Agriculture, Ecosystems and Environment 83 (2001) 55–63

Agriculture Ecosystems & Environment

www.elsevier.com/locate/agee

Decomposition of and nutrient release from ruminant manure on acid sandy soils in the Sahelian zone of Niger, West Africa

P.C. Esse[a], A. Buerkert[b,*], P. Hiernaux[c], A. Assa[a]

[a] *Unité de Formation et de Recherche des Sciences de la Terre et des Ressources Minières, Université de Cocody, 22 BP 582, Abidjan 22, Ivory Coast*

[b] *Institute of Plant Nutrition (330), University of Hohenheim, Steinstr. 19, D-37213 Witzenhausen, Germany*

[c] *International Livestock Research Institute (ILRI), International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Centre, BP 12404, Niamey, Niger*

Received 31 December 1999; received in revised form 8 May 2000; accepted 29 August 2000

Abstract

In ago-pastoral systems of the semi-arid West African Sahel, targeted applications of ruminant manure to the cropland is a widespread practice to maintain soil productivity. However, studies exploring the decomposition and mineralisation processes of manure under farmers' conditions are scarce. The present research in south-west Niger was undertaken to examine the role of micro-organisms and meso-fauna on in situ release rates of nitrogen (N), phosphorus (P) and potassium (K) from cattle and sheep–goat manure collected from village corrals during the rainy season. The results show that (1) macro-organisms played a dominant role in the initial phase of manure decomposition; (2) manure decomposition was faster on crusted than on sandy soils; (3) throughout the study N and P release rates closely followed the dry matter decomposition; (4) during the first 6 weeks after application the K concentration in the manure declined much faster than N or P. At the applied dry matter rate of 18.8 Mg ha^{-1}, the quantities of N, P and K released from the manure during the rainy season were up to 10-fold larger than the annual nutrient uptake of pearl millet (*Pennisetum glaucum* L.), the dominant crop in the traditional agro-pastoral systems. The results indicate considerable nutrient losses with the scarce but heavy rainfalls which could be alleviated by smaller rates of manure application. Those, however, would require a more labour intensive system of corralling or manure distribution.

Keywords: Corralling; Manure; Millet; Niger; Nutrient release; Termites

1. Introduction

In the West African Sahel, bush fallow systems have traditionally helped to restore the productivity of repeatedly cropped acid sandy soils. Fallow periods between 10 and 30 years allowed (1) the enrichment of the topsoil with mineral nutrients and organic carbon by diazotrophic N_2-fixation from the herbaceous layer or shrubs in the order 5–10 kg N ha^{-1} per year, and the decay products of between 400 and 500 kg ha^{-1} per year of leaf, twig and fruit products of woody plants (Hiernaux, 1983; Krul et al., 1982); (2) the transfer of minerals from deeper soil layers and their recycling with falling leaves; (3) the capture of bird droppings estimated at up to 40 kg DM ha^{-1} per year containing 2.2 kg N, 0.4 kg P and 0.7 kg K (Soumaré, 1995), and (4) the deposition of substantial amounts of base-rich

* Corresponding author. Present address: Institute of Crop Science, University of Kassel, Steinstr. 19, D-37213 Witzenhausen, Germany. Tel.: +49-5542-98-1228; fax: +49-5542-98-1230.
E-mail address: buerkert@wiz.uni-kassel.de (A. Buerkert).

0167-8809/01/$ – see front matter
PII: S0167-8809(00)00264-4

'Harmattan' dust from the Sahara reported to contribute up to 3 kg N ha^{-1}, 1 kg P ha^{-1} and 15 kg K ha^{-1} per year (Herrmann et al., 1994). However, the expansion of cropland due to population growth has led to the reduction of fallow periods to often less than 4 years or their complete disappearance (Berger, 1996). As a consequence of farmers' low cash income and poor terms of trade for millet (*Pennisetum glaucum* L.), the dominant crop of the rainfed agricultural system, the use of mineral fertilisers in the Sahel is stagnating (van Reuler and Prins, 1993). Given this, the need to intensify and optimise the use of animal manure and crop residues as soil fertility amendments has become crucial to the sustained productivity of Sahelian farming systems.

Under farmers' conditions, increases of millet grain yield per tonne dry matter of applied manure vary from 15 to 86 kg (McIntire et al., 1992). While it is evident that manure application does not add nutrients to the agro-pastoral system as a whole, but merely is a means to transfer minerals and organic carbon at different scales (Hiernaux et al., 1997; Buerkert and Hiernaux, 1998), the high demand for manure by millet farmers is reflected in elaborate agreements with pastoral herders who exchange manure for grain and grazing rights on harvested millet fields. The strong decrease in the ratio of grazing land to cropping land in most of Africa stimulated research to optimise farmers' traditional manure application strategies by decreasing unproductive losses (Murwira et al., 1995; Brouwer and Powell, 1998). In the Sahel, manure rates of over 10 Mg ha^{-1} per year have been reported for the typical confined areas (corrals) of 10–20 m in diameter close to farmers' homesteads in the cropland, whereas application rates in uncorraled manured fields average 1.5 Mg ha^{-1} (Powell and Williams, 1993). Given the low buffering capacities of the predominantly acid sandy soils, this uneven distribution of manure contributes to a marked pattern of variability in crop growth short distances (microvariability) often described as characteristic for the Sahel (Brouwer et al., 1993; Buerkert et al., 1996). That manure application at high rates can lead to considerable leaching losses of nutrients on sandy soils has been concluded by Brouwer and Powell (1995) from a trial under controlled conditions.

Given the range of rainfall intensities and termite activities in Sudano–Sahelian West Africa, more on-farm studies are needed to determine the pattern of manure decomposition and nutrient release as a function of edaphic and biotic factors. The objective of this study, therefore, was to investigate the role of micro- and macro-organisms in the decomposition of manure from cattle and small ruminants (sheep and goats) throughout the rainy season, and to measure release rates of N, P and K for both manure types.

2. Materials and methods

2.1. Site description and experimental layout

The experiment was conducted at Chikal (3°26′E, 14°14′N), a village 170 km north of Niamey, the capital of Niger, on fields in a palaeo valley called 'Dallol Bosso' with alluvial Arenosols (Projet Tapis Vert, 1977). With an average annual rainfall of 350 mm, Chikal is climatically at the northern border of the 'Southern Sahelian Zone' which is characterised by a 9-month dry season from September to May, and a 3-month rainy season lasting from June to August. The long-term (1986–1997) mean annual temperature is 30°C.

Four farmer-fields were chosen as trial sites based on differences in their topographic position and the quantity of active mounds of harvester-type *macrotermitidae*. These termites are able to carry bits of organic material larger then themselves to their often distant and partly underground nests. Two sites were in the valley bottom ('Dallol'; D1 and D2) on loose sandy soils with low presence of termite mounds, and two sites were at the eroded bottom of the lateral hills ('Glacis'; G1 and G2) on soils with a slope of about 1%, a surface crust of between 10 and 20 mm thickness and a higher apparent presence of termites.

Animal manure mixed with minor amounts of bedding and feed refusals from different cattle and sheep–goat corrals in the village was collected in May 1997, mixed within faeces type and dried in the sun. At the onset of the rainy season (2–4 June) the dry manure was placed in metallic cages with 4 mm mesh on the soil surface permitting easy access of meso-fauna such as termites, beatles or arthropods. To study decomposition processes without meso-fauna but with bacteria, protozoa and nematodes, transparent nylon bags with 100 μm mesh were used. Manure quantities were 75 g dry weight (at 55°C) for a container

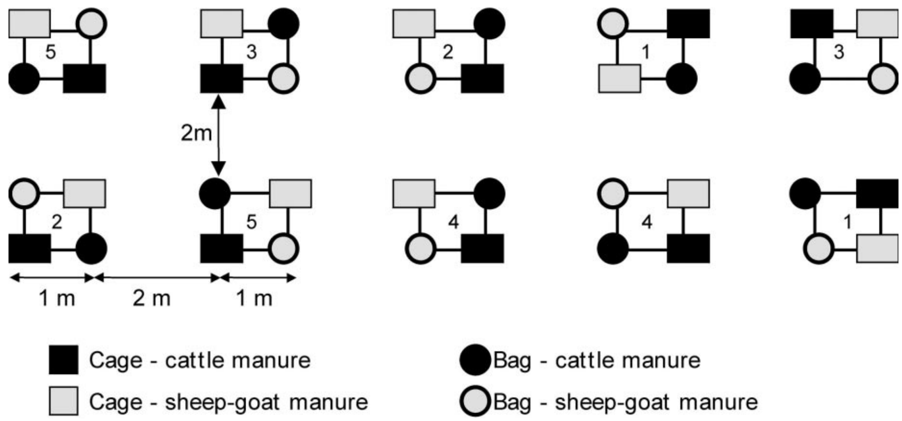

Fig. 1. Experimental layout of an experimental block in each of the four farmer-fields at Chikal, south-west Niger, 1997. Note that each block contains two replicates of each treatment (statistically considered as subsamples) to account for short distance variation in manure decomposition. Numbers from 1 to 5 indicate the respective collection periods of 3, 6, 10, 13 and 17 weeks after manure application.

surface of 0.4 m^2 equivalent to an application rate of 18.8 Mg ha^{-1}. This manure load may appear high but it is still below the maximum of 30 Mg ha^{-1} found in farmers' fields by Powell et al. (1996). The 20 treatments in each of the three blocks per field comprised factorial combinations of: (1) two types of manure (that is, manure of cattle and manure of sheep–goat); (2) two types of container with or without access of meso-fauna (that is, metallic cage or nylon bag); and (3) five dates of sample collection at 3, 6, 10, 13 and 17 weeks after manure application. To account for termite-induced short distance spatial variability in decomposition rates, the 20 treatment units were laid out twice in each block in rows of 2 m distance (Fig. 1).

2.2. Data collection and analysis

Upon sample collection, the remaining quantity of manure was cleaned with a brush to remove loosely adhering soil particles. At all sites, manure samples were oven-dried to constant weight at 55°C to determine total dry matter. Initial and all subsequent manure samples were ground to 2 mm to analyse N by colorimetry, P by colorimetry with ascorbic acid and K by flame emission spectrophotometry (Walinga et al., 1995). Subsamples were dry-ashed in an oven for 5 h at 500°, therefore all results are based on organic matter. To limit the number of chemical analyses, only samples from the G2 site were analysed separately for all dates, manure and container types in each of the three blocks. The samples from each of the three other sites were analysed separately for dates, manure and container types but averaged across blocks. Manure disappearance was calculated as the difference between initial manure weight (organic matter basis) and manure weight at the respective date. The same procedure was used to determine nutrient release. All dry matter data were subjected to analysis of variance using GENSTAT® 5 Release 3.2 (Lawes Agricultural Trust, 1993) and at each site treatment means were plotted to derive curves of organic matter disappearance and nutrient release. Time-related changes in nutrient concentrations were plotted with their respective standard errors of the mean. Disappearance of manure organic matter was expressed as a percentage of the initial rate applied. Nutrient concentrations in similar datasets were not normally distributed, but *F*-values of log-transformed data did not significantly differ from those of untransformed data (Buerkert et al., 1998). For improved readability all data in this study are reported untransformed with the understanding that the respective *F*-probabilities are only approximate.

3. Results and discussion

3.1. Manure disappearance

Container type and surface soil characteristics had large, however, only partly statistically significant,

Table 1
Organic matter disappearance of cattle and sheep–goat manure surface applied at a rate of 18.8 t ha^{-1} and respective release of nitrogen (N), phosphorus (P) and potassium (K) after 17 weeks with (cages) and without (bags) access of meso-fauna at two sites with a crusted (G1 and G2) and two sites with a loose (D1 and D2) topsoil, Chikal, south-west Niger, 1997

Site	Container type	Manure type	Manure disappearance (%)	Nutrient release		
				N	P	K
G1	Cage	Cattle	86.3	179	31	152
		Sheep–goat	78.8	250	38	132
	Bag	Cattle	65.0	109	23	104
		Sheep–goat	57.9	183	30	132
G2	Cage	Cattle	60.6	157	28	141
		Sheep–goat	73.9	207	31	138
	Bag	Cattle	29.4	56	17	120
		Sheep–goat	49.0	146	23	120
D1	Cage	Cattle	59.8	176	30	148
		Sheep–goat	36.6	106	17	101
	Bag	Cattle	21.1	61	11	116
		Sheep–goat	25.9	71	11	106
D2	Cage	Cattle	17.0	62	11	86
		Sheep–goat	24.4	76	10	105
	Bag	Cattle	13.1	45	11	98
		Sheep–goat	17.7	50	9	107
Analysis of variance			*F*-probability			
		Site	<0.001	<0.001	<0.001	<0.001
		Container	<0.001	<0.001	<0.001	0.041
		Manure	0.766	0.020	0.687	0.059
		Site × container	0.383	0.339	0.106	0.109
		Site × manure	0.231	0.017	0.035	0.004
		Container × manure	0.424	0.265	0.263	0.180

effects on the decomposition (as indicated by the organic matter disappearance) of both manure types (Table 1; Fig. 2). With meso-fauna (in cages) and averaged across both types of manure, on the crusted 'Glacis' soils with large termite presence as evidenced by a larger number of mounts per area compared to 'Dallol' soils, 75% of the applied manure disappeared during the first 10 weeks after application. This compares to a disappearance rate of only 28% on the loose 'Dallol' soils. Without meso-fauna (in nylon bags) manure decomposition at 10 weeks was much lower being 38% on 'Glacis' soils and 16% on 'Dallol' soils. These differences remained unchanged throughout the rest of the study period and demonstrated the important role of meso-fauna in the decomposition process in this environment. The higher termite activity on the crusted 'Glacis' sites may be linked to the heavier texture of their more wind- and water-eroded surface soil compared to the lighter textured soil surfaces of the 'Dallol' sites, although no analysis of particle size distribution such as reported by Buerkert et al. (2000) for mulched and unmulched surface soils in the same area was performed to verify texture differences in this study. Boyer (1975) and Bachelier (1978) observed that a critical level of 100 g kg^{-1} clay and silt content was necessary for successful establishment of termite mounds, but only further research into the hydraulic properties of both soil types could clarify to what degree, e.g., differences in water retention may also be contributing to differences in termite activity on both soil types. It has been shown by Mando et al. (1996) that an increase in termite activity can lead to large changes in the physical conditions affecting crop growth on Sudano–Sahelian soils by increasing water infiltration, moisture storage and aggregate stability. The application of organic materials, such as

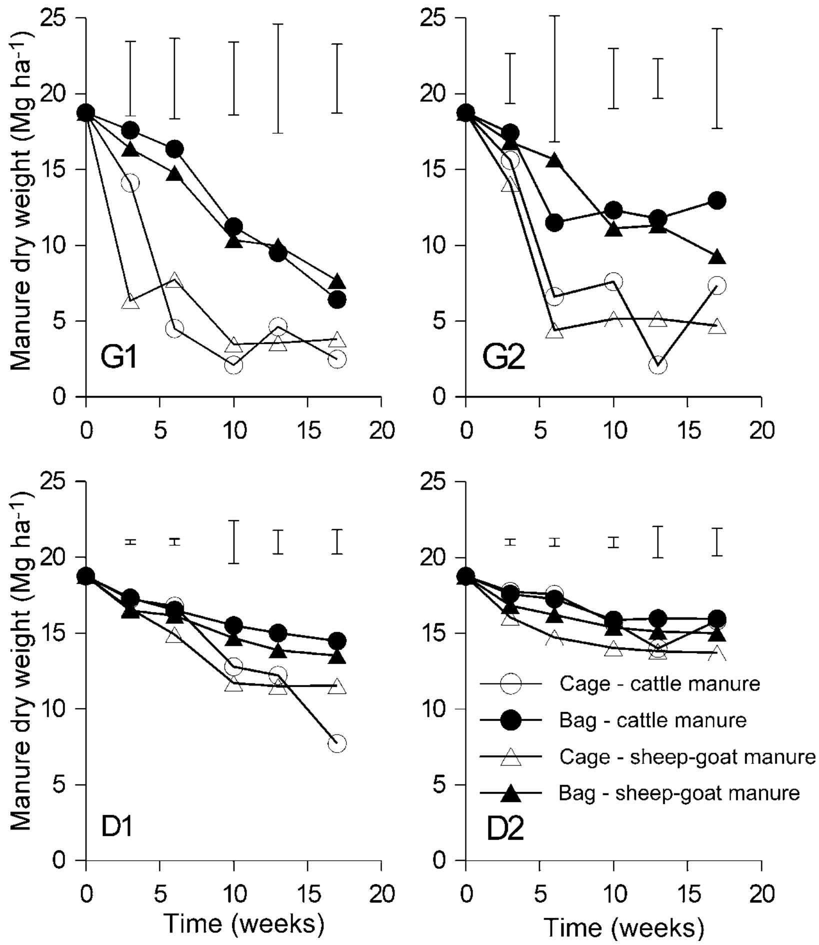

Fig. 2. Organic matter disappearance of cattle and sheep–goat manure applied in metallic cages of 4 mm mesh or in nylon bags of 100 μm mesh placed on the soil surface between 2 and 4 June 1997 at four sites in Chikal, south-west Niger. The eroded 'Glacis' sites G1 and G2 had crusted, the sandy 'Dallol' sites D1 and D2 loose topsoils. Vertical bars represent ±1 S.E. of the difference of means.

manure or crop residues to crusted topsoils, is thus an effective but labour intensive method of soil reclamation and rehabilitation, which as such is also widely practised by local farmers on the generally untilled soils of the Northern Sahel (Feil and Lamers, 1996).

There were no significant differences in disappearance rates between the two types of manure regardless of container or soil type. This is in contrast to results by Powell et al. (1998) obtained at a site further south in Niger with 560 mm average annual rainfall. With termite access they reported a complete disintegration and disappearance of cattle manure within less than 3 months compared to a 13.8% recovery of sheep dung after 12 months.

The consistent decline of the manure decomposition rate after the 10th week of application (Fig. 2) could reflect a relative increase of components more difficult to mineralise, such as lignin and polyphenols. The large variations in manure disappearance over time, particularly in cages after the 10th week on crusted soils, likely reflected site-specific differences in termite attack combined with the effects of the limited number of replicates within the experiment. In this context, it has to be noted that the disappearance of manure from the cages or the bags does not necessarily mean that there was a complete mineralisation of the removed fraction and a subsequent availability of the therein-contained nutrients to plants. Also heavy rainfall could have contributed to the removal of manure from the cages.

3.2. Nutrient concentrations in the manure and nutrient release

With $12\,g\,kg^{-1}$ N in cattle and $15\,g\,kg^{-1}$ N in sheep–goat manure, initial N concentrations in both manure types were lower than the 20 and $23\,g\,kg^{-1}$, respectively, reported by Brouwer and Powell (1998). These differences likely reflect the fact that the manure collected in this study came from traditional village corrals where it had been mixed with feed refusals and left in the sun unprotected against ammonia volatilisation, whereas the faeces of Brouwer and Powell (1998) were mixed with urine right at the trial site. Initial N concentrations were higher in sheep–goat manure than in cattle manure which confirms findings of Brouwer and Powell (1998), Landais and Lhoste (1993) and Schleich (1986), but there were only minor differences between manure types for P and K concentrations (Fig. 3). Phosphorus concentrations of $2\,g\,kg^{-1}$ and K concentrations of $9\,g\,kg^{-1}$ for cattle and $8\,g\,kg^{-1}$ for sheep–goat manure were similar to those reported by Landais and Lhoste (1993) and Schleich (1986). Under on-farm conditions, the observed differences in N concentrations between manure types may be due to differences in the feed and specific physiological characteristics of both ruminant species. Schlecht et al. (1997) showed that faecal N concentrations were significantly higher for small ruminants than for cattle when fed with green forage, whereas concentrations were similar for both types of ruminants with straw feeding. Given their higher ability for fodder selection, the freely grazing sheep and goats of the Chikal herds may have had better access to fresh browse leaves with higher N concentrations on naturally occurring bushes and small trees in the Savannah landscape than cattle. While concentrations of N and P in the manure did not significantly change over the entire 17-week decomposition period, K concentrations in both manure types rapidly dropped during the first 6 weeks and stabilised thereafter (Fig. 3). Consequently, N and P liberation mirrored dry matter disappearance, whereas K release was much larger in the first weeks after manure application likely reflecting the higher water solubility of this nutrient compared to N and P (Fig. 3). After 17 weeks, liberation of N, P and K with meso-fauna was with $198\,kg\,N\,ha^{-1}$ 1.9 times, with $32\,kg\,P\,ha^{-1}$ 1.9 times and with $141\,kg\,K\,ha^{-1}$ 1.3 times higher on crusted soils than on sandy soils. Similar differences, although at lower absolute levels, were derived from the nylon bag data without the access of meso-fauna (Table 1; Fig. 4). Irrespective of container type and at equal application rate, sheep-goat manure released

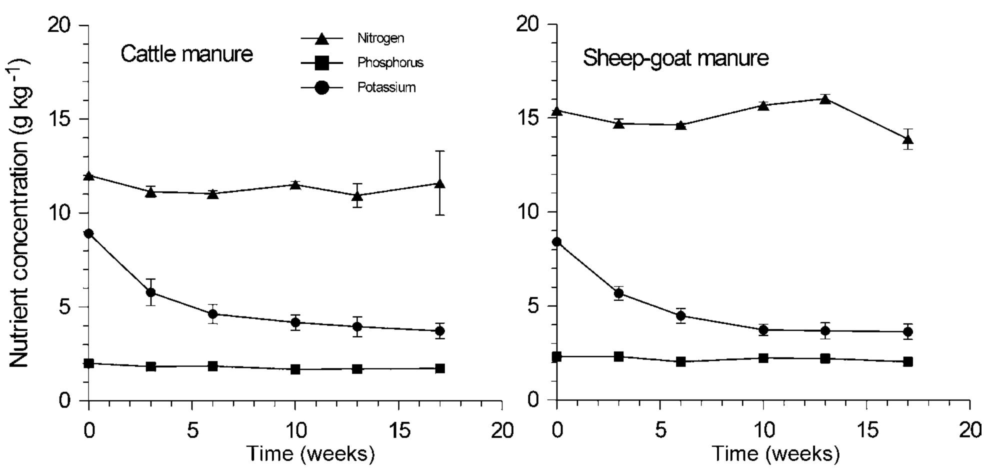

Fig. 3. Average decline of nitrogen (N), phosphorus (P) and potassium (K) concentration in cattle and sheep–goat manure during the first 17 weeks after manure application at the onset of the rainy season at four sites in Chikal, south-west Niger. Wherever larger than the symbol, vertical bars represent ±1 S.E. of the mean.

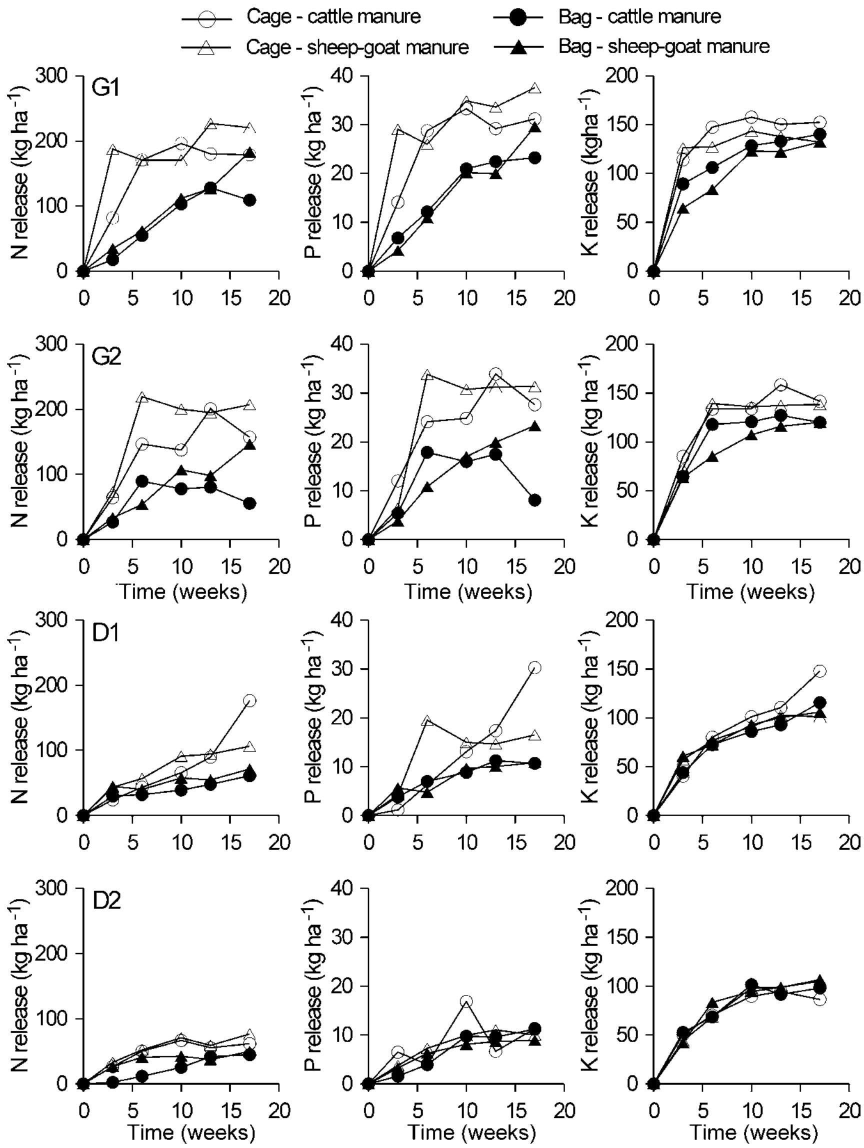

Fig. 4. Cumulative release of nitrogen (N), phosphorus (P) and potassium (K) over 17 weeks at four sites ('Glacis' sites G1 and G2 had crusted, 'Dallol' sites D1 and D2 loose sandy topsoils) for cattle and sheep–goat manure placed at the onset of the rainy season 1997 in metallic cages or nylon bags at Chikal, south-west Niger.

larger quantities of N and K than cattle manure but release of P was similar (Table 1).

Overall the quantities of nutrients released during the 17 weeks of this study were much larger than the nutrient demand of landrace millet under farmers' moisture-induced low plant densities between 3000 and 5000 hills ha^{-1}. With these densities total crop nutrient uptake may reach between 21 kg N ha^{-1}, 1.7 kg P ha^{-1} and 35 kg K ha^{-1} at 300 kg grain and 1700 kg straw and 28 kg N ha^{-1}, 2.3 kg P ha^{-1} and 37 kg K ha^{-1} at 500 kg grain and 2300 kg straw (Buerkert, unpublished data). This oversupply of nutrients to sandy soils may still be temporarily exacerbated by the slow shoot development and nutrient uptake of millet seedlings during the first 6 weeks of growth (Hafner et al., 1993) and likely causes considerable N losses by leaching below the rooting zone of millet with high intensity rainfalls. However, this risk is evidently smaller in the 350 mm rainfall zone at Chikal than with 560 mm at Sadoré from which Brouwer and Powell (1995) reported leaching losses of up to 91 kg N ha^{-1} and 19 kg P ha^{-1} most likely transferred as organic P within 12 months after the application of 10 Mg ha^{-1} manure plus urine. In drought prone areas such as Chikal, lateral removal of nutrients by surface runoff or wind erosion, particularly on 'Glacis' sites with a crusted topsoil and poor plant growth seem more severe, even if it may at the watershed level merely lead to a transfer of nutrients to nearby deposition sites (Buerkert and Hiernaux, 1998). Moreover, at least in the short run, considerable amounts of mineral nutrients that had disappeared from applied manure may have been sequestered in the termite mounts themselves and will only be released once the mounts are destroyed or abandoned.

4. Conclusions

Under the conditions of low rainfall and high termite activity at this Sahelian site most of the manure disappearance during the rainy season occurred very quickly (Fig. 2). Despite large nutrient losses due to high manure loads on selected spots of croplands, labour constraints and erratic availability of nomadic livestock may make it difficult for farmers to replace the current practice of prolonged corralling of animals on the same spot by more widespread applications of manure to their fields. This is not valid, though, for the manual spread of manure from permanent village corrals, which is to maximise nutrient uptake by plants, should be applied only about 4 weeks after sowing. Annual manure application at rates of 2–3 Mg ha^{-1} rather than large 'once-in-10-year applications' could in principle help to reduce nutrient losses at the field level. Manure application is an effective yield enhancing method to recycle nutrients from crop residues over short distances in the field or to transfer nutrients from rangeland to cropland. As such it certainly merits further research to quantify climate- and soil-related differences in nutrient release and uptake by crops. However, even if the most labour intensive techniques were used to make nutrient release from manure fit plant needs, this could not offset the large negative nutrient balances at the watershed scale estimated at 15 kg N ha^{-1} per year, 2 kg P ha^{-1} per year and 15 kg P ha^{-1} per year (Buerkert and Hiernaux, 1998) which call for supplementary applications of mineral fertilisers.

Acknowledgements

The authors are grateful to F. Mahler, E. Schlecht, B. Buerkert, R.D. Stern, T. Winkel and J.M.K. Ambouta for their collaboration and advice, to B. Gérard for his critical comments, to ICRISAT Sahelian Centre for infrastructural support and to the Deutsche Forschungsgemeinschaft (SFB 308) for funding.

References

Bachelier, G., 1978. La faune du sol, son action. Editions de l'ORSTOM, Paris, France, 391 pp.

Berger, M., 1996. Les règles pratiques de la fumure organique. Fiche technique numéro 6. In: Agriculture et développement, No. H.S. Département des cultures annuelles du Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD-CA), Montpellier, France, 8 pp.

Boyer, P., 1975. Les différents aspects de l'action des *Bellicositermes* sur les sols tropicaux. Ann. Sci. Nat. 17, 447–504.

Brouwer, J., Powell, J.M., 1995. Soil aspects of nutrient cycling in a manure application experiment in Niger. In: Powell, J.M., Fernandez-Rivera, S., Williams, T.O., Renard, C. (Eds.), Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa. International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia, pp. 211–226.

Brouwer, J., Powell, J.M., 1998. Increasing nutrient use efficiency in West-African agriculture: the impact of micro-topography on nutrient leaching from cattle and sheep manure. Agric. Ecosyst. Environ. 71, 229–239.

Brouwer, J., Fussell, L.K., Herrmann, L., 1993. Soil and crop growth micro-variability in the West African semi-arid tropics: a possible risk-reducing factor for subsistence farmers. Agric. Ecosyst. Environ. 45, 229–238.

Buerkert, A., Hiernaux, P., 1998. Nutrients in the West African Sudano–Sahelian zones: losses, transfers and role of external inputs. J. Plant Nutr. Soil Sci. 161, 365–383.

Buerkert, A., Mahler, F., Marschner, H., 1996. Soil productivity management and plant growth in the Sahel: potential of an aerial monitoring technique. Plant and Soil 180, 29–38.

Buerkert, A., Haake, C., Ruckwied, M., Marschner, H., 1998. Phosphorus application affects the nutritional quality of millet grain in the Sahel. Field Crops Res. 57, 223–235.

Buerkert, A., Bationo, A., Dossa, K., 2000. Mechanisms of residue mulch induced cereal growth increases in West Africa. Soil Sci. Soc. Am. J. 64, 346–358.

Feil, P., Lamers, J.P.A., 1996. Farmers' perceptions about wind erosion and its control. In: Buerkert, B., Allison, B.E., von Oppen, M. (Eds.), Wind Erosion in Niger. Implications and Control Measures in a Millet-based Farming System. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 215–231.

Hafner, H., George, E., Bationo, A., Marschner, H., 1993. Effect of crop residues on root growth and nutrient acquisition of pearl millet in an acid sandy soil in Niger. Plant and Soil 150, 117–127.

Herrmann, L., Sponholz, B., Stahr, K., 1994. Quellregionen für den Harmattan-Staub in Westafrika: Ein mineralogischer und geochemischer Ansatz. Mitt. Deutsch. Bodenk. Gesell. 74, 367–370.

Hiernaux, P., 1983. Les ressources végétales et leur productivité. In: Wilson, R.T., de Leeuw, P.N., De Haan, C. (Eds.), Recherches sur les systèmes des zones arides du Mali: résultats préliminaires. Research Report No. 5. International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia, pp. 28–50.

Hiernaux, P., Fernández-Rivera, S., Schlecht, E., Turner, M.D., Williams, T.O., 1997. Livestock-mediated nutrient transfers in Sahelian agro-ecosystems. In: Renard, G., Neef, A., Becker, K., von Oppen, M. (Eds.), Soil Fertility Management in West African Land Use Systems. Margraf Verlag, Weikersheim, Germany, ICRISAT, INRAN, University of Hohenheim and Niamey, Niger, pp. 339–347.

Krul, J.M., Penning de Vries, F.W.T., Traoré, F., 1982. Le processus du bilan d'azote. In: Penning de Vries, F.W.T., Djitèye, M.A. (Eds.), La productivité des pâturages sahéliens. Une etude des sols, des végétations et de l'exploitation de cette ressource naturelle. Pudoc, Wageningen, the Netherlands, pp. 226–246.

Landais, E., Lhoste, P., 1993. Systèmes d'élevage et transferts de fertilité dans la zone des savanes africaines. 2. Les systèmes de gestion de la fumure animale et leur insertion dans les relations entre l'élevage et l'agriculture. Cahier d'Etudes et de Recherche Francophones Agriculture, Vol. 2. Institut National de la Recherche Agronomique (INRA), Centre de Versailles, France, pp. 9–25.

Lawes Agricultural Trust, 1993. GENSTAT 5 Release 3 Reference Manual. Oxford University Press, Oxford.

Mando, A., Stroosnijder, L., Brussaard, L., 1996. Effects of termites on infiltration into crusted soil. Geoderma 74, 107–113.

McIntire, J., Bourzat, D., Pingali, P., 1992. Crop–Livestock Interaction in Sub-Saharan Africa. The World Bank, World Bank, Regional and Sectoral Studies, Washington, DC, 246 pp.

Murwira, K.H., Swift, M.J., Frost, P.G.H., 1995. Manure as a key resource in sustainable agriculture. In: Powell, J.M., Fernandez-Rivera, S., Williams, T.O., Renard, C. (Eds.), Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa. International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia, pp. 131–148.

Powell, J.M., Williams, T.O., 1993. Livestock, nutrient cycling and sustainable agriculture in the West African Sahel. Gatekeeper Series SA37. International Institute for Environment and Development (IIED), London, 15 pp.

Powell, J.M., Fernandez-Rivera, S., Hiernaux, P., Turner, M.D., 1996. Nutrient cycling in integrated rangeland/cropland systems of the Sahel. Agric. Syst. 52, 143–170.

Powell, J.M., Ikpé, F.N., Somda, Z.C., Fernandez-Rivera, S., 1998. Urine effects on soil chemical properties and the impact of urine and dung on pearl millet yield. Expl. Agric. 34, 259–276.

Projet Tapis Vert, 1977. Compte rendu des études préliminaires et des recherches réalisées à Chikal, Vol. 1. International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia, Institute for the Study and Application of Integrated Development, Ont., Canada, 21 pp.

Schlecht, E., Fernandez-Rivera, S., Hiernaux, P., 1997. Timing, size and N-concentration of faecal and urinary excretions in cattle, sheep and goats: can they be exploited for better manuring of cropland? In: Renard, G., Neef, A., Becker, K., von Oppen, M. (Eds.), Soil Fertility Management in West African Land Use Systems. Margraf Verlag, Weikersheim, Germany, ICRISAT, INRAN, University of Hohenheim and Niamey, Niger, pp. 361–367.

Schleich, K., 1986. Le fumier peut-il remplacer la jachère? Possibilité d'utilisation du fumier: exemple de la savane d'Afrique occidentale. Revue d'Elevage et de Médecine Vétérinaire des Pays Tropicaux, Vol. 39. Institut d'Elevage et de Médecine Vétérinaire des Pays Tropicaux (IEMVT), Maisons-Alfort, France, pp. 97–102.

Soumaré, A., 1995. Utilisation des elements nutritifs par deux arbres du Sahel: Acacia seyal et Sclerocarya birrea. Thèse Doc. ISFRA, Spec., Bamako, Mali, 137 pp.

van Reuler, H., Prins, W.H., 1993. The Role of Plant Nutrients for Sustainable Food Crop Production in Sub-Saharan Africa. Vereniging van Kunstmest Producenten, Leidschendam, the Netherlands, 259 pp.

Walinga, I., van Der Lee, J.J., Houba, V.J.G., van Vark, W., Novozamsky, I. (Eds.), 1995. Plant Analysis Manual. Kluwer Academic Publishers, Dordrecht, the Netherlands.