in the plots with grass strips. Grass strips increase the ET because at full growing stage their water need (transpiration) can be as high as 35 mm over an 8-day period (Ringersma and Sikking, 2001).

In 2001, crop water demand was satisfactory (ET:ETc > 0.75) during the vegetation and maturation stages of sorghum (Figure 1a). There was no water-deficient period in 2001. In that year, the ratio started to decrease from 1 October (90 DAS), but this could not affect sorghum production, as the crop was almost mature. At that time, the decreasing order of ET:ETc ratio was TSRC-TSRU-TSR for the stone row treatments and TGSU-TGSC-TGS (Figure 6a) for the grass strip treatments. The ratio for TSRC was greater than that of TGSC while TC, TU and T0 showed the smallest ratios.

In 2000 there was much more water deficit. The ET:ETc ratio curve for 2000 can be divided into two periods (Figure 1b). In the first phase, which corresponds to the sorghum growth stage (0–50 DAS), the crop water demand was satisfactory: ET:ETc > 0.75. A moderate to severe water deficiency phase was observed throughout September (51–79 DAS). This critical phase corresponded to the sorghum flowering stage and could have depressed grain production. Crop water demand became satisfactory again during the first half of October (80–95 DAS) before decreasing until the end of the rainy season.

Comparisons between treatments in 2000 did not show significant differences during the first phase. However, slight differences (< 10 %) in the ET:ETc ratio between treatments appeared during the water deficiency phase. The decreasing order of ET:ETc ratio was TGSC-TGSU-TGS-TGSM-T0 for grass strip treatments and TSRC-TSRU-TSR-TSRM for the stone row treatments. The water demand in TSRC was more satisfactory than in TGSC. The ratios for TGS and TSR, TGSM and TSRM, TGSU and TSRU were quite similar.

Table 2. *Cumulative evapotranspiration (ET), cumulative drainage (D) below 80 cm depth and annual runoff rate over the sorghum cropping seasons in 2000 and 2001 at Saria, Burkina Faso.*

	Cumulative ET (mm)		Cumulative D below 80 cm depth (mm)		Annual runoff rate (% ΣP)	
	2000	2001	2000	2001	2000	2001
TSRU	379 ab	439	217 b	107	8.3 c	4.2 c
TGS	383 a	431	217 b	109	8.3 c	5.9 c
TSR	378 ab	435	221 b	105	7.1 c	3.5 c
T0	370 ab	427	197 d	100	15.9 a	12.2 a
TGSC	388 a	427	219 b	106	7.1 c	4.5 c
TGSU	387 a	405	209 c	114	11.4 ab	9.5 b
TGSM/TC	381 ab	425	217 b	106	8.2 c	8.2 b
TSRC	388 a	435	219 b	106	6.8 c	3.2 c
TSRM/TU	368 b	448	222 a	110	7.5 c	6.6 c
	*	n.s.	*	n.s.	*	*

Where there are significant differences, treatments with the same letter are not statistically different at p= 0.05; ΣP: cumulative rainfall; *: significant at the 0.05 level of probability; n.s.: not significant.
Treatments: T0: neither SWC technology nor nutrient supply (control plot); TSR: stone rows without any supply; TSRC: stone rows + compost; TSRM : stone rows + manure; TSRU: stone rows + urea; TGS : grass strip, without any nutrient supply; TGSC : grass strip + compost; TGSM : grass strip + manure; TGSU : grass strip + urea; TC: Compost application, no SWC technology; TU: Urea application, no SWC technology.

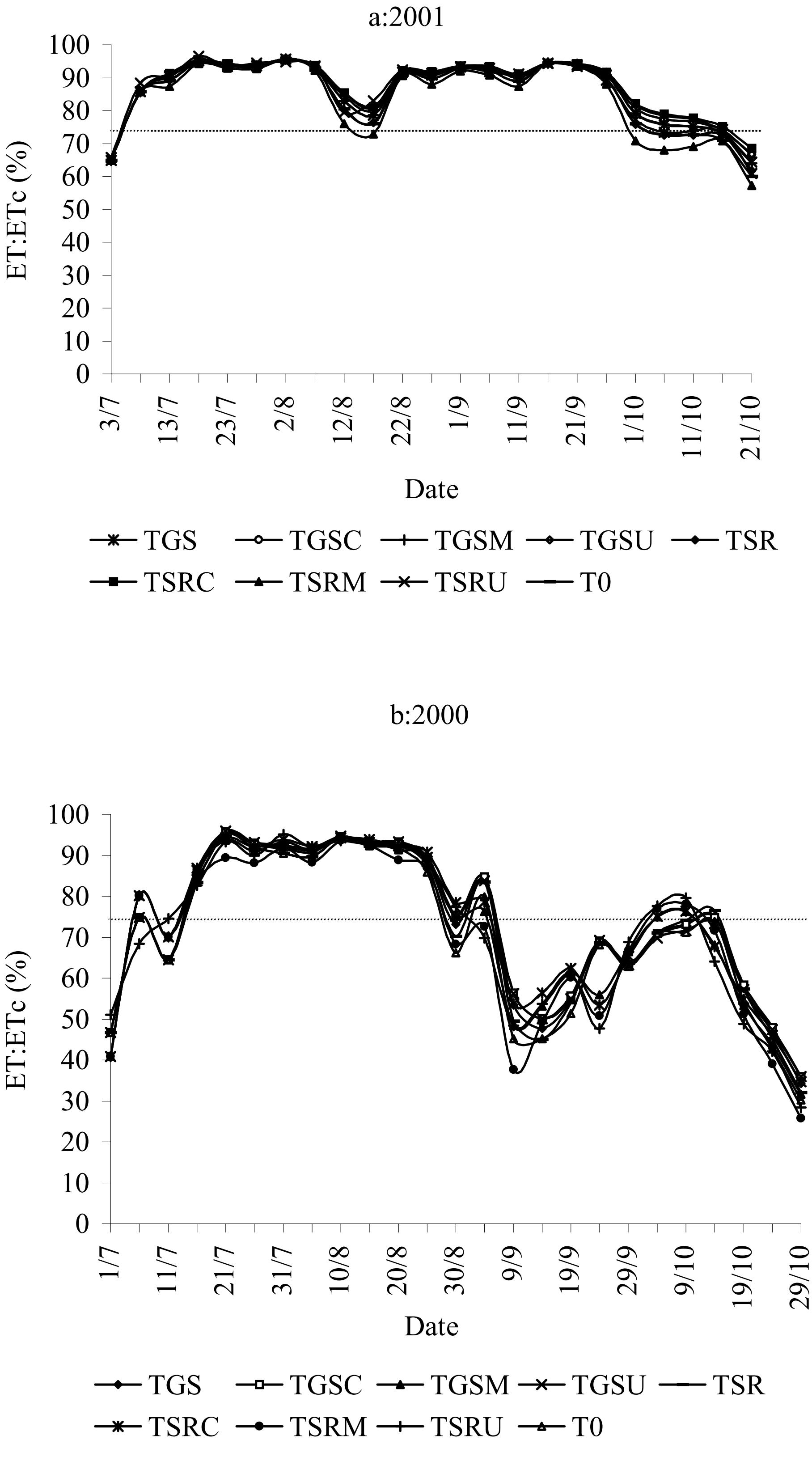

Figure 1. *Plant water demand satisfaction rate (ET:ETc ratio) for the sorghum crop at Saria, Burkina Faso; (a) 2001, (b) 2000.*

Vegetation barriers

Introduction

Barriers along contours trap water and the impedance of runoff prolongs the opportunity for infiltration. This is a useful WC practice in areas with high runoff percentages and where crop production is largely water limited. The efficacy of different semi-permeable barriers in reducing runoff was evaluated in an alley-crop experiment in Burkina Faso (Spaan et al, 2003). To determine the runoff interception efficiency of barriers and to find out the influence of slope length and alley treatment, runoff induced by a large number of storms was measured on plots with slope lengths of 1.25 m, 6.25 m, and 12.5 m. Plots without a barrier ('no barrier') were used as the control.

Materials and methods

The study (Spaan, 2003) was conducted on a 3 ha site in the centre of Burkina Faso near Gampela (1° 20' W, 12° 20' N). The experimental site was a crop field with an average slope of 2 % in which only a few trees remained. The soil is classified as a Luvisol low in fertility and productivity. It consists of sandy loam overlying clay with hydromorphic properties. Average rainfall is 790 mm y^{-1}.

In 1994 twenty-one plots of 20 x 20 m were laid out within the 3 ha experimental site, which had been fenced to exclude free-roaming cattle. Barriers 1 m wide were established along the contour, with the centre of the barrier 15 m downslope from the top of the plot, dividing the plot roughly into a 14.5 m alley, a 1 m vegetation barrier and a 4.5 m downslope section.

There were seven treatments in three replications, randomly distributed over the research area. The species, chosen on the basis of their local availability, vegetative growth and soil and water conservation properties, were; (1) the control 'No barrier', (2) the shrub *Ziziphus mauritiana*, (3) the succulent *Agave sisalana*, (4) the small tree *Piliostigma reticulatum*, (5) stone rows, (6) the local perennial grass *Andropogon gayanus*, and (7) a 'natural barrier' from spontaneous germination of grasses and herbs.

The choice of crop or pasture on the alley was based on the palatability of the barrier species. Barrier species unpalatable for cattle can be used as a WC practice on the silvo-pastoral (range) areas and were as such combined with pasture. Sorghum is grown on alleys with palatable barriers.

Runoff was determined after each erosive storm. Overland flow was trapped by runoff plots and channelled through a drainpipe into collection tanks, each with a capacity of 0.2 m^3. For the bigger plots a number of collection tanks in series were used.

Results and discussion

The effectiveness of the barriers is expressed in the following equation: $R\% = 100 * \sum R/\sum P$, where R = cumulative measured annual runoff and P = cumulative rainfall in mm. Table 3 shows these annual runoff percentages for different barriers, slope lengths and alley land use. Not all combinations of barrier and alley land use exist and some combinations do not exist for all three years. The figures in Table 3 are averages over two replicates; numbers in parenthesis give the standard deviation. For all combinations of no barrier, Agave (1.25 m) and natural (6.25 m) the s.d. is significant.

Grass barriers and stone rows proved to be very effective (called effective barriers hereafter) reducing runoff to only 20 % of precipitation. The runoff through woody species and succulents was about 50 % of precipitation (less effective barrier). By comparison with the control, a barrier always resulted in water conservation. A general conclusion is that for longer slopes, all factors such as type of barrier, land use and rain intensity became less important. In that situation, large runoff volumes exceed the quantity of water that can be dammed by the vegetation barriers (threshold), and can be intercepted as a result of land use activities and vegetation on the alley. It is concluded that barriers improve water conservation and are most effective when closely spaced.

Table 3 *Annual runoff percentages (R% = 100 * ΣR/ΣP) for different barriers, slope lengths and alley land use in Gampela, Burkina Faso.*

barrier	alley use	1.25 m 1997	1998	1999	6.25 m 1997	1998	1999	12.5 m 1997	1998	1999
No barrier	bare	67(12)			54(10)			48(12)		
	sorghum		50(10)	48(6)		42(12)	42(6)		38(7)	38(6)
	pasture		42(16)	47(5)		39(17)	49(7)		53(11)	47(6)
Ziziphus	bare				46(13)			35(7)		
	sorghum		42(7)	35(4)		39(8)	30(3)		25(4)	20(2)
Agave	bare				41(6)			36(7)		
	pasture		31(12)	23(2)		27(4)	21(2)		30(7)	29(4)
Piliostigma	pasture			21(2)			17(1)			22(3)
Stone row	sorghum		30(6)	25(3)		21(3)	13(1)		31(5)	28(3)
Andropogon	bare				19(3)			22(3)		
	sorghum		8(2)	17(3)		8(2)	19(4)		11(2)	24(2)
Natural	bare				4(7)			13(3)		
	sorghum		8(3)	12(4)		4(2)	6(1)		8(2)	13(1)

Numbers between parenthesis = s.d.

Water Conservation Tillage

Introduction

Most soils in Africa have poor physical and chemical characteristics and are vulnerable for crust formation leading to considerable runoff. Crusts are also forming an obstacle for seeding emergence. Soil tillage is therefore an essential agricultural operation to produce a crop. Soil tillage operations do on the other hand also promote soil and nutrient losses (Hoogmoed, 1999). Sustainable farming practices should therefore take into account the inevitability of soil tillage operations and the conflicting climatic characteristics.

Conservation tillage is based on the principle that soil manipulation is reduced to a minimum, but leaves some room for those operations required for sowing, weeding and in-field water conserving measures. Zero tillage is a method of planting crops that involves no seedbed preparation other than opening the soil (a small slit or hole) for the purpose of placing seed at the desired depth. Chemicals are normally used to control weeds. Both methods rely on the use of crop residue, green manures, cover crops or farmyard manure. This material forms a protective layer on the soil surface (less soil structural damage such as crusting or sealing, better rainwater infiltration and lower evaporation losses). The organic mulch layer also increases biological activity (microbial action, earthworms, termites, etc.), which improves soil structure.

Zero tillage is a success story in South America (where large areas in Brazil and Paraguay are now farmed exclusively under this system), and to a lesser degree in the USA and Canada. Elsewhere, conservation agriculture is receiving intense attention from international institutions, e.g. during the recent Madrid conference (Garcia-Torres et al., 2001). Boosted by the recent droughts in southern and eastern Africa, FAO is initiating the distribution of conservation tillage equipment for animal traction in Africa.

However, conservation tillage in the form of reduced or zero tillage is not a viable option in semi-arid Africa given the physical characteristics of the soil, the prolonged dry season and the lack of crop residues (Spaan et al., 2003). However, there seems to be scope for water conservation tillage. In Mali farmers that use animal traction apply a special form of water conservation tillage. Because their loamy sandy soils are sensitive to crust formation they till their soils every 15 days. The effects on infiltration and yield were investigated by Stroosnijder et al. (1994).

Materials and methods

First an elaborated rainfall analysis was carried out to define 12 standard showers as given in Table 4. Cumulative infiltration (CUMI), for the 12 standard showers, is computed with the equation: $CUMI = S * t^{0.5}$. S is an expression for the soil's capacity to absorb water. This calculation is performed for three S-values (depending on tillage) leading to 3 * 12 = 36 cumulative infiltration values. For each of the above 36 cases, runoff can then be calculated with the equation $r = P – CUMI – SS$. P is the shower size and SS the surface storage, i.e. the amount of precipitation that can be held in the surface irregularities without running off. Three SS values are assumed leading to 36 * 3 = 108 runoff values. For crusted, tilled and intermediate soils values for S and SS were taken from Hoogmoed and Stroosnijder (1984). This leads to runoff values given in Table 5.

The duration of the effect of tillage is made a function of the cumulative amount of rainfall since last tillage. If the latter reaches 100 mm and 200 mm, the intermediate and crusted stages as defined in Table 5 have been reached respectively. It is assumed that seedbed preparation tillage and sowing starts after the first rains. Plant growth starts after a decade with more than 20 mm of infiltration since then there is a good chance for viable germination and plant establishment.

Table 5. *Runoff percentages for 3 classes of showers and 3 stages of soil surface conditions for loamy sandy soil in the West African Sahel.*

Class	Average rainfall in class (mm)	Crusted	Intermediate	Tilled
< 10 mm	4.4	12	0	0
10 – 20 mm	14.6	50	14	0
> 20 mm	32.9	74	44	24

Crusted soil: Sorptivity S = 1 mm $min^{-0.5}$ and Surface storage SS = 0 mm
Intermediate soil: Sorptivity S = 2 mm $min^{-0.5}$ and Surface storage SS = 2 mm
Tilled soil: Sorptivity S = 3 mm $min^{-0.5}$ and Surface storage SS = 5 mm

Table 4. *Average rainfall per class and intensities representative for 25% of rainfall in that class.*

Class	Average rainfall in class (mm)	i(1) mm h^{-1}	i(2) mm h^{-1}	i(3) mm h^{-1}	i(4) mm h^{-1}
< 10 mm	4.4	3	8	18	32
10 – 20 mm	14.6	5	18	37	61
> 20 mm	32.9	7	34	62	116

Results and discussion

Without conservation tillage the runoff during the growing season is as high of 36.5 % (average over 30 years, SD = 3.4) and decreases with water conservation tillage till 25.6 %

while the standard deviation increases till 4.8. Rooting dept increases from 112 cm (SD = 37) till 121 cm (SD = 40). The GWUE is 8.0 % (SD = 3.3) without conservation tillage and increases only slightly till 8.8 % (SD = 3.6) if water conservation tillage is applied. The conclusion is that water conservation tillage alone (without an additional increase in external nutrient inputs) has a marginal effect. Indeed while without conservation tillage in 66 % of the years grain production is nutrient limited this increases till 77 % with conservation tillage. So, for larger water conservation by tillage other systems like tied ridges are needed.

On a 2 % sloping part of farmers' fields using animal drawn tillage in Mali ties between ridges, constructed with a hoe at a distance of 4 m, gave an estimated surface storage of 40 mm (Stroosnijder and Hoogmoed, 1984). During the period of measurements (2 months) no runoff was observed, except for the heaviest shower of the season (80 mm), which did some damage to the ties.

The functioning of the ties is most important during the beginning of the rainy season, and the gradual flattening of the ridges by subsequent rains reduces the risk for prolonged periods with water stagnating in the depressions (aeration problems). At Niono, Mali, it was estimated that with a complete prevention of runoff (as seems possible with tied ridging) the vegetative period is prolonged by 30 days in a normal rainfall year and by 40 days in a dry year. It could also be calculated that a 20 days longer vegetation period may have an effect on grain production of already 200 kg ha^{-1}. With an average production of 500, this means an increase in yield of no less than 40 %.

Termites

Introduction

The combined effects of difficult climatic conditions, overgrazing and trampling by cattle, continuous cultivation and other unsustainable management practices have resulted in the expansion of the area of bare soils with a degraded structure and a sealed surface (crusts) that impedes water infiltration and root growth. Termites, which are widespread and abundant in drier areas in the tropics, are not merely pests; they can also play an important beneficial role in rehabilitating degraded ecosystems (Mando and Stroosnijder, 1999). Farmers in Burkina Faso and in other areas of West Africa are making extensive use of termite-mediated processes to enhance soil restoration and agricultural production in their farming systems; e.g., the zai/tassa system, where organic material is put into small holes in which termites enhance decomposition and increase water infiltration (Mando et al., 2000).

The stimulation of soil fauna, especially termites, in semi-arid regions is a viable option to improve soil structure (Mando et al., 1996; Mando, 1997). Termites can affect the soil by their burrowing and excavation activities in search of food, or by constructing living spaces or storage chambers in the soil or above-ground. In fact, soil structure, structural stability, porosity, decomposition processes and chemical fertility are greatly altered by termite activities. Termites also enhance the decomposition of surface-applied organic materials, stimulating the release of nutrients that can then be used by growing plants.

Based on this presupposition, the role of termites and mulch in the rehabilitation of crusted soil was examined.

Materials and methods

The study site was located in Bam Province, Northern Burkina Faso. Here the rainfall is irregular (400–700 mm y^{-1}) and mean temperature ranges from 20–30º C, with great diurnal variation. The indigenous vegetation consists mostly of annual herbs and shrubs, with few annual grasses. Soils in the region are ferric and haplic Lixisols and chromic Cambisols. Bare areas are abundant and human pressure on the environment is high. Termites are the predominant soil fauna in the region and consist mostly of the subterranean type that do not build mounds on the soil surface. Three species of termites were found in the experimental field: *Odontotermes smeathmani* (Fuller), *Microtermes lepidus* (Sjöst) and *Macrotermes bellicosus* (Sjöst).

A split plot design with three replications was used to study the biological and physical role of termites in the improvement of crusted soil and water balance during three consecutive years (1993–1995). The insecticide dieldrin was used to obtain termite and non-termite infested plots. Four treatments with or without three different mulches were randomly applied in subplots: (1) no mulch (bare plot) (2) straw of *Pennisetum pedicellatum,* at 3 Mg ha^{-1}, (3) woody material of *Pterocarpus lucens,* at 6 Mg ha^{-1}, (4) composite (woody material and straw) treatment, at 4 Mg ha^{-1}.

Results and discussion

On the plots without the pesticide, the application of organic materials (mulch) to the soil surface triggered termite activity, and termite colonisation occurred in a relatively short time. Termite activity was similar under the different mulch types. The species mainly responsible for the termite-created features observed was *Odontotermes smeathmani*. These features included: (1) transport of material to the soil surface to construct sheaths for protection while searching for food, (2) opening up of large voids on the sealed surface of the soil and throughout the entire soil profile, (3) soil aggregation, particularly below 10 cm, through the construction of bridged grains, coatings and crumbs that form the fillings of voids.

All three features had a critical influence on soil properties and processes. The transport of material to the soil surface loosened the soil, enabling water to infiltrate more rapidly (Table 6). Both termites and mulch reduced runoff and increased soil water content (and hence the water storage capacity) throughout the plant growing period.

Table 6 *Runoff (% of annual rainfall) for bare and mulched plots with and without termites in 1993-1995 in Burkina. Treatments in the same column having the same letter(s) are not significantly different (after Mando and Stroosnijder, 1999).*

Treatment	1993	1994	1995
Bare	82b	68b	60b
Mulch without termites	79b	53b	49c
Mulch with termites	68a	47a	39a

Within a year, mulching a completely bare and crusted soil surface resulted in the rehabilitation of primary production. However, the plant diversity, plant cover and biomass and rainfall use efficiency of plants growing in mulched plots with termite activity were greater than in the plots without termite activity. Woody species only established in plots with termites.

In the first year of the experiment, plant performance was best when straw and composite mulch were applied, moderate when woody mulch was used, and worst without mulch application (bare plots). In subsequent years, the performance of the vegetation in termite plots improved but this phenomenon was more apparent in wood-mulched plots than in those that were straw-mulched. Straw had a quicker but shorter effect on vegetation performance, whereas woody material had a slower but longer-lasting effect. Bare plots remained bare throughout the experimental period.

The study demonstrated how locally available organic resources (straw and woody materials, manure) can be applied to the surface of crusted soil to trigger regenerative termite activity within a few months. Despite the additional labour involved in gathering and spreading these materials (human constraints), the benefits are not only immediate, but also long-lasting. The major natural constraint on the widespread adoption of this technique however, would be the removal of plant material from one area to regenerate another. The amount of material removed must never reach a level where it causes degradation of the site it is being removed from, as otherwise the activity defeats its purpose. But once the productive capacity of the ecosystem has been restored, it is likely that the vegetation produced can act as the continuing source of food for the termites, who will then use the organic materials to continue their bioturbation activities that are critical to the maintenance of soil structure and plant production.

Water-nutrient synergy

Introduction

Under traditional conditions in east Burkina Faso, with almost zero external inputs, farmers steadily improve their cultural practices through the use of a variety of agronomic SWC-measures in social networks in a 'cultural economy' (Mazzucato and Niemeijer, 2000). Their best achievement is that crop productivity does not decline but instead shows an almost constant gradual increase of 2–3 % per year over the last 40 years (Niemeijer and Mazzucato, 2002). This situation explains why, if expectations of productivity increase exceeds this 2–3 % per year, WC results under continuous non-fertilised cereal cropping are often disappointing (Zougmoré et al., 2002). This implies that there is no efficient WC without improved nutrient management. If agricultural systems are to be sustained in the region there is therefore an urgent need to address water and nutrient issues simultaneously.

Materials and methods

Materials and methods are similar to that described under stone rows.

Results and discussion

The treatment effect on sorghum grain and straw yields was statistically significant (Table 7). In composted treatments the total crop yield in 2000 was 1.4 times higher than in the manured plots, 1.6 times higher than in the plots given urea and 2.3 times higher than in the control plots and the plots with barriers only. The comparable figures for grain yield are 1.4, 2.0 and 3.3 respectively. At 1 m upslope from the stone rows, the sorghum grain yields were 45–60 % greater than those obtained at 17 m from the stone rows. However, yields at 1 m upslope from the grass strips were 35–60 % less than yields at 17 m.

Table 7 *Effect of treatments on sorghum performance (Mg ha^{-1}) for rainy season 2000 at Saria, Burkina Faso.*

Treatment	Grain	Straw	Total
SR compost (*stone rows + compost)*	2.31	4.84	7.15
GS compost (*grass strips + compost)*	2.32	4.99	7.31
SR manure (*stone rows + manure)*	1.69	3.53	5.22
GS manure (*grass strips + manure)*	1.56	3.59	5.15
SR urea (*stone rows + urea)*	1.44	3.89	5.33
GS urea *: (grass strips + urea)*	0.93	2.82	3.75
SR control (*stone rows, no nutrient supply)*	0.74	2.44	3.18
GS control (*grass strips, no nutrient supply)*	0.66	2.32	2.98

The crop production on plots without nutrient input was not significantly different from that on the control plots. This demonstrates that under the average annual rainfall of this region, and if this rainfall is well distributed over time, implementing water conservation measures without adding nutrients will not produce impressive yields (Zougmoré et al. 2002). The results shown in Table 7 are consistent with those of Ouédraogo et al. (2001), who observed in the same region and for the same type of soil that the highest sorghum dry matter production was obtained in composted plots. When used as organic amendments, compost and manure release not only the macronutrients such as nitrogen and phosphorus, but also considerable amounts of micronutrients for plants. The reason sorghum production was less near the grass strips than further away was probably the shading from the grass and competition for nutrients and water. As stones do not compete with plants, the opposite trend was observed with stone rows.

Stone rows or grass strips without nutrient input did not induce a significant increase of sorghum production. Supplying compost or manure in combination with stone rows or grass strips resulted in sorghum grain yield increasing by about 180 %, while the same permeable barriers combined with mineral fertilisers induced an increase of about 70 %. The sorghum grain yields about one metre upslope from the grass strips were less than those 17 m from the grass strips. Again, as stones do not compete with plants, the opposite trend was observed with stone rows. The conclusion was that permeable barriers improve nutrient use efficiency and therefore crop production, but that grass strips must be properly managed to alleviate shade and other negative effects of the bunds on adjacent crops.

The field water balance

Finally, all the above information was combined and the effect of 7 conservation scenarios (i.e. technology packages) on the various terms of the field water balance was estimated (Stroosnijder et al., 2001). In Table 8 the evaporation, transpiration and leaching fractions of the effective rain are given for 3 landscape units in Sanmatenga, Burkina Faso. Effective rainfall is above ground rainfall * ((100 – runoff %)/100) * a runoff reduction factor depending on the WC-practice used. Evaporation is length of the growing season * seasonal average daily evaporation which depends on the WC-practice used. Transpiration is the total biomass (grain + straw + roots + stubble) * the transpiration coefficient / 10000. Leaching is effective rainfall – evaporation – transpiration – storage capacity of the root zone.

It is striking how low the GWUE is under traditional cropping. With WC-practices and a limited nutrient supply this fraction doubles leading to a three-fold grain production. And still there is an enormous potential for further GWUE improvement since due to the WC-practices also leaching increases. As Stroosnijder (1991) puts it: semi-arid Africa suffers either from drought or from drowning. This raised the question how use can be made of the extra available water, also in deeper layers. At present research is going-on in Ethiopia to use rows of Eucalyptus trees along field boundaries as an extraction medium for excess water. (Kidanu et al., 2003a; 2003b).

Conclusions

Although the presented WC practices are known and already used by farmers the extend of its use is limited. Previous attempts to convince farmers to apply more WC practices or increase their extend have not been very successful. This has frustrated researchers, extension services, local governments and donors. Ongoing participatory research is trying to overcome previous failures and errors. In this respect important lessons can be drawn for the results presented in this paper.

Two important lessons must be draw from this report and be part of any future WC intervention. (1) It does not make sense to conserve water without adding nutrients to the cropping system, and (2) Easily too much water can infiltrate into the soil. In permeable soils this causes nutrient leaching below the root zone and replenishment of the groundwater (in some case a much wanted effect). In soils with a less impermeable deep layers this leads to saturation of the top soil causing water logging and risk for saturation overland flow. Farmers seem well aware of this risk and deliberately only construct WC practices at a limited scale.

Landscape unit SLOPE (rootable depth = 1.2 m, standard annual runoff % = 30 %, storage capacity = 240 mm))

Technology	T0	T1	T2	T3	T4	T5	T6	T7
Effective rain	461	482	605	585	647	647	605	626
Evaporation	205	214	202	260	216	287	135	139
Transpiration	**23**	25	28	28	30	28	45	**51**
Leaching	0	2	136	57	161	92	186	196
Grain yield (kg/ha)	279	311	342	342	373	342	621	776

Landscape unit SAND (rootable depth = 2 m, standard annual runoff % = 25 %, storage capacity = 200 mm)

Technology	T0	T1	T2	T3	T4	T5	T6	T7
Effective rain	499	516	619	602	654	654	619	636
Evaporation	222	229	206	268	218	290	138	141
Transpiration	**33**	37	40	40	44	40	65	**63**
Leaching	44	50	173	94	192	123	217	232
Grain yield (kg/ha)	405	450	495	495	540	495	900	956

Landscape unit CLAY (rootable depth = 1.5 m, standard annual runoff % = 25 %, storage capacity = 450 mm)

Technology	T0	T1	T2	T3	T4	T5	T6	T7
Effective rain	499	516	619	602	654	654	619	636
Evaporation	222	229	206	268	218	290	138	141
Transpiration	**28**	31	34	34	37	34	55	**63**
Leaching	0	0	0	0	0	0	0	0
Grain yield (kg/ha)	344	383	421	421	459	421	765	956

Technology characteristics

Technology	T0	T1	T2	T3	T4	T5	T6	T7
Conserv. practice	N	N	M	S	SM	G	S	S
Mechanisation level	H	H	H	H	H	H	A	A
Crop residues	N	Y	Y	Y	Y	Y	Y	Y
Fallow practise	Y	Y	Y	Y	Y	Y	N	N
Manure application	N	N	N	N	N	N	Y	Y
Nitrogen fertilisation	N	N	N	N	N	N	N	Y
Runoff red. Factor	1.1	1	0,4	0,5	0,2	0,2	0,4	0,3
Evaporation (mm/d)	2	2	1,5	2	1,5	2	1	1

Table 8. *Terms (mm/year) of the water balance in Sanmatenga Province (Burkina Faso) for a 'normal' rainfall year (688 mm).*

Conservation practice: N No intervention, M Mulch application at 1.5 MgDM ha^{-1} y^{-1}, S Stone rows placed every 50 m, SM Stone rows with mulch application, G Grass strips planted every 50 m. Mechanization level: H Manual labor, A Animal traction. Crop residues: N Crop residues removed, Y Crop residues left on the field, Fallow practice: Y Fallow is practiced, N No fallow is practiced, intensive/semi-intensive cultivation Manure application: N No manure is applied, Y Variable quantity applied, Inorganic fertilizer applied: N No inorganic fertilizer is applied, Y Inorganic fertilizer application varies depending on crop.

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