Expl Agric. (1999), volume 35, pp. 437–448
Printed in Great Britain

EFFECTS OF PRIMARY TILLAGE AND SOIL AMENDMENT PRACTICES ON PEARL MILLET YIELD AND NUTRIENT UPTAKE IN THE SAHEL OF WEST AFRICA

By F. N. IKPE†, J. M. POWELL‡, N. O. ISIRIMAH†, T. A. T. WAHUA† *and* E. M. NGODIGHA†

International Livestock Research Institute, BP 12404 Niamey, Niger

(*Accepted 8 March 1999*)

SUMMARY

The main objective of this study was to determine the best soil amendment and tillage practices for sustainable millet yield and grain and stover quality. The treatments included tillage practices (immediate-, late- and no-till) and soil amendments (sheep manure plus urine, manure, millet stover (stalks, leaf blades and leaf sheaths) and millet stover ash) in factorial combinations with fertilizer nitrogen levels of 0, 15 and 30 kg ha^{-1} plus controls. Results showed that (i) higher yields were obtained in tilled plots than in no-till plots; (ii) tillage timing may not be a significant yield determining factor; (iii) the application of animal urine resulted in significantly higher yield and greater nitrogen, phosphorus and potassium uptake than the application either of manure alone or of millet stover. Urine application (ruminant urine contains virtually no phosphorus), which elevates soil pH especially during the first week after application, may have resulted in the dissolution of phosphorus from the aluminium–iron complexes of kaolinitic clays. This is corroborated by the significantly higher phosphorus uptake from the manure-plus-urine plots than from plots amended with either manure alone or millet stover. Long-term implications of 'mining' soil phosphorus with repeated applications of animal urine in these fragile ecosystems remains unclear.

INTRODUCTION

In the Republic of Niger, the sustainability of mixed farming systems requires soil management strategies that limit the loss of nutrients from recycling. Pearl millet (*Pennisetum glaucum*), perhaps the most important food crop of semi-arid West Africa, is cultivated for grain and stover. Of the total biomass produced, approximately 15% is food (millet grain) and 85% can be regarded as potential feed (millet leaves, stalks and threshed panicles). The beneficial effects of millet stover application on soil fertility are well recognized (Lamers and Feil, 1993). However, the competitive use of millet stover makes its harvest and sale attractive at local markets, especially in years when drought spells result in a poor grain harvest (Hopkins and Reardon, 1989). Millet stover is used as livestock feed, for the construction of houses, granaries and fences and for making mats. It also serves as fuel for cooking in areas where firewood is scarce. Millet stover grazed after the

Current address: † Rivers State University of Science and Technology, PMB 5080, Port Harcourt, Nigeria; ‡ Dairy Forage Research Center, 1925 Linden Drive West, Madison, WI 53706-1108, USA.

grain harvest is perhaps the major source of animal feed during the six- to seven-month dry season. Livestock graze millet stover by day and deposit manure and urine directly on croplands by night (overnight corralling). Harvesting millet stover to feed animals held in paddocks (stalls) near homesteads, requires labour to harvest and transport stover often using animal-drawn carts. Labour and transportation are also required for manure collection, storage, transportation from homesteads to fields and the spreading of manure on croplands. More importantly, the paddock system results in substantial nutrient losses because the nutrients in animal urine are not recycled through cropping as with the practice of overnight corralling of animals on croplands.

Earlier studies have shown that the systematic application of crop residues (Pichot *et al.*, 1981; Powell and Fons, 1991) and animal manures (Bationo and Mokwunye, 1991a; Powell and Ikpe, 1992) can lead to substantial increases in grain and stover yields and nutrient uptake. However, the implications of either the direct application of millet stover to the soil, the recycling of nutrients through the corralling of livestock on croplands, the hand-spreading of manure alone from stall-fed animals, the burning of millet stover, or its complete removal from farmers' fields in these crop–livestock systems have not been documented properly.

The feed value of crop residues such as groundnut (*Arachis hypogaea*) (Powell, 1985) and cowpea (*Vigna unguiculata*) hay (J. M. Powell, personal communication) are considered high. Since the nutrients in millet stalks and leaves have been reported widely on a stover basis (Bationo and Mokwunye, 1991a;b; Duivenbooden and Cissé, 1992; Hafner *et al.*, 1993), millet stover is generally regarded to be low in feed value so that supplementation is believed to be necessary for animals to maintain body condition (O'Donovan, 1983). The grazing pattern of stover depends on the palatability and nutritional quality of plant parts (Powell, 1985) and their digestibility (Hacker and Minson, 1981). Since small ruminants (goats and sheep) graze millet leaves alone, their intake of nitrogen (N) and phosphorus (P), may be underestimated while the intake of potassium (K) is overestimated. This, however, is not the case for large ruminants (cattle and camels) and donkeys which consume both stalks and leaves (stover). The specific objectives of this study were to determine the best soil amendment practices, to find out the most appropriate tillage practice for the incorporation of these soil amendments and to determine the partitioning of nutrients to millet plant parts.

MATERIALS AND METHODS

Site description

The experiment was conducted at the ICRISAT Sahelian Centre (ISC), Sadoré (lat 13°N, long 2°E) in the Republic of Niger, West Africa and located on acidic Labucheri soil, classified as Psammentic Paleustalfs (sandy, siliceous, isohyperthermic) having a surface (0–0.2 m) texture of 850–900 g kg^{-1} sand,

and 50–100 g kg^{-1} clay-size particles, with the latter made up of roughly equal proportions of very fine quartz and kaolinitic minerals (West *et al.*, 1984). The average annual rainfall, of which nearly 95% falls between May and September, was generally above the long-term average of 560 mm (Sivakumar, 1986). However, rainfall distribution in 1992 was less favourable than in 1991. The amounts of rainfall for 1991 and 1992 were 603 and 586 mm respectively.

Experimental treatments

There were three types of treatments: (1) tillage practices: (i) immediate-till (tillage at the beginning of the cropping season performed on the day of amendment application on the soil surface), (ii) late-till (tillage at the beginning of the cropping season performed two weeks after amendment application on the soil surface) and (iii) no-till; (2) soil amendments: (i) sheep manure-plus-urine, (ii) sheep manure alone, (iii) millet stover and (iv) ash of millet stover; (3) fertilizer N: (i) zero N, (ii) 15 kg N ha^{-1} and (iii) 30 kg N ha^{-1}. Soil amendments and the N fertilizer rates were factorially arranged to give 12 treatments plus a control in a split-plot arrangement with four replicates. The tillage practices formed the main plots with the 12 combinations plus the control randomized perpendicularly in plots measuring 6 × 6 m within the main plots. Tillage was accomplished by ploughing to a depth of 10 cm with a two-oxen plough. Prior to tillage the equivalent of 10 kg P ha^{-1} was applied as single superphosphate to meet the optimum P requirement of millet (Bationo and Mokwunye, 1991b) before pearl millet was planted as a test crop. The amounts of sheep manure and millet stalks applied (1.5 t ha^{-1}) were determined in village-level surveys in the Republic of Niger. The manure:urine ratio of 1:3 on a w/w basis, was determined in an International Livestock Research Institute (ILRI) sheep metabolism experiment at ISC (J. M. Powell, personal communication). The amounts of N, P and K in the amendments in 1991 are presented in Table 1.

In the first year, millet stalks (leaf blades and sheaths removed) were chopped and sampled for chemical analyses. For the stalk ash treatment, the same amount of stalks applied to stalk amended plots were burnt in open half drums, and the ashes were sampled for chemical analyses. The manure and urine from sheep fed millet-based diets were collected and stored in sacks and plastic containers

Table 1. Amounts of nitrogen, phosphorus and potassium in soil amendments applied to field plots at the onset of the experiment at Sadoré.

	Nutrient concentration			Nutrient application		
Amendment applied	Nitrogen	Phosphorus (g kg^{-1} dry matter)	Potassium	Nitrogen	Phosphorus (kg ha^{-1})	Potassium
Millet stalks	7.3	0.5	43.5	11.0	0.8	62.3
Millet stalk ash	4.1	6.8	563.3	0.5	0.8	65.3
Sheep manure	17.6	3.2	13.9	26.4	4.8	21.0
Sheep urine	5.6	3.2	0.5	25.2	0.0	2.1

respectively. These were also sampled for analyses prior to application to field plots. The urine samples were frozen until chemically analysed. After receiving rainfall deemed sufficient for tillage, the amendments were hand-spread and four main plots were tilled within six hours of amendment application. Four other main plots were tilled two weeks later and the remaining four plots were left untilled. On the day of late till, all plots were planted with pearl millet cv. CIVT (Composite Inter-Varietal de Tarna) at 0.75-cm spacings with three plants per stand within rows 1 m apart giving a plant population of approximately 40 000 per ha^{-1}. At the first weeding and thinning, approximately three weeks after planting, half the fertilizer N (calcium ammonium nitrate, CAN) was surface banded and the remaining half was applied in a similar fashion six weeks later after the second and final weeding. In 1992, millet stover (stalks + leaf sheaths + leaf blades) was retained on plots that received millet stalks the previous year while stover from the ash plots was collected, burnt and the ashes applied. The sheep manure and urine were applied at the same rates as for 1991.

Chemical analyses of N, P and K in soil amendments. Samples of millet stalks and manure were milled to pass a 1-mm screen and triplicate samples of approximately 0.3 g stalk, manure and ash and 1 ml defrosted urine were digested in sulphuric acid with a catalyst in an aluminium block digester for 1 h (Bremner and Mulvaney, 1982). Cooled digests were brought to 100 ml with distilled water and analysed for N and P contents on a Technicon automated analyser while flame emission spectrophotometry was used to determine K concentrations.

Determination of millet yield and N, P and K uptake. Millet was harvested manually from the interior of each plot. The millet panicles were separated from the stover and the grains were threshed manually from the panicles. Two millet stands from each plot were sampled for stalk and leaf yield. Entire plants were cut 2 cm above the soil surface and the stover was divided into leaves (blades and sheaths) and stalks. Leaves and stalks were chopped into approximately 5-cm sections and sampled for moisture determination by oven drying at 60 °C for 48 h and then analysed for N, P and K concentrations. Samples of grains, leaves and stalks from immediate-till plots and no-till plots were ground to pass a 1-mm screen before storing in coin envelopes for analyses. Approximately 0.3-g samples of each plant part were digested in sulphuric acid in an aluminium block digester. Digests were analysed for N and P on an autoanalyser and for K concentrations by flame emission spectrophotometry. The concentrations of N, P and K in grains were multiplied by their respective DM yields to determine the annual amounts of each nutrient taken up from each plot.

Statistical analysis

All the tests performed assumed a probability level of $p < 0.05$ to be significant. The differences in the pearl millet grain, leaf and stalk yields and N, P and K uptake due to treatments were determined using the ANOVA of the GLM procedures (SAS, 1985). Regression analysis was used to investigate the relationship between the applied fertilizer N and millet grain, leaf and stalk yields, and the N, P and K uptake in grains, leaves and stalks (SAS, 1985).

RESULTS AND DISCUSSION

Millet yield

Millet yields varied considerably in the 1991 and 1992 study years due to rainfall, tillage and amendment type. In 1991, the highest yields were obtained from the plots where tillage was done immediately after the application of amendments (Fig. 1). Millet yields from the late-till and the no-till plots were statistically the same. In 1992, grain yields in the immediate-till and the late-till plots were similar but higher than in the no-till plots. Average yields in the immediate-till plots and in the late-till plots (4.9 ± 0.67 t ha^{-1}) were not significantly different, whereas the yield advantage from immediate tillage was significantly higher than the no-till practice (3.7 ± 0.67 t ha^{-1}). The higher grain yield obtained in the tilled plots was attributed to less NH_3-volatilization, especially from manure and urine, greater available soil moisture (Hoogmoed *et al*., 1991), faster mineralization of the manure and millet stalks (Hargrove *et al*., 1991) and reduced loss of ash by wind-blow than under the no-till practice.

Average yields were highest in plots amended with sheep manure-plus-urine (5.2 ± 0.67 t ha^{-1}), followed by the manure alone and the stover amended plots (4.6 ± 0.67 t ha^{-1}), stover ash plots (4.1 ± 0.67 t ha^{-1}) and the control plots (3.7 ± 0.67 t ha^{-1}) (Fig. 2). The complete return of stover (stalks plus leaves) from the 1991 harvest was probably responsible for yields being the same from the millet stover amended and the manure-plus-urine amended plots in 1992 (Fig. 2). Thus, the corralling of livestock on farmers' fields overnight for direct deposition of manure and urine can ensure that more nutrients are applied and recycled when compared with the application of manure alone gathered from stalls where animals are fed.

Most (approximately 80%) of the ruminant-excreted N is in urine, while nearly all the P is excreted in faeces (Whitehead, 1970). The N in urine is readily available for plants while the faeces require further decomposition before the N becomes available (Stillwell and Woodmansee, 1981). Urine N transformation, that is, from deamination of nitrogenous compounds, hydrolysis of urea to ammonium and to ammonia, which is highly volatile, is a rapid process and is completed within 4 d (Stillwell and Woodmansee, 1981). Under the semi-arid conditions of the Sahelian region, where evapotranspiration exceeds precipitation several times (Sivakumar, 1986), it was been estimated that between 30 and 50% N from animal urine is lost through ammonia volatilization a week after it is voided on farmers' fields (Powell *et al*., 1998). Thus, incorporating manure and urine into the soil immediately after corralling of livestock may have reduced the amount of N losses and resulted in higher yields and greater uptake of nutrients in immediate-till plots amended with manure-plus-urine compared with no-till

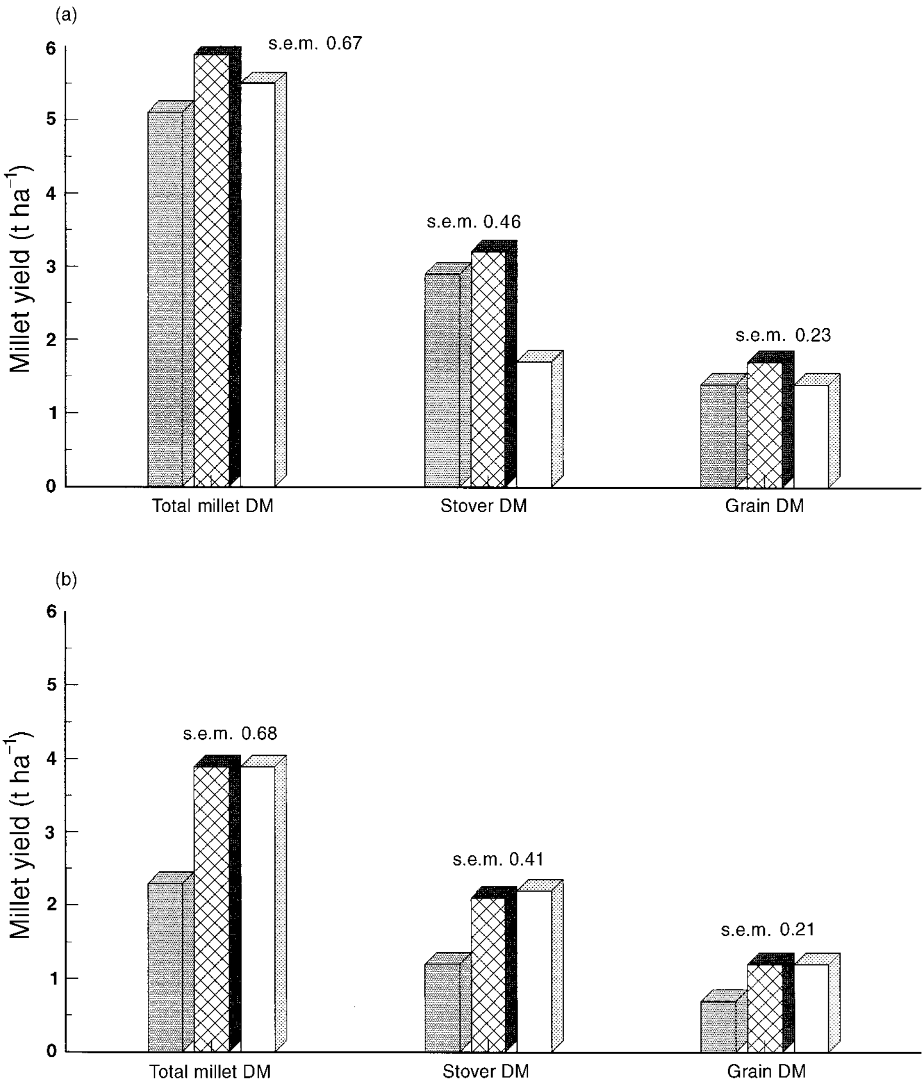

Fig. 1. Effect of primary tillage practices, no-till (▒), immediate-till (⊠), late-till (□), on pearl millet dry matter (DM) yields in (a) 1991 and (b) 1992 at Sadoré.

plots. Faster release of nutrients from urine than from sheep manure, which decomposes slowly (Powell *et al.*, 1998), possibly synchronized nutrient requirements with pearl millet demands.

Uptake of nutrients and partitioning to millet plant parts

The uptake and partitioning of N, P and K to millet plant parts were influenced by amendment practices (Fig. 3 and Table 2). In both study years, nutrient uptake in the manure-plus-urine amended plots was highest. In the first year, N, P

https://doi.org/10.1017/S0014479799354053 Published online by Cambridge University Press

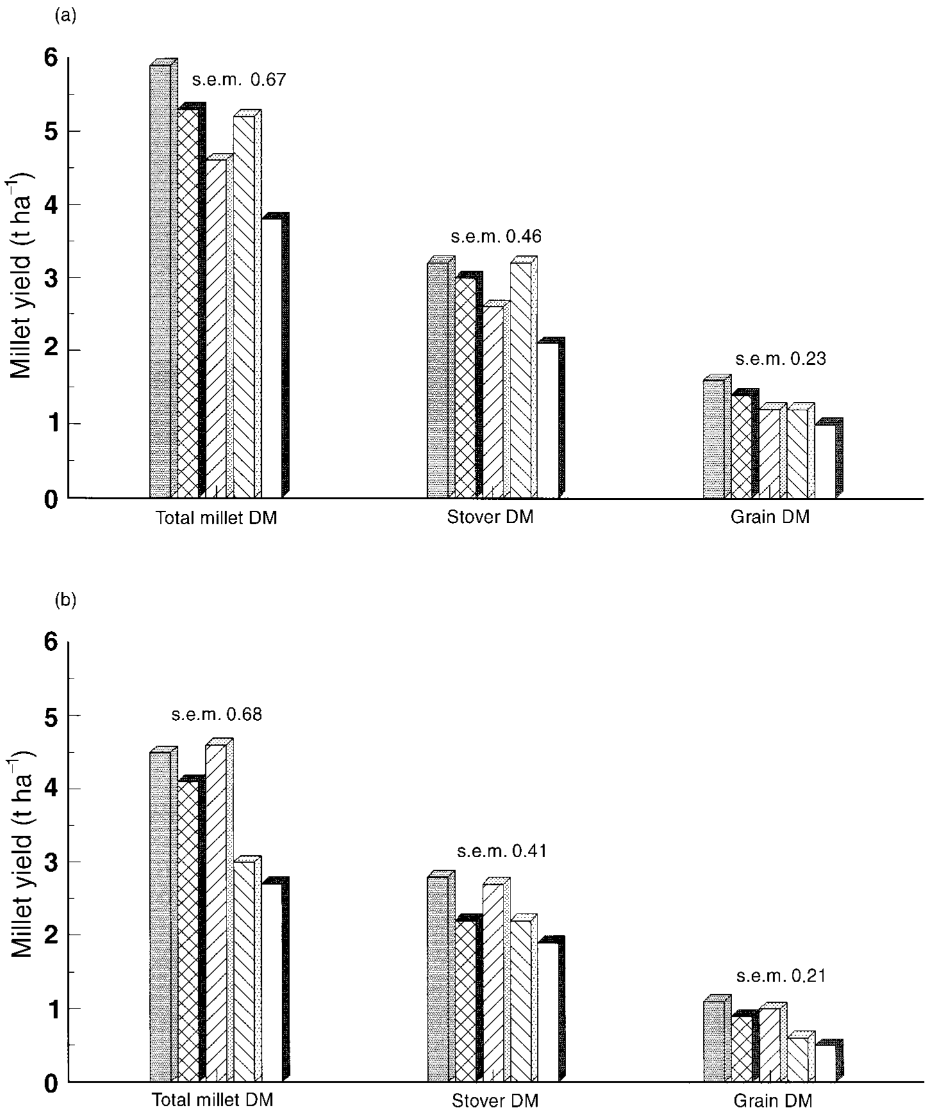

Fig. 2. Effects of amendment type, manure + urine (▒), manure alone (☒), millet stover (▨), millet stover ash (▧) and control (□), on pearl millet dry matter (DM) yields in (a) 1991 and (b) 1992 at Sadoré.

and K uptake in plots amended with millet stalks and millet stalk ash were not significantly different. However, when stover was applied in the following year the uptake of nutrients, particularly N was significantly higher than in the stover ash-amended plots (Fig. 3). This was due to the return of nutrients in millet leaves. Burning of millet residue leads to the loss of N through volatilization.

Nitrogen. The average concentrations of N in millet grains, 19.2 $\pm$ 1.02 g kg^{-1}

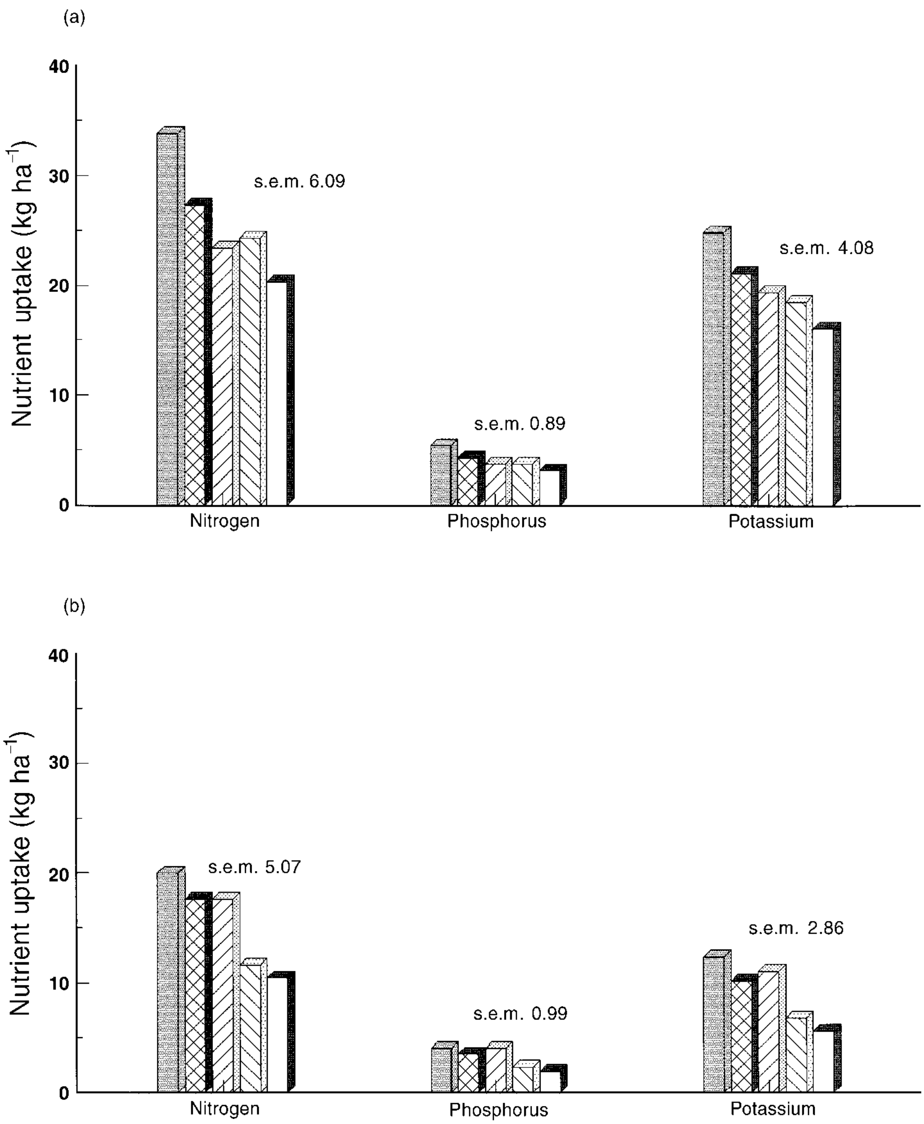

Fig. 3. Effects of amendment type, manure + urine (▨), manure alone (⊠), millet stover(▨), millet stover ash (▧) and control (□), on nitrogen, phosphorus and potassium removal (uptake) by millet grain at harvest in (a) 1991 and (b) 1992 at Sadoré.

in 1991 and 17.6 ± 0.79 g kg^{-1} in 1992 were less than those found by Hafner *et al.* (1993). In a long-term N balance study with millet residue and fertilizer N applications, Hafner *et al.* (1993) reported that despite large differences in grain yields, N concentrations in millet grain at Sadoré were 20.0, 23.0 and 22.3 g kg^{-1} in 1985, 1987 and 1988 respectively; N concentrations in stover were 7.3 g kg^{-1} in 1985, 8.2 g in 1987 and 7.8 g in 1988. In the present study, N concentrations in

Table 2. The effects of amendment type on the partitioning of nutrients to millet grains, stalks and leaves.

	Nutrient concentration ($g\ kg^{-1}$ dry matter)								
	Nitrogen			Phosphorus			Potassium		
Amendment	Grains	Stalks	Leaves	Grains	Stalks	Leaves	Grains	Stalks	Leaves
				1991					
Manure + urine	21.1	14.1	20.7	3.4	1.2	1.4	15.5	32.6	25.1
Manure	19.5	13.1	19.0	3.1	1.1	1.3	15.1	31.3	24.0
Millet stalks	19.0	11.9	18.7	3.1	1.0	1.2	16.2	30.0	23.0
Millet stalks ash	18.5	11.0	18.2	3.1	1.0	1.1	16.4	28.5	22.5
Control	18.1	8.4	15.6	3.0	0.9	1.0	15.0	24.0	21.7
s.e.	1.02	1.66	1.73	0.16	0.05	0.22	1.14	3.21	2.37
				1992					
Manure + urine	20.6	6.9	10.5	4.0	0.9	1.4	11.2	25.6	14.9
Manure	19.1	6.6	9.4	3.9	0.8	1.3	11.2	20.9	13.3
Millet stalks	18.6	6.8	9.1	3.9	0.7	1.3	11.4	19.8	12.1
Millet stalks ash	17.2	6.0	8.3	3.8	0.7	1.2	11.2	18.7	11.8
Control	12.5	5.5	8.0	3.1	0.5	0.9	11.0	17.7	10.5
s.e.	0.79	0.77	1.21	0.17	0.22	0.29	0.20	1.85	1.12
s.e. 1991–92	0.75	1.16	1.09	0.17	0.12	0.18	1.20	3.36	2.88

millet grains were consistent with the 17.2 $g\ N\ kg^{-1}$ obtained by Bationo and Mokwunye (1991a) but exceeded the minimum value of 13.0 $g\ N\ kg^{-1}$ reported from world-wide experiments with millet (Duivenbooden and Cissé, 1992). Similar trends were observed for N concentrations in millet leaves and stalks (Table 2). Higher rainfall in 1991 than in 1992, probably favoured faster mineralization of soil amendments and more N uptake.

Phosphorus. Average P contents in millet grains (3.5 $g\ kg^{-1}$), were higher than the value of 1.8 $g\ P\ kg^{-1}$ obtained in the world-wide experiments with millet (Duivenbooden and Cissé, 1992) and the value of 2.5 $g\ P\ kg^{-1}$ reported by Bationo and Mokwunye (1991a). Average P contents in the stalks (0.9 $g\ kg^{-1}$) and leaves (1.2 $g\ kg^{-1}$) were higher than the value of 0.3 $g\ kg^{-1}$ reported from world-wide experiments with millet (Duivenbooden and Cissé, 1992) and the value of 0.3 $g\ kg^{-1}$ (Bationo and Mokwunye, 1991a) reported on a stover basis (Table 2).

In a related experiment, higher P uptake in plots amended with manure-plus-urine compared with plots that received manure alone (Fig. 3), was attributed to the higher level of available P in the soil for most of the cropping season due to increased soil pH, particularly during the first week of application (Powell and Ikpe, 1992). A soil reaction close to neutrality, which was likely in plots where sheep urine was applied, resulted in maximum dissolubility of P from iron and aluminium complexes in the soil. Furthermore, in the present study, the higher concentration of NH_4-N in plots amended with manure-plus-urine (Ikpe and

https://doi.org/10.1017/S0014479799354053 Published online by Cambridge University Press

Powell, 1997), possibly increased the uptake of NH_4-N, with a resultant increase in $H_2PO_4^-$ uptake in order to maintain ionic electro-neutrality (Marschner, 1990).

The application of millet residue to soil leads to increased P nutrition by millet due to an increase in the population of N-fixing bacteria which leads to an increase in the millet root surface area (Kretzschmar *et al.*, 1991). Millet plant rhizosphere associations and particularly the activity of N-fixing bacteria, diazotrophs, have been shown to contribute substantially to millet P nutrition. The activity of these root microbial associations have been found to be responsible for a phytohormone-induced increase in millet root surface area, which is a crucial factor in P acquisition by millet in P-deficient soils (Kretzschmar *et al.*, 1991), such as those of semi-arid West Africa.

Potassium. If more N and P were partitioned to grains, then greater proportions of K were partitioned to millet stalks than to the leaves and grains, amendment practices notwithstanding (Table 2). However, K uptake was higher in plots amended with manure-plus-urine than in other amended and control plots. This trend remained the same for N and P uptake (Fig. 3).

Drought spells are a common feature during the cropping season in Sahelian agriculture (Sivakumar, 1991). Among the major plant nutrients, potassium has the greatest hydrated ionic radius (Marschner, 1990). This property enhances the role of potassium in osmoregulation on which millet tolerance to drought conditions depends. Thus soil management practices that increase K uptake may lead to greater millet tolerance to moisture stress conditions and thereby result in sustainable yield. The concentration of K in millet plant parts was due partly to differences in the amount and distribution of rainfall in 1991 and 1992 and differences in the amounts of K in the amendments (Table 1). The average concentration of K in grains (13.4 ± 1.14 g kg^{-1}) was greater than the 4.8 g K kg^{-1} reported by Bationo and Mokwunye (1991a) and the 3.0 g K kg^{-1} reported from world-wide experiments with millet (Duivenbooden and Cissé, 1992). The average concentrations of K in leaves (18.1 ± 2.88 g kg^{-1}) and in stalks (24.5 ± 3.36 g kg^{-1}) were greater than that reported on a stover basis (17.7 g kg^{-1}) by Bationo and Mokwunye (1991a) and that reported from world-wide experiments with millet (10.0 g kg^{-1}) (Duivenbooden and Cissé, 1992).

CONCLUSIONS

The results of this experiment show that livestock can play a significant role in the cycling of nutrients in the crop–livestock systems of the Sahel of West Africa. The incorporation of soil amendments greatly increased millet yields and nutrient uptake over the no-till management while the application of manure-plus-urine also resulted in higher yields compared with other amendment practices.

The shift from nomadic to less nomadic forms of livelihood in Sahelian West Africa has led to a tendency away from extensive, grazing-based livestock management (corralling animals overnight on farmers' fields) to intensive, stall-feeding systems where only manure is available for cropping (Winrock International, 1992). Such a tendency will lead to losses of nutrients, reduced yields and land degradation.

There is a need to adopt technologies that capture animal urine and transfer nutrients to farmers' fields. Improved soil management strategies, such as primary tillage which is not a widespread practice among farmers, can be used to minimize N loss through volatilization. However, the profitability of incorporating soil amendments into soil by tillage using animal traction vis-à-vis the present predominantly no-till practice, needs to be studied.

REFERENCES

Bationo, A. & Mokwunye, A. U. (1991a). Role of manures and crop residue in alleviating soil fertility constraints to crop production: with special reference to the Sahelian and Sudanian zones of West Africa. *Fertilizer Research* 29:117–125.

Bationo, A. & Mokwunye, A. U. (1991b). Alleviating soil fertility constraints to increased crop production in west Africa: the experience in the Sahel. *Fertilizer Research* 29:95–115.

Bremner, J. M. & Mulvaney, C. S. (1982). Total nitrogen. In *Methods of Soil Analysis, American Society of Agronomy Monograph 10, Vol. 2*, 594–624 (Eds L. A. Page, R. H. Miller & D. R. Keneey). Madison, Wisconsin: American Society of Agronomy.

Duivenbooden, N. van & Cissé, L. (1992). Fertilization of millet cv. Souna III in Senegal: dry matter production and nutrient uptake. *Fertilizer Research* 32:78–89.

Hacker, J. B. & Minson, D. J. (1981). The digestibility of plant parts. *Herbage Abstracts* 51(9):459–482.

Hafner, H., Bley, J., Bationo, A., Martin, P. & Marschner, H. (1993). Long-term nitrogen balance for pearl millet (*Pennisetum glaucum* L.) in an acid sandy soil of Niger. *Zeitschrift fuer Pflanzenernährung und Bodenkunde* 156:169–176.

Hargrove, W. L., Ford, P. B. & Somda, Z. C. (1991). Crop residue decomposition under controlled and field conditions. *Proceedings of International Soil Tillage Research Organization Meetings*. Ibadan, Nigeria: ISTRO.

Hoogmoed, W. B., Klaij, M. C. & Brouwer, J. (1991). Infiltration, runoff and drainage in the Sudano-Sahelian zone. In *Soil Water Balance in the Sudano-Sahelian Zone. (Proceedings of the Niamey Workshop, February 1991). IAHS Publication No. 199*, 85–98.

Hopkins, J. & Reardon, T. (1989). Household Crop and Livestock Transactions Behaviour in Western Niger. IFPRI/ICRISAT Collaborative Project Working Paper. Niamey, Niger: IFPRI/ICRISAT.

Ikpe, F. N. & Powell, J. M. (1997). Pearl millet yield and changes in soil properties under the crop–livestock systems of the Sahel of west Africa (submitted to *Agricultural Systems*).

Kretzschmar, R. M., Hafner, H., Bationo, A. & Marschner, H. (1991). Long- and short-term effects of crop residues on aluminium toxicity, phosphorus availability and growth of pearl millet in an acid sandy soil. *Plant and Soil* 136:215–223.

Lamers, J. & Feil, P. (1993). The many uses of millet residues. *ILEIA Newsletter* 9(3):15.

Marschner, H. (1990). *Mineral Nutrition of Higher Plants*. London: Academic Press.

O'Donovan, P. B. (1983). Untreated straw as livestock feed. *Nutrition Abstracts and Reviews* 53:442–455.

Pichot, J., Sedego, M. P., Poulain, J. F. & Arivets, J. (1981). Evolution de la fertilité d'un sol ferrugineux tropical sous l'influence des fumures minérales et organiques. *L' Agronomie Tropical* 36:122–133.

Powell, M. (1985). Contribution of fractionated crop residues to dry-season livestock feed resources in the Abet plains, Central Nigeria. *ILCA Newsletter* 4(4):5–7.

Powell, J. M. & Fons, F. M. (1991). Sorghum stover removal effects on soil organic matter, extractable nutrients, and crop yield. *Journal of Sustainable Agriculture* 2:25–38.

Powell, M. & Ikpe, F. (1992). Nutrient cycling through livestock. *ILEIA Newsletter* 3:13–14.

Powell, J. M., Ikpe, F. N., Somda, Z. C. & Fernández-Rivera, S. (1998). Manure and urine effects on pearl millet yield and soil chemical properties. *Experimental Agriculture* 34:259–276.

SAS Institute Inc. (1985). *SAS User's Guide: Statistics, Version 5 Edition*. Cary, NC: SAS Institute Inc.

Sivakumar, M. V. K. (1986). *Climate of Niamey. Progress Report-1. ICRISAT Sahelian Centre*, Niger, West Africa: ICRISAT.

Sivakumar, M. V. K. (1991). *Drought Spells and Drought Frequencies in West Africa. ICRISAT Research Bulletin 13*. Patancheru, India: ICRISAT.

Stillwell, M. A. & Woodmansee, R. G. (1981). Chemical transformations of urea–nitrogen and movement of nitrogen in a Shortgrass Prairie Soil. *Soil Science Society America Journal* 45:893–898.

West, L. T., Wilding, L. P., Landeck, J. K. & Calhoun, F. G. (1984). *Soil Survey of the ICRISAT Sahelian Centre, Niger, West Africa*. College Station, Texas: Texas A & M University Soil and Crop Science Departments/TropSoils.

Whitehead, D. C. (1970). *The Role of Nitrogen in Grassland Productivity, Commonwealth Agricultural Bureaux Bulletin 48*. Farnham Royal: CAB.

Winrock International (1992). *Assessment of Animal Agriculture in Sub-Sahara*. Morrilton, Arkansas: Winrock International Institute for Agricultural Development.