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On-farm evaluation of ridging and residue management options in a Sahelian millet-cowpea intercrop. 2. Crop development

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Abstract. In the Sahel, promising technologies for agricultural intensification include millet stover mulching and ridging. A four year on-farm experiment was set-up in order to assess the effect of various combinations of these two technologies on crop development and yield in a millet (*Pennisetum glaucum* (L.) R. Br.) - cowpea (*Vigna unguiculata* (L.) Walp.) intercropping system. Treatments included bare surface, ridging, a surface applied banded millet stover mulch ($2\,t\,ha^{-1}$) and a banded millet stover mulch ($2\,t\,ha^{-1}$) buried in ridges. The latter three treatments were implemented exclusively in the cowpea rows, with an annual rotation between the millet and cowpea rows. On bare and ridged plots, millet yields fell below $100\,kg\,grain\,ha^{-1}$ after the first year. This was ascribed mainly to soil acidification and loss of soil organic matter rather than to soil physical constraints or water availability despite extensive surface crusting and high soil penetration resistance and bulk density. Compared to the bare plots, ridging increased cowpea hay production by 330% over the four years which was attributed to lower soil penetration resistance and bulk density but also to a reduction of $0.15\,cmol_{+}\,kg^{-1}$ exchangeable acidity in the ridges. Except during the severe drought year of 1997, millet grain yield in the banded mulch treatment remained fairly stable over time at $526 \pm 9\,kg\,ha^{-1}$. However, a detailed analysis revealed yield compensation mechanisms between various yield components depending on the timing of occurrence of the abiotic stresses. Cowpea productivity was always higher in buried banded mulch plots than in surface applied banded mulch plots but the former treatment appeared unable to sustain millet yields. This decline was attributed to a greater nutrient uptake by cowpea and more rapid acidification in the buried mulch treatment compared to the banded mulch treatment.

Keywords: Sahel, tillage, mulches, intercropping, rotations, crop yield, available water

INTRODUCTION

In the Sahel, technically suitable options for intensification of the main staple crop millet (*Pennisetum glaucum* (L.) R. Br.) and the principal legume cowpea (*Vigna unguiculata* (L.) Walp.) have been identified for the sandy, low fertility soils on the basis of long-term on-station experiments or on-farm trials. Promising technologies include the use of small doses of fertilizer placed in the planting hole, millet stover mulching, ridging, and cereal-legume rotation (e.g. Ly *et al.* 1998; Subbarao *et al.* 2000).

In western Niger, cowpea, a legume traditionally intercropped with millet, is usually produced for its value as a forage crop rather than a grain crop. Especially near urban markets where urban animal husbandry is a major outlet, the economic value of cowpea hay can be substantial. Intensification of cowpea production could therefore provide a means of increasing farm income given suitable access to markets.

The present study investigated options derived from promising existing technologies for intensification of cowpea hay production in a millet-cowpea relay intercrop. Two technologies, mulching and ridging, were chosen for their ability to maintain soil fertility, to conserve the soil against soil losses by wind erosion, and to improve soil physical conditions in the topsoil. However, food security dictates that intensification of cowpea production should not be at the expense of millet production. Therefore an annual rotation between millet and cowpea rows was introduced in the intercropping system so as to allow millet to benefit from the residual effects of the inputs applied to cowpea in the previous year.

In a previous paper, the effect of the above-mentioned technologies on wind erosion was discussed (Bielders *et al.* 2000). The present paper discusses the impact of the

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selected technologies on crop development and yield, whereas a companion paper discussed the impact of the surface management practices on soil quality (Bielders *et al.* 2002).

MATERIALS AND METHODS

Study site

The experimental field was located in western Niger near the village of Banizoumbou (13°31′8″N, 2°39′5″E). Rainfall distribution is monomodal with a long-term annual average of 560 mm. The soils at the experimental site are classified as psammentic Paleustalfs (Soil Survey Staff 1990) or Luvic Arenosols (FAO 1998).

Experimental layout

Details of the experimental layout and treatments have been reported by Bielders *et al.* (2002). The four year experiment was initiated in 1995 and consisted of 4 treatments in a randomized block design with 4 replications. All plots were cropped with a millet-cowpea intercrop planted in alternating rows spaced 0.75 m apart and oriented perpendicular to the mean direction of the erosive easterly convective storms. The millet variety was a partly photoperiod sensitive, local landrace with a length of growing period of 110–120 days. The cowpea variety was a highly vegetative, photoperiod sensitive, spreading local landrace maturing in more than 90 days. Millet and cowpea were sown in planting holes ('poquets') spaced 1 m apart. Missing poquets of millet and cowpea were resown once each year. No fertilizer or pesticides were used.

The experimental treatments consisted of:

(1) 'bare' soil (no mulch, no ridging);
(2) a banded mulch ($2\,\mathrm{t\,ha^{-1}}$ of millet stover applied in the cowpea rows prior to millet sowing);
(3) ridging in the cowpea rows; and
(4) banded millet stover ($2\,\mathrm{t\,ha^{-1}}$) applied in the cowpea rows and buried in ridges ('ridge+buried residue' treatment).

Crop rows were rotated annually.

Data collection and analysis

Plant emergence 6 days after sowing (DAS), the number of poquets resown as well as the poquet density at harvest were monitored each year. For the first three years, in conjunction with windblown sediment flux measurements using BSNE sand traps (Bielders *et al.* 2000), millet straw and cowpea hay were harvested in 2 row sequences, excluding a single border row on each side, in order to assess any east-west trend in crop productivity due to seedling burial or sandblasting damage. Otherwise yields were assessed on a whole plot basis. All harvested products were left to air dry for 2 to 3 weeks before weighing. Daily rainfall was determined at the experimental site. In the present study, cowpea grain production was considered a bonus rather than an essential product. Indeed, high cowpea grain yields cannot be achieved without the repeated use of insecticides, a treatment that was deemed unrealistic in the present context.

Different growth phases (GP) have been identified for millet during its development (Maiti & Bindinger 1981): GP 1 from emergence to panicle initiation (0–45 DAS), and GP 2 and 3 from panicle initiation to maturity (45–120 DAS). The length of the GPs was defined following Rockström & de Rouw (1997), adjusting for the slightly longer growth period of the local landrace used in the present study.

Millet grain yield reflects the combined effect of plant survival and yield components at the individual plant level:

$$Y = \mathrm{S} \times \mathrm{N_h} \times \mathrm{N_pg} \times \mathrm{Wg} \qquad (1)$$

where Y is the plot grain yield ($\mathrm{kg\,ha^{-1}}$), S is the sowing density (6660 poquets $\mathrm{ha^{-1}}$), $\mathrm{N_h}$ is the poquet survival rate at harvest (% of poquets sown), $\mathrm{N_p}$ is the number of panicle-bearing tillers per poquet (panicles $\mathrm{(poquet)^{-1}}$), and $\mathrm{W_g}$ is the weight of grain per panicle (kg $\mathrm{(panicle)^{-1}}$).

Volumetric water content (VWC) profiles were measured from 0.15 to 2.4 m depth at 0.15 m depth increments on a weekly basis from the time of sowing to the time of harvest using one neutron probe access tube placed at the centre of each plot. The Didcot® neutron probe had been calibrated *in situ* for each depth on soils with similar textural and mineralogical properties.

Readily available soil water for plants (PAW) (mm) was estimated using the following equation:

$$\mathrm{PAW_j} = \sum_{i=1}^{n_j} (\theta_{\mathrm{i,\,j}} - \theta \mathrm{c}_{\mathrm{i,\,j}})\ \Delta_{\mathrm{z_i}} \text{ for all i such that } \theta_{\mathrm{i}} \geq \theta \mathrm{c}_{\mathrm{i,\,i}} \qquad (2)$$

where the subscripts i and j represent soil layers and time, respectively; θ_i is the average measured VWC [$\mathrm{m^3m^{-3}}$] of layer i; θc_i is the average measured VWC at the critical water content (CWC) of layer i; and Δz_i (mm) represents the thickness of each layer. VWC was linearly interpolated between measurement depths. CWC is defined as the volumetric water content below which millet starts to experience water stress, which is greater than the permanent wilting point (PWP). CWC was set at PWP + 0.03 for the top 0.6 m of the soil profile, and PWP + 0.04 for the 0.6–1.5 m depth layers. Rooting depth was calculated on the basis of a root growth rate of $0.02\,\mathrm{m\,day^{-1}}$, up to a maximum rooting depth of 1.5 m. CWC, PWP, root growth rate and maximum rooting depth were derived from the data of Rockström & de Rouw (1997). Plant available water at a given time was calculated for the same rooting depth irrespective of the treatment, thereby providing an estimate of the existence of climate-induced rather than soil-induced drought stress under optimal farm growth conditions (e.g. van Duivenbooden *et al.* 2000). The length of the growth phases, root growth rate during the growing season and maximum rooting depth were assumed constant in the present study, irrespective of treatment and year.

Statistical analysis

All statistical analyses were carried out in Genstat™ (Lawes Agricultural Trust 1996). Analysis of variance for treatment effect over the 4 years was carried out using a randomized

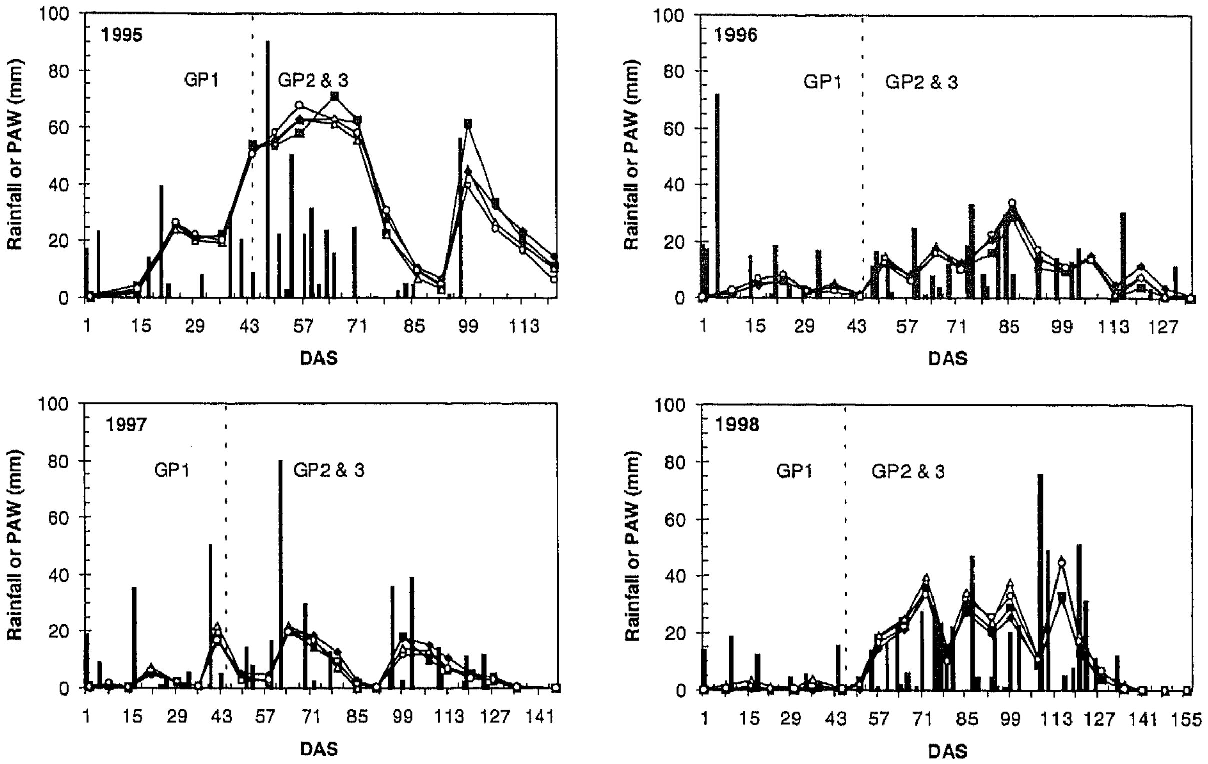

Figure 1. Change in readily available water for plants (PAW, continuous lines) and daily rainfall (vertical bars) from the time of sowing of the first millet crop (= DAS 0) to the harvest of the last crop over the period 1995 to 1998 as a function of residue management and tillage. ■ = bare, ∇ = banded mulch, ◆ = ridge, ○ = ridge+buried residue. Vertical dashed line indicates approximate limit between growth phase 1 and growth phases 2 and 3.

block structure with 4 treatments and 4 replicates, in which years where considered at the split-plot level. Treatment differences were regarded as significant when error probabilities were <5%.

In order to assess crop competition, a bivariate analysis (Mead *et al.* 1993) was carried out on cowpea hay *versus* millet grain and on cowpea hay *versus* millet straw after square root transformation of the data. Since cowpea grain production was not a major goal of the present experiment, no joint analysis was carried out for cowpea grain.

Linear regression analysis for determination of the east-west trend in poquet survival rate and in millet straw and cowpea hay yield was carried out for individual plots for the first 3 years. The slope of the linear regressions was then used independently in an analysis of variance as described above.

Analysis of variance of repeated measurements over time was carried out for PAW for individual years. For reasons of variance homogeneity, the repeated measures analysis was carried out on logarithmic transformed data. However, data transformation did not substantially modify the outcome of the ANOVA and therefore statistics of untransformed data are reported here for convenience, keeping in mind that true probabilities may slightly differ from those reported.

RESULTS AND DISCUSSION

Millet was sown on 21 June 1995, 4 June 1996, 28 May 1997, and 19 May 1998, and cowpea on 8 July 1995, 26 June 1996, 8 July 1997, and 13 July 1998. Both crops were harvested between 10 and 22 October each year.

Total annual rainfall was 523, 495, 425, and 672 mm in 1995, 1996, 1997, and 1998, respectively. Despite a short rainy season and the occurrence of an extended low rainfall period from 30 August to 26 September, sufficient and well distributed rainfall during the months of July and August ensured sufficient PAW reserves throughout the 1995 growing season (Figure 1). In 1996, fairly limited but well distributed rainfall events ensured proper water supply conditions. In 1997, an extended drought in August coincided with the time of millet flowering and resulted in PAW reserves falling below 0 for a period of 1 to 2 weeks for all treatments. In 1998, rainfall was deficient during the first 45 days of the season prior to cowpea sowing. The crops experienced between 13 and 23 sand storms each year (Bielders *et al.* 2000).

Crop development and yield

No abnormal pest damages were recorded for millet and for cowpea hay during the 4 years, except for a severe locust attack during the millet establishment phase in 1998. This damage was partially compensated for by resowing, with up to 36% of millet poquets replaced in the banded mulch and ridge+residue treatments. In the remaining discussion, crop development and yields are discussed solely in terms of climatic (rainfall and sandstorms) and edaphic (soil physical and chemical quality) constraints.

Table 1. Impact of residue management and ridging on the number of millet tillers poquet^{-1} and millet grain yield panicle^{-1} for the period 1995–1998. Rainfall corresponds to cumulative rainfall during growth phases 2 and 3 (45–120 days).

		Tillering					Grain yield panicle^{-1}				
	Rainfall	Bare	Banded mulch	Ridge	Ridge+ buried residue	mean	Bare	Banded mulch	Ridge	Ridge+ buried residue	mean
	mm			panicles (poquet)$^{-1}$ –					g (panicle)$^{-1}$		
1995	353	2.6	3.5	2.9	3.3	3.0	19.1	24.1	22.9	27.1	23.3
1996	329	1.5	4.1	1.6	3.7	2.7	13.3	23.3	13.8	22.2	18.1
1997	289	1.1	3.2	1.6	3.0	2.2	11.8	16.3	9.6	13.9	12.9
1998	562	1.6	4.7	1.6	3.8	2.9	12.3	26.8	9.1	21.1	17.3
mean		1.7	3.9	1.9	3.4		14.1	22.6	13.8	21.1	
ANOVA		s.e.	Pr > F	CV			s.e.	Pr > F	CV		
Year		0.36	0.204				1.97	0.004			
Treatment		0.18	<0.001				1.27	<0.001			
Year x Treatment		0.47	<0.001				2.95	0.010			
Block x Year x Plot				19					20		

Millet, bare and ridge treatments. There being no residual effect of ridging on soil properties in the millet row (Bielders *et al.* 2002), millet development and yield followed a similar pattern on the bare and ridged plots, with a rapid stabilization of yields at values <100 kg ha^{-1} grain after the first year of cultivation (Figure 2). The low yields resulted from low poquet survival rates at harvest (35–69%; not shown), very low tillering and low grain yield per panicle (Table 1). The low survival rate resulted from the death of millet plants after emergence rather than from poor emergence; emergence on the bare and ridge treatments was not significantly different from the other treatments (not shown).

The trend in millet yields on the bare and ridge treatments (Figure 2) reflected soil-related constraints rather than climate-related constraints. Indeed, in this rainfall zone, the latter would result in high inter-annual yield variability rather than yield stabilization (Subbarao *et al.* 2000). In addition, PAW reserves in the bare and ridge treatments were not significantly different from other treatments (Figure 1). As demonstrated by the yields in the banded mulch and ridge+buried residue treatment (Figure 2), PAW reserves in the bare and ridged plots were therefore sufficient to sustain higher yields than observed in these treatments, even in a drought year such as 1997. PAW reserves also demonstrate that the extensive occurrence of erosion and discontinuous structural crusts on the bare and ridge treatments (Bielders *et al.* 2002) did not restrict water supply at the present productivity levels. The absence of a significant treatment effect on the percentage of millet emergence 6 DAS further indicates that these thin crusts did not impede plant emergence. Bielders *et al.* (2002) also showed that the bare and ridged plots did not experience any degradation in soil physical quality over time in terms of penetration resistance and bulk density. Consequently, the millet yield decline in the bare and ridge treatment can most likely be attributed to soil chemical limitations to growth.

Both the bare and ridge treatments were strongly affected by soil acidification, had lower soil organic matter levels, very low exchangeable K^{+} levels and low available P (Bielders *et al.* 2002). According to Kretzschmar *et al.* (1991), millet growth on the acid sandy soils of western Niger is not restricted by Al toxicity. However, acidification promotes P adsorption by iron and aluminium compounds, further reducing the availability of this most limiting nutrient for millet on these sandy soils (Bationo *et al.* 1990). Buerkert & Lamers (1999) reported large reductions in water soluble P on bare plots subject to severe degradation by wind and water.

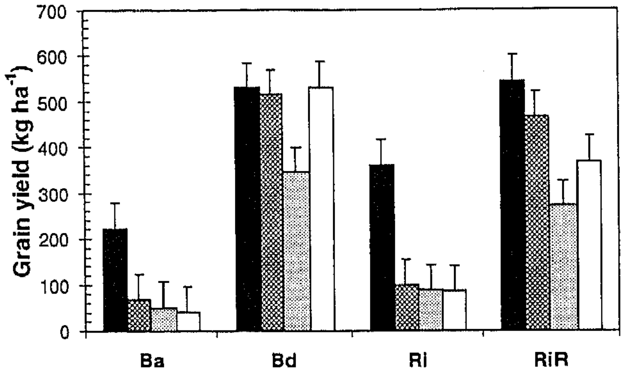

Figure 2. Millet grain yield over the period 1995 to 1998 as a function of residue management and tillage. Ba = bare, Ri = ridge, Bd = banded mulch; RiR = ridge+buried residue. ■ 1995, ▩ 1996, ▨ 1997, □ 1998. Bars = s.e.d. for treatment x year interaction.

Millet, mulched treatment. Compared to the other treatments, the banded mulch treatment resulted in the highest yields across years (Figure 2). In addition, with the exception of 1997, yields on the banded mulch treatment remained virtually constant at around 526±9 kg grain ha^{-1} despite rather variable climatic conditions. The satisfactory yields achieved by this treatment can be attributed to the positive residual effects of banded mulching on plant available P and exchangeable Mg^{++} and K^{+} content (Bielders *et al.* 2002). In addition, a small residual effect of lower bulk density

(0–0.07 m; $P<0.001$) and penetration resistance (0–0.05 m; $P<0.001$) may have promoted root growth and aboveground biomass (Nicou *et al.* 1993). Strong positive correlations between soil porosity and millet root development have been reported by Chopart & Nicou (1985).

In 1995 and 1996, millet yields in the banded mulch treatment were not limited by water (Figure 1). However, different yield components contributed to the overall grain yield in those two years. In 1995, poquet survival at harvest was high (93%) whereas in 1996 plant emergence was significantly lower (80%; s.e.d.=4.6%) possibly as a result of the occurrence of strong sandstorms with little rainfall after the second sowing. The lower survival rate in 1996 was, however, compensated for by a 19% increase in the number of tillers compared to 1995, from 3.5 to 4.1 panicles poquet^{-1} (s.e.d.=0.35 panicles poquet^{-1}), most likely as a result of decreased competition between millet plants for soil nutrients. The same yield compensation mechanism was also observed in 1998 when plant survival in the banded mulch treatment was the lowest of all 4 years at 65%, reflecting the drought stress and locust attack during GP 1. In that year, tillering was increased by 40% compared to 1995 (Table 1).

In the drought year of 1997, neither poquet survival (not shown) nor tillering (Table 1) differed significantly from 1995. In the absence of stresses other than drought stress, effects on specific yield components will depend on the timing of drought (Lambert 1983; Ong & Monteith 1984). In the present case, the drought stress occurred during growth phases 2 to 3 and resulted solely in a decrease in grain yield per panicle compared to the previous two years.

Millet, ridge+residue treatment. Excluding 1997, a steady decline in grain yields was apparent over time for the ridge+buried residue treatment (Figure 2). This decline was mostly due to a gradual reduction in grain yield per panicle (Table 1). Bielders *et al.* (2002) have shown that residual effects of mulching on the soil physical properties in the millet row of the banded mulch and ridge+buried residue treatment were comparable. Given that water availability also did not constitute a constraint in any year except 1997, the yield decline in the ridge+residue treatment probably related to a degradation of soil chemical quality compared to the banded mulch treatment, and in particular to the lower soil pH and exchangeable K^+ and Mg^{2+} content (Bielders *et al.* 2002).

Cowpea. Temporal trends in cowpea hay and grain yields were remarkably similar across treatments, reflecting a greater impact of climate than in the case of millet (not shown). Cowpea hay production peaked in 1996 and 1998 at 149 and 136 kg ha^{-1}, respectively, with a minimum in 1995 at 50 kg ha^{-1} (s.e.d.= 22.6 kg ha^{-1}; Figure 3). The low productivity of 1995 may be the result of the short growing season available for cowpea. Indeed, 55% of the cowpea poquets were resown 39 DAS of millet and harvest took place 82 days later, which was too short a growing season for the late-sown cowpea. As for millet, the cowpea hay yield depression in 1997 (Figure 3) most likely resulted from the August drought. Average cowpea grain yield was lowest in 1995 (10 kg ha^{-1}) and peaked at 89 kg ha^{-1} in 1997 (s.e.d.=9.0 kg ha^{-1}; Figure 3), possibly as a result of reduced pest incidence. There was no significant year x treatment interaction for cowpea hay.

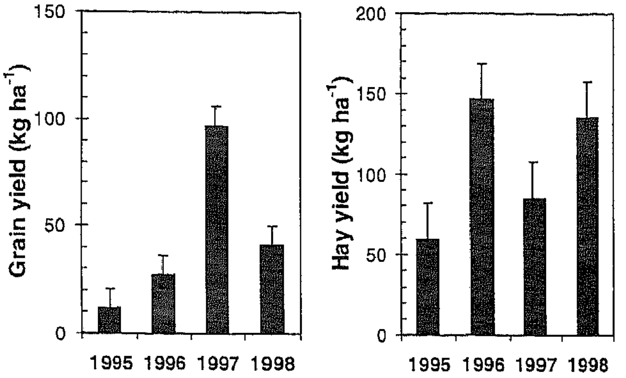

Figure 3. Cowpea grain and hay yield over the period 1995 to 1998. Average values over all treatments. Bars = s.e.d.

On the bare plots, hay yields remained low as a result of the severe soil chemical degradation of this treatment (≤ 65 kg ha^{-1}. not shown). On average over the 4 years ridging increased cowpea yields by 330 and 285% for hay and grain, respectively, compared to the bare treatment. This was in part the result of a 9% increase in poquet survival rate (s.e.d.=2.4%), but mainly due to a large increase in plant productivity per poquet (+13.5 g poquet^{-1} for hay) compared to the bare plots (8.1 g poquet^{-1}; s.e.d.=2.68). The increase in cowpea hay yield on ridges compared to bare soil may in part have resulted from the increased soil porosity and reduced penetration resistance (Nicou *et al.* 1993; Bielders *et al.* 2002). However, Bielders *et al.* (2002) also observed that total exchangeable acidity was 17% less in the ridges than in the cowpea row of bare plots. Cowpea has been reported to be more sensitive to high levels of Al than millet (Kretzschmar *et al.* 1991). The lower levels of exchangeable Al^{3+} in the ridges may therefore have contributed to better cowpea growth on ridges. Lower Al concentrations may also have improved P availability compared to bare plots.

Compared to the ridge treatment (21.6 g poquet^{-1}), cowpea hay productivity on the banded mulch treatment was similar (21.0 g poquet^{-1}; s.e.d.=2.68). The improved soil chemical quality (higher organic carbon and exchangeable cations content and reduced acidity; Bielders *et al.* 2002) apparently compensated for the greater soil bulk density and penetration resistance observed in the banded mulch plots compared to the ridge plots.

Burial of residue in ridges significantly increased both hay and grain yield compared to the banded mulch and ridge treatments. Again, this difference in productivity resulted mostly from a higher production per poquet (30.9 g poquet^{-1}), given that plant survival rates were not significantly different (77–80%; s.e.d.=2.4%). The burial of residue in ridges improved soil physical properties to a similar extent as in the ridge alone treatment (Bielders *et al.* 2002). In addition, nutrient levels were greater in the ridge+buried residue treatment than in the banded mulch treatment, probably as a result of faster residue decomposition. The improved physical and chemical soil quality compared to the ridge alone and banded mulch treatments therefore most likely provided for the higher cowpea grain and hay production.

East-west productivity trend. Only in the case of millet poquet survival rate was a significant treatment effect observed in the east-west trend (P=0.02). For the bare and ridge plots, the trend reached values of, respectively, 1.9 and 2.1% m^{-1} on average over the first 3 years (s.e.d.=0.97%), corresponding to an absolute increase in survival rate of about 30% from east to west across the plot. For the banded mulch and ridge+residue treatment, this trend was negligible (<0.2% m^{-1}). The observed spatial trend reflects a lower plant survival rate on the eastern, windward side of the bare and ridge plots. This trend could potentially be explained by lower soil fertility due to higher soil erosion or by more plant damage (seedling burial and/or sandblasting) on the eastern side than on the western side. However, Bielders *et al.* (2000) measured an increase in sediment flux from east to west across the bare and ridge plots. In the case of the bare plots, this increase was linear, which indicates that soil loss by wind erosion was constant across those plots. At least for the bare treatment, it appears therefore that the observed east-west trend cannot be satisfactorily explained by differential soil erosion, seedling burial or sandblasting across the plots.

Crop competition

Treatment differences were similar for the millet grain *versus* cowpea hay (Figure 4) and millet straw *versus* cowpea hay bivariate analyses, and treatment effects were highly significant in both cases (P<0.001). No year x treatment interaction was observed for either joint analysis. On average over the 4 years, the ridge+buried residue treatment increased cowpea hay yield by 61 kg ha^{-1} (s.e.d.=16.1 kg ha^{-1}) over the banded mulch treatment (108 kg ha^{-1}). Millet grain and straw yields in the ridge+buried residue and banded mulch treatments were not significantly different, indicating that millet yields were not depressed by the increased cowpea hay production.

Compared to the banded mulch treatment, the ridge treatment resulted in a large decrease in millet grain yield, but cowpea yields were not significantly different (Figure 4). The bare treatment resulted in an even greater decline in millet production compared to the banded mulch plots but also in a large decline in cowpea hay production. The fact that millet yields in the bare and ridge treatments remained uniformly low after the first year of cultivation irrespective of cowpea hay yields is indicative of the absence of strong competition between the two crops in these treatments.

Overall, it appears that competition between millet and cowpea did not constitute a limitation in the present experiment. This probably results from the low planting densities and low cowpea biomass yields obtained even in the most productive treatments (<250 kg hay ha^{-1}).

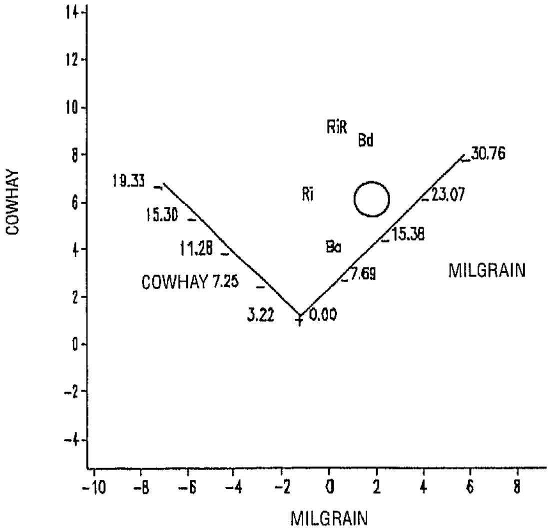

Figure 4. Bivariate analysis of cowpea hay (COWHAY) *versus.* millet grain (MILGRAIN) yield. Circle radius equals the radius of significance at the 95% probability level. Ba = bare, Ri = ridge, Bd = banded mulch; RiR = ridge+buried residue.

Both in the banded mulch and ridge+buried residue treatment, millet straw yields never exceeded 1600 kg ha^{-1}, well below the 2000 kg straw ha^{-1} applied as mulch. The mulching rate adopted in the present experiment was based on extensive evidence that a 2000 kg ha^{-1} mulch is an effective soil fertility management and soil conservation practice (e.g. Geiger *et al.* 1992; Rebafka *et al.* 1994; Michels *et al.* 1995; Bationo *et al.* 2000; Buerkert *et al.* 2000). Very little evidence exists about the effectiveness of lower application rates. Sterk & Spaan (1997) and Michels *et al.* (1995) have tested lower application rates from the point of view of wind erosion control and have found rates of ≤1000 kg ha^{-1} to be ineffective. It is clear from the present results that the mulching rate used in the banded mulch or ridge+buried residue treatments cannot be sustained without external input of nutrients to boost millet production. In addition, millet stover is subject to multiple uses, including fodder for livestock and construction material (Lamers & Bruentrup 1996), which further reduces stover availability for mulching. The adoption of mulching will therefore depend to some extent on whether a farmer has livestock and on the opportunity costs of the various uses of millet stover. In order to ensure a sufficient supply of stover for mulching, feed and construction, future experiments should aim at testing mulching rates between 1000 and 2000 kg ha^{-1} in combination with the use of small quantities of organic or inorganic amendments needed to increase millet productivity. Such an experiment is presently undertaken at the same test site using the poquet-placed fertilizer technology.

CONCLUSIONS

At the millet productivity levels reached after the first year of cultivation in the bare and ridge treatments, farmers would most likely abandon their fields for more productive land. From a farmer's point of view, those 2 treatments are therefore of little relevance. However, they are useful for elucidating yield response mechanisms. For these treatments, neither soil penetration resistance nor bulk density constituted significant constraints for millet production. Similarly, even though crusting was a clear indicator of soil degradation, it did not constitute a constraint for millet production in any of the treatments. Nutrient depletion and soil acidification, whether by nutrient mining, wind erosion or other mechanisms, appears to have been the major cause of productivity decline in the bare and ridge treatments. Ridging, however, was able to sustain higher cowpea hay yields than in the bare plots, probably as a result of improved soil physical conditions but also reduced acidity in the ridges.

To overcome the degradation observed on bare and ridged plots, adequate soil cover against wind erosion as well as organic matter and nutrient inputs are required. Mulching, whether surface applied in bands or buried in ridges, provided an effective means of achieving both conditions. In addition, mulching resulted in significant improvements in soil physical quality in both the millet and cowpea rows, which may have favourably impacted root development. Because of larger residual effects, the yield benefit of the banded mulch treatment on millet was larger than for the buried residue treatment and the introduction of an annual rotation between millet and cowpea rows appears justified for this technique. The present results indicate that banded mulching in the cowpea row ensured reasonable cowpea yields while sustaining millet yields at adequate levels. This was attributed to the slower decomposition of the millet stover in the banded mulch treatment compared to the ridge+buried residue treatment, which somewhat reduces cowpea productivity in the year of application but ensures a better nutrient status in the millet row in the following year. Faster residue decomposition in the ridge+buried residue treatment boosted cowpea yields but resulted in a slow decline in millet yields over time, making this treatment unsustainable in the long-term.

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