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Crop yield and the fate of nitrogen and phosphorus following application of plant material and feces to soil

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Abstract

Organic materials are the most important sources of nutrients for agricultural production in farming systems of semi-arid West Africa. However, reliance on locally available organic nutrient sources for both crop and livestock production is rapidly becoming unsustainable. A series of feeding and agronomic trials have been conducted to address the role of livestock in sustainable nutrient cycling. This paper reports results of a greenhouse study that evaluated the effects of applying crop residue and browse leaves, or feces derived from these feeds, at equal organic-N application rates (150 kg ha^{-1}), alone or with fertilizer-N (60 kg ha^{-1}), on pearl millet (*Pennisetum glaucum* [L.] R.Br.) dry matter (DM) yield, nitrogen (N) and phosphorus (P) uptake, on soil nutrients, and on total, labile and recalcitrant fractions of soil organic matter (SOM). Millet DM and cumulative N uptake were most affected by fertilizer-N, followed by plant species and amendment type, although various interactions among these treatments were noted due to variations in the composition of the applied amendments. Fertilizer-N increased total millet DM by 39%, N uptake by 58% and P uptake by 17%, and enhanced N mineralization from most organic amendments, but was applied insufficiently to totally offset N and P immobilization in pots containing leaves of low initial N and P content. Feces alone appeared to supply sufficient N to meet millet-N demands. Nitrogen use efficiency was, in most cases, higher in pots amended with feces than with leaves. Nitrogen in feces apparently mineralized more in synchrony with millet-N demands. Also, the relatively high cell wall content of feces may have provided an effective, temporary sink for fertilizer-N, which upon remineralization provided more N to millet than pots amended with leaves. Whereas most of the P contained in feces mineralized and was taken up by millet, most leaves immobilized P. Assessing the costs and benefits associated with the direct land application of biomass as a soil fertility amendment *versus* feeding biomass first to livestock then using feces (and urine) to fertilize the soil requires information on both crop and livestock production and associated impacts on nutrient cycling.

Introduction

The potential to increase crop and livestock production in mixed, crop/livestock farming systems of semi-arid West Africa using current technologies is limited due to low and erratic rainfall, poor soil fertility, and very limited use of external nutrient sources in the form of inorganic fertilizers and feed supplements. Organic materials consisting of crop residues, and vegetation from fallow and rangeland are the most important sources of nutrients for agricultural production in these farming systems. The cycling of plant biomass through livestock (cattle, sheep and goats) into feces and urine enhances both livestock and crop production. For this low-input system to remain viable, most plant biomass must be fed to livestock with feces and urine used as soil fertility amendments.

During the dry season, crop residues, the most predominant of which are derived from pearl millet (*Pennisetum glaucum* [L.] R.Br.), cowpea (*Vigna unguiculata*), and tree and shrub leaves are primary ingredients of the livestock diet. It is during this time of

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the year that farmers apply manure to cropland. Therefore, these feeds provide a major source of nutrients for crop production in these farming systems through the feces and urine they produce (Breman and Traoré, 1986; Swift et al., 1989).

Up to 95% of the feed nutrients consumed by ruminant livestock may be excreted in feces and urine. Most of the N voided in urine can be lost via volatilization and leaching (Woodmansee, 1979; Floate, 1981; Russelle, 1992). However, the proportion of N excreted in feces and urine, and, therefore, the amount of N available for recycling, can be altered through diet manipulation (Coppock and Reed, 1992; Powell et al., 1994). Whereas nitrogen (N) is voided in both feces and urine, most phosphorus (P) is voided in feces (CAB, 1984; Ternouth, 1989). Therefore, much of the P release from feces in soils is governed by soil organic matter immobilization-mineralization processes. The predominantly sandy soils of West Africa are inherently very low in organic matter (Kowal and Kassam, 1978; Pieri, 1989), N, and especially P (Breman and de Wit, 1983). The application of feces (and urine) greatly improves these soil properties and crop yields (Abdullahi and Lombin, 1978; Bationo and Mokwunye, 1991; Powell et al., 1996, 1998).

The synchrony of organic matter decomposition and nutrient release with plant nutrient demands can greatly increase the efficiency of nutrient cycling in farming systems that rely principally on organic forms of nutrients for crop production (Myers et al., 1994). When organic amendments are applied to soil, microorganisms readily decompose soluble forms of N (cell contents), followed by N associated with the cell wall (Paul and Clark, 1989). Organic material high in N concentration (>20 g kg^{-1}) generally decomposes more quickly in soil than material low in N (Stevenson, 1986). Plant materials high in lignin and polyphenolic compounds typically decompose and release nutrients slowly (Fox et al., 1990; Palm and Sanchez, 1991; Oglesby and Fownes, 1992).

Previous research (Powell et al., 1994) showed that feeding sheep crop residues in combination with browse leaves reduced the excretion of urine-N, and caused a shift from fecal soluble-N (microbial- and endogenous-N) to fecal insoluble-N (undigested plant-N). It was suggested that nutrient cycling could be enhanced by developing diets that satisfy the nutritional demands of livestock while producing excreta less susceptible to losses when applied to cropland. After incorporation in soil the feeds and feces from the source feeding trial, feces decomposed and released nutrients quickly whereas plant biomass decomposed slowly, released less nutrients than feces, and in some cases, continued to immobilize soil N and P throughout the three season-long trial (Somda et al., 1995). The objectives of this study were to evaluate the effects of applying the same plant biomass and feces on pearl millet yield, N and P uptake, on soil extractable nutrients and soil organic matter (SOM), and to determine whether fertilizer-N could reduce the N and P immobilization by vegetative material observed in the previous field study.

Materials and methods

A greenhouse experiment was conducted at the International Crops Research Centre for the Semi-Arid Tropics (ICRISAT) Sahelian Center (ISC) located approximately 40 km south of Niamey in the Republic of Niger, West Africa.

Origin of leaf and fecal material

Six leaf- and six fecal-types were used in the study (Table 1). Leaves (blades plus sheaths) of mature pearl millet; cultivar CIVT: Composite Inter-Varietal de Tarna (PG), hay of mature *Vigna unguiculata* (VU), and leaves of the browses *Acacia trachycarpa* (AT), *Combretum glutinosum* (CG), *Guiera senegalensis* (GS) and *Pterocarpus erinaceus* (PE) were applied to the soil either directly or as feces from sheep fed these materials. Experimental details of the feeding trial were given by Powell et al. (1994). Briefly, pearl millet leaves (blades plus sheaths) were offered *ad libitum* alone (PG), or in amounts of 200 g in combination with 500–600 g of the other forage leaves to attain daily offers of approximately 12 g N per animal. The leaves of CG, GS, PE, PG and VU are common feeds in the region and AT was introduced recently from Australia.

Treatments

A factorial arrangement of two types of material (feces and feeds), six plant species (AT, CG, GS, PE, PG and VU) and two fertilizer-N levels (equivalent to 0 and 60 kg ha^{-1}applied as urea), plus controls (no leaf or feces additions but with or without fertilizer-N), were evaluated in a completely randomized design, replicated four times. Leaves were broken by hand into approximately 1 cm pieces and whole feces were applied to pots. Leaves and feces were added to 6 kg of

Table 1. Chemical composition of leaves and feces[1] used in greenhouse trial

Amendment	Total-N	NDIN[2]	P	NDF	Lignin	Polyphenols	IAPC[3]
				g kg^{-1}			
LEAVES							
Acacia trachycarpa (AT)	18.5	11.3	1.5	520	219	191	0.594
Combretum glutinosum (CG)	17.4	9.1	0.7	492	127	232	0.090
Guiera senegalensis (GS)	16.4	12.3	0.8	524	205	284	0.497
Pterocarpus erinaceus (PE)	30.8	4.4	1.2	435	163	70	0.070
Pennisetum glaucum(PG)	9.5	5.2	0.8	693	79	39	0.060
Vigna unguiculata (VU)	23.6	17.3	1.9	447	113	53	0.043
FECES							
Acacia trachycarpa (AT)	31.5	23.8	3.2	693	325	not detected	0.214
Combretum glutinosum (CG)	20.6	16.2	4.4	602	140	not detected	0.086
Guiera senegalensis (GS)	24.6	18.5	3.8	692	280	not detected	0.142
Pterocarpus erinaceus (PE)	20.2	15.1	3.0	685	242	not detected	0.163
Pennisetum glaucum (PG)	14.5	6.7	2.3	836	85	not detected	0.050
Vigna unguiculata (VU)	20.4	18.2	3.1	602	161	not detected	0.044

[1]Feces of PG came from diets containing 100% PG leaves. Feces of AT, CG, GS, PE and VU came from diets containing 200 g PG leaves plus 500–600 g of AT, CG, GS, PE or VU leaves (see Powell et al., 1994).
[2]Neutral detergent insoluble nitrogen.
[3]Absorbance at λ 500 nm g^{-1} DM.

air-dried Labucheri (sandy siliceous, isohyperthermic Psammentic Paleustalfs) topsoil (0–20 cm) to supply approximately 282 mg N (an equivalent of 150 kg N ha^{-1}) and mixed thoroughly. Selected properties of the Labucheri soil include: 900–960 g kg^{-1} sand, pH in water of 5.4, organic C of 1.72 g kg^{-1} soil, and total-N, total-P, and Bray1-P contents of 110, 54 and 4.6 mg kg^{-1} soil, respectively. Soil was sieved through a 1-mm screen prior to amendment application. Before each cropping cycle, all pots were fertilized (top-dressed) with KH_2PO_4 at the rate equivalent to 20 kg P ha^{-1}. Fertilizer-N applications were split, one-half applied as a top dressing at the time of fertilizer-P application and one-half approximately 20 days after planting millet.

Crop cycles, harvesting and sampling

After the initial fertilizer, leaf and manure applications, soil was kept moist (180–200 ml distilled water kg^{-1}soil) and left fallow for 20 days before planting pearl millet as a test crop. Two millet plants per pot were grown for 40 days, followed by another 20-day fallow period. Four such crop/fallow cycles were used in the experiment. At the end of each crop cycle, all shoots and roots were harvested from each plot. Shoots were cut 2 cm above the soil surface and roots were separated manually from the soil. The distilled water used to rinse soil from roots was returned to its respective pot. Fertilizer-N and -P treatments were repeated at the beginning of each fallow pe-

riod. Each pot was relocated randomly twice weekly to minimize possible effects due to shading, temperature differences, etc.

Plant and fecal analyses

The chemical composition of leaves and feces used in the trial are shown in Table 1. Subsamples of leaves, feces and millet shoots and roots were oven dried (60 °C) for dry matter (DM) determination. Leaf, feces, shoot and root samples were milled to pass a 1-mm screen before acid-digestion (Nelson and Sommers, 1980) and analyzed for total-N and -P using an autoanalyzer (Technicon, 1977). Additional chemical analysis of leaves and feces included cell wall and lignin contents using the detergent fiber system (Goering and van Soest, 1970), N in the neutral detergent insoluble fraction (NDIN), soluble phenolics (Reed et al., 1985), and insoluble proanthocyanidins (Reed et al., 1982). The soluble-N fraction (NDSN) in leaves and feces was calculated by subtracting NDIN from total-N. Soluble-N in leaves corresponds to the N in cell contents, whereas NDSN in feces consists of microbial and endogenous sources of N. The insoluble-N fraction in leaves and feces is N associated with the cell wall.

Feces varied in physical appearance. The density and water absorption capacity of feces was determined to see if physical properties of feces affect nutrient cycling. The density of dry feces (g DM per cm^3) was calculated after determining the volume by water displacement. The water absorption capacity of feces (g H_2O g^{-1} DM) was determined by the difference between the DM of 50 pellets and their wet weights after placement in a petri dish and covering with water for 24 h.

Nitrogen use efficiency

The efficiency with which applied organic-N (leaf- and fecal-N) and inorganic-N were taken up by millet, relative to millet grown in control pots, was determined at the end of the 4 cropping cycles by the equation $[(A - B) / C]100$ where A = total-N uptake per pot, B = average total-N uptake in control pots receiving no fertilizer-N and C = amount of N applied to each pot.

Soil analyses

At trial's end, soil samples from each pot were analyzed for pH (1:2.5 soil:water), total organic carbon (dry combustion method), total Kjeldahl-N, NH_4–N (2 M KCl method) and Bray1 extractable-P. The soil organic matter (SOM) remaining in each pot was divided into a light fraction (0.5 mm < labile SOM fraction < 1 mm) by flotation on water and a heavy fraction (1 mm < recalcitrant SOM fraction < 2 mm) by sieving (Anderson and Ingram, 1989). Each SOM fraction was dried at 60 °C to constant weight and then combusted at 550 °C for 6 h in a muffle furnace. The light and heavy SOM fractions were acid digested and N and P contents determined on an autoanalyzer.

Statistics

Analysis of variance using the general linear models procedure of the Statistical Analysis Systems Institute Inc. (SAS, 1987) was used to determine the effects of plant species, organic amendment and fertilizer-N on cumulative millet DM, and N and P uptake. Differences in cumulative millet DM and N and P uptake were delineated using Tukey's studentised range test when appropriate. Relationships between the chemical composition of organic amendments and millet DM and N and P uptake were determined by correlation analysis (SAS, 1987).

Results

Yield and nutrient uptake

The analysis of variance (Table 2) showed that most of the variation in cumulative millet DM and N uptake could be accounted for by fertilizer-N (N), plant species (S), and to a lesser extent by amendment type (A), and S×A interaction. Fertilizer-N increased total millet DM by 39%, N uptake by 58% and P uptake by 17%.

Responses to plant species also depended on fertilizer-N (i.e. significant S × N interaction). The S × N interaction on millet DM (Figure 1) and N uptake (Figure 2) can be summarized as follows: in pots that received no fertilizer-N, greater ($P < 0.05$) millet DM and N uptake were obtained in pots amended with the leaves of VU and PE than in pots amended with the leaves of PG; in pots that received fertilizer-N, higher ($P < 0.05$) millet DM was obtained in pots amended with the leaves or feces of CG, GS and VU, than in pots amended with the leaves or feces of other plant species.

The A × S interactions on millet DM and N uptake were due to response differences in pots containing

Table 2. F ratios for treatment effects on cumulative millet DM, N and P uptake, and soil properties

Source of variation	DM (g pot^{-1})	N uptake (mg pot^{-1})	P uptake (mg pot^{-1})	Total soil-N (mg kg^{-1})	Soil NH_4–N (mg kg^{-1})	Bray1-P (mg kg^{-1})	Total SOM (mg kg^{-1})	Heavy SOM (g pot^{-1})	N heavy SOM (mg pot^{-1})	P heavy SOM (mg pot^{-1})	N light SOM (g kg^{-1})	P light SOM (g kg^{-1})
Species (S)	19.3	21.9	2.4	4.3	NS	NS	NS	45.0	41.3	0.3	1.8	3.5
Amendment (A)	6.1	9.6	69.1	9.3	NS	24.1	NS	4.3	284	136	8.2	146
Fertilizer-N (N)	374	585	38.0	18.1	NS	NS	4.5	NS	30.8	NS	NS	NS
S × A	9.1	16.4	4.3	3.7	NS	NS	NS	27.0	2.9	NS	NS	NS
S × N	3.1	2.6	NS	NS	NS	NS	NS	NS	NS	5.6	NS	NS
A × N	NS	NS	NS	5.0	NS	NS	NS	NS	19.7	NS	19.5	NS
S × A × N	NS	2.5	NS	NS	NS	NS	NS	NS	NS	NS	NS	3.5
MSE	5.69	602	66.1	81.5	0.90	0.20	0.23	2.01	15.4	0.10	1.11	0.01

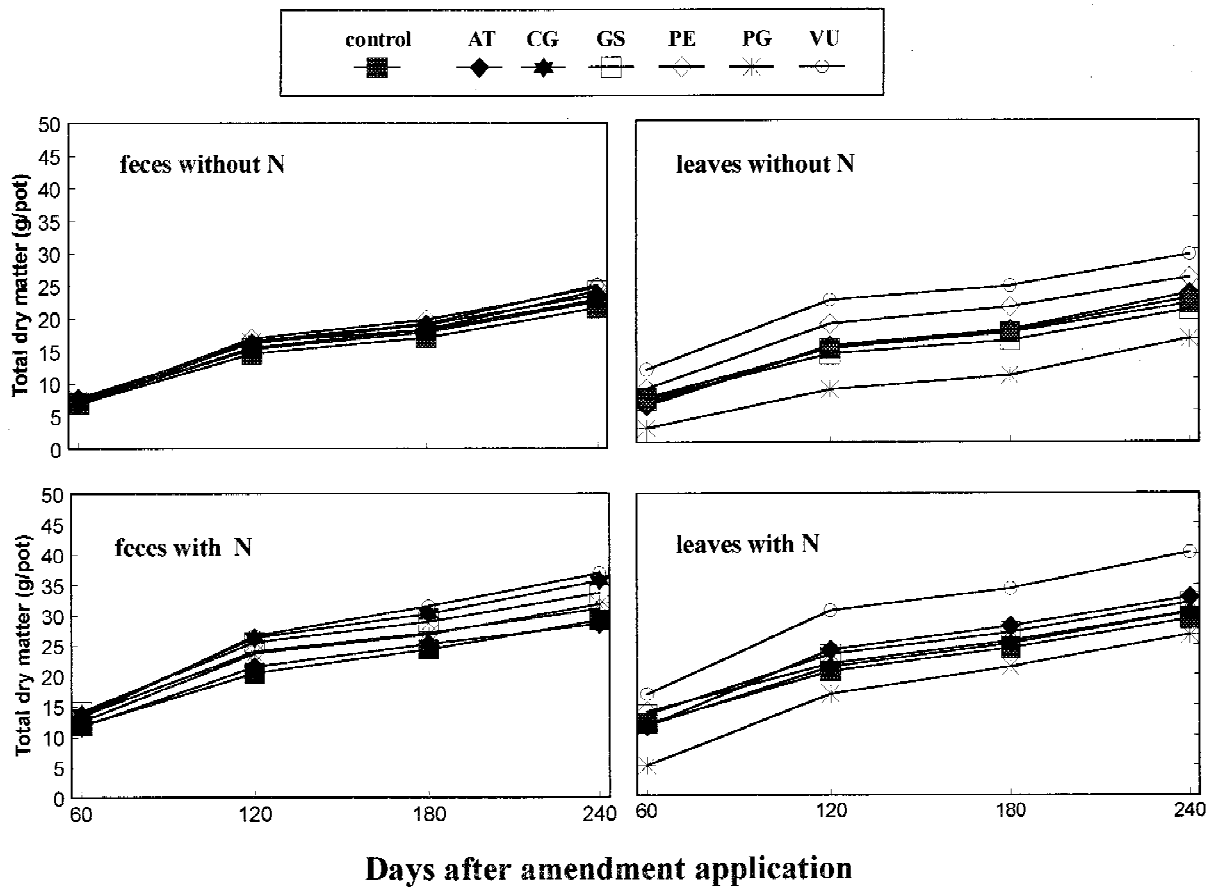

Figure 1. Cumulative dry matter production by millet

the leaves of PG and VU. Whereas the feces derived from all plant species, on average, produced similar amounts of DM and N uptake over the 4 crop cycles, pots containing the leaves of PG produced less DM and had lower N uptake than pots containing the leaves of VU (Figures 1 and 2).

Total-P uptake by millet was most affected by amendment type followed by fertilizer-N (Table 2). The effect of amendment type on millet P uptake depended to some extent on plant specie (i.e. relatively low F ratio for S × A interaction). On average, millet in pots containing feces accumulated about 37%

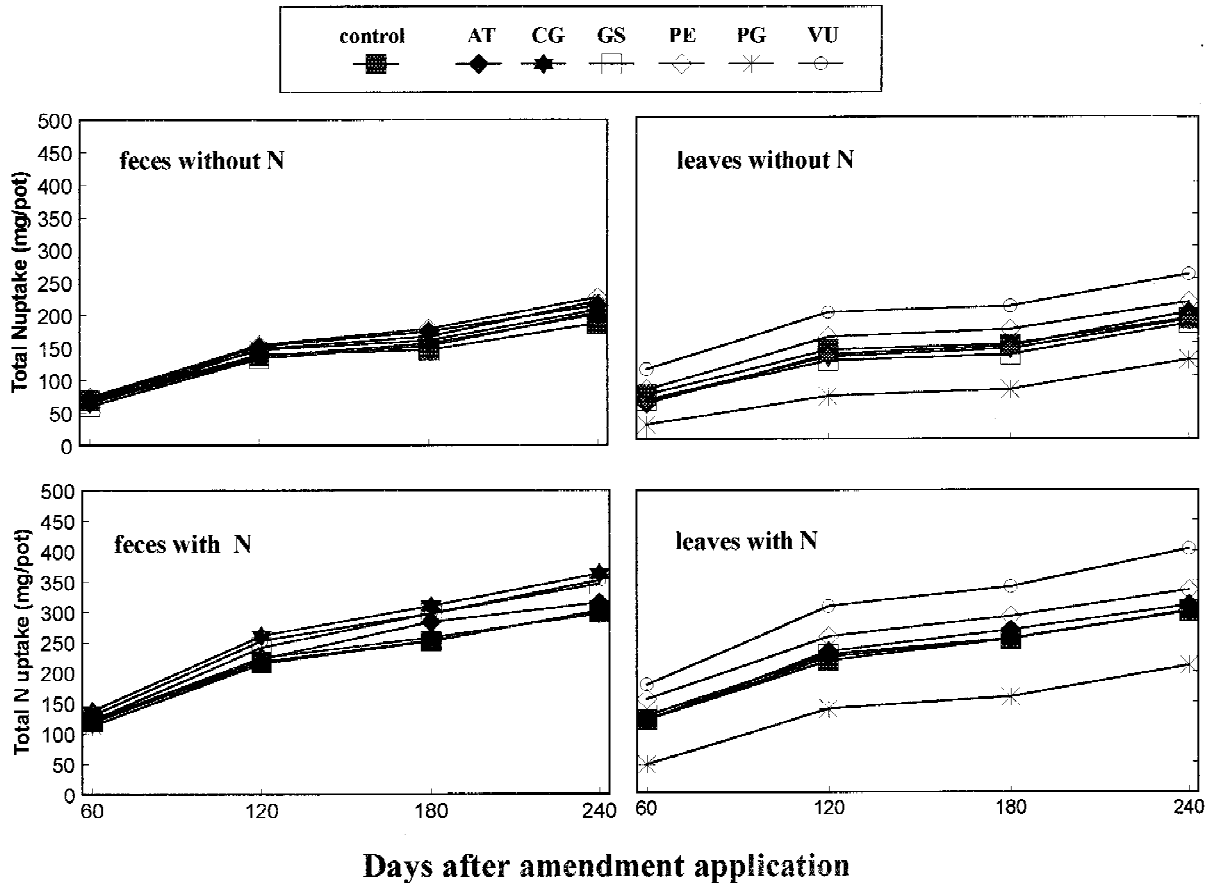

Figure 2. Cumulative N uptake by millet

more P than those amended with leaves. Addition of leaves generally reduced millet-P uptake relative to the control (Figure 3). Millet grown in pots containing the leaves of GS, PE and PG had less ($P < 0.05$) P uptake than millet grown in control pots. Whereas addition of most leaves apparently immobilized P, addition of feces derived from PE, GS and VU, increased ($P < 0.05$) P uptake by millet.

Relationships between amendment composition and yield and nutrient uptake

The amounts of leaf DM and cell wall (NDF) added to pots, and the NDF:N ratio of the leaves added to pots accounted for about 60% (i.e. single correlation coefficients squared) of the variation in cumulative millet DM yield and N and P uptake (Table 3). In pots that received fertilizer-N, the negative effects of these leaf additions were most pronounced during the first millet growing cycle, and diminished thereafter. The opposite response trend was observed in pots that did not receive fertilizer-N: the negative effects of leaf DM, NDF and NDF:N application became more pronounced during the 2nd, 3rd and 4th millet growing cycles. Millet DM and N uptake was positively related to the total N concentration of leaves. Fractionation of total-N into soluble- and insoluble-N did not improve prediction of millet DM and N uptake over predictions using total-N as a dependent variable. Neither leaf lignin, polyphenol, nor IPAC (or their ratios with N) proved to be related to millet response to either leaf or feces additions, in the presence or absence of fertilizer-N.

In contrast to leaves, chemical and physical characteristics of feces accounted for no more than about 25% of the variation in millet response (Table 4). In pots that received no fertilizer-N, the amount and chemical composition of applied feces did not affect millet DM yields, and N and P uptake. In pots that received fertilizer-N, fecal NDIN, NDF and density

Table 3. Single correlation coefficients ($P < 0.05$) for linear regression relationships between composition of leaves added to pots and cumulative[1] millet DM and N and P uptake

Leaf composition	Cumulative DM yields (g pot^{-1})				Cumulative N uptake (mg pot^{-1})				Cumulative P uptake (mg pot^{-1})			
	1	2	3	Total	1	2	3	Total	1	2	3	Total
Without fertilizer-N												
DM (g pot^{-1})	−0.79	−0.85	−0.86	−0.82	−0.79	−0.86	−0.86	−0.85	−0.70	−0.77	−0.65	−0.56
N (g kg^{-1})	0.73	0.80	0.81	0.77	0.72	0.79	0.79	0.75	0.44	0.62	0.50	0.45
NDSN (g kg^{-1})	0.68	0.72	0.72	0.67	0.65	0.70	0.70	0.66	NS	0.52	0.40	NS
P (g kg^{-1})	0.72	0.77	0.75	0.76	0.75	0.77	0.77	0.77	0.58	0.60	0.45	NS
NDF (g kg^{-1})	−0.82	−0.87	−0.88	−0.83	−0.83	−0.88	−0.88	−0.86	−0.71	−0.76	−0.64	−0.53
Lignin (g kg^{-1})	NS	NS	NS	NS	NS	NS	NS	NS	−0.51	−0.44	−0.40	NS
NDSN:NDIN ratio	0.48	0.49	0.49	0.43	0.45	0.47	0.47	0.43	0.54	NS	NS	NS
NDF:N ratio	−0.79	−0.84	−0.85	−0.81	−0.80	−0.85	−0.86	−0.84	−0.74−	0.78	−0.67	−0.56
Lignin:N ratio	−0.47	−0.51	−0.52	−0.50	−0.49	−0.49	−0.49	−0.42	NS	NS	NS	NS
With fertilizer-N												
DM (g pot^{-1})	−0.82	−0.61	−0.56	−0.51	−0.89	−0.85	−0.86	−0.80	−0.70	−0.47	NS	NS
N (g kg^{-1})	0.69	0.44	0.42	NS	0.79	0.74	0.75	0.71	0.59	NS	NS	NS
NDSN (g kg^{-1})	0.63	NS	NS	NS	0.72	0.66	0.67	0.63	0.55	NS	NS	NS
P (g kg^{-1})	0.58	0.76	0.76	0.74	0.64	0.72	0.72	0.75	NS	0.50	0.43	NS
NDF (g kg^{-1})	−0.84	−0.63	−0.59	−0.55	−0.90	−0.86	−0.87	−0.82	−0.68	−0.43	NS	NS
Lignin (g kg^{-1})	NS	NS	NS	NS	NS	NS	NS	NS	0.49	0.50	NS	NS
NDSN:NDIN ratio	0.47	NS	NS	NS	0.53	0.45	0.44	0.40	0.46	NS	NS	NS
NDF:N ratio	−0.83	−0.62	−0.58	−0.53	−0.89	−0.85	−0.87	−0.81	−0.71	−0.48	NS	NS
Lignin:N ratio	NS	NS	NS	NS	NS	NS	NS	−0.40	NS	NS	NS	NS

[1]Cumulative DM yield, and N and P uptake are as follows: 1 = stems + roots of harvest 1; 2 = harvest 1 + harvest 2; 3 = harvests 1 + 2 + 3; and total = harvests 1 + 2 + 3 + 4.

Table 4. Single correlation coefficients ($P < 0.05$) for linear regression relationships between composition of feces added to pots and cumulative[1] millet DM and N and P uptake

Feces composition	Cumulative DM yields (g pot^{-1})				Cumulative N uptake (mg pot^{-1})				Cumulative P uptake (mg pot^{-1})			
	1	2	3	Total	1	2	3	Total	1	2	3	Total
Without fertilizer-N: No significant relationships between fecal components, DM yield and N and P uptake were observed												
With fertilizer-N												
Soluble-N (g kg^{-1})	NS	NS	NS	NS	NS	NS	0.53	0.42	NS	NS	NS	NS
Insoluble-N (g kg^{-1})	NS	NS	−0.47	−0.53	NS	−0.42	−0.53	−0.61	NS	NS	NS	NS
P (g kg^{-1})	NS	NS	NS	NS	NS	0.50	0.59	0.58	NS	NS	0.44	0.50
NDF (g kg^{-1})	NS	NS	−0.47	−0.46	NS	−0.54	−0.56	−0.55	NS	NS	NS	NS
Lignin (g kg^{-1})	NS	NS	NS	−0.42	NS	NS	NS	NS	NS	NS	NS	NS
Sol.-N:Insol.-N ratio	NS	NS	0.52	0.53	NS	0.44	0.50	0.54	NS	NS	NS	NS
NDF:N ratio	NS	NS	NS	NS	NS	NS	−0.48	NS	NS	NS	NS	NS
Density (g DM per cm^3)	NS	−0.41	−0.44	−0.54	NS	NS	NS	NS	NS	NS	NS	NS

[1]Cumulative DM yield, and N and P uptake are as follows: 1 = stems + roots of harvest 1; 2 = harvest 1 + harvest 2; 3 = harvests 1 + 2 + 3; and total = harvests 1 + 2 + 3 + 4.

reduced millet yield and N uptake. A significant relationship was noted between the density of feces (y, DM per cm^3) and fecal lignin content (x, g kg^{-1}) as described by the equation y = 0.322 + 0.0062x (r^2 =

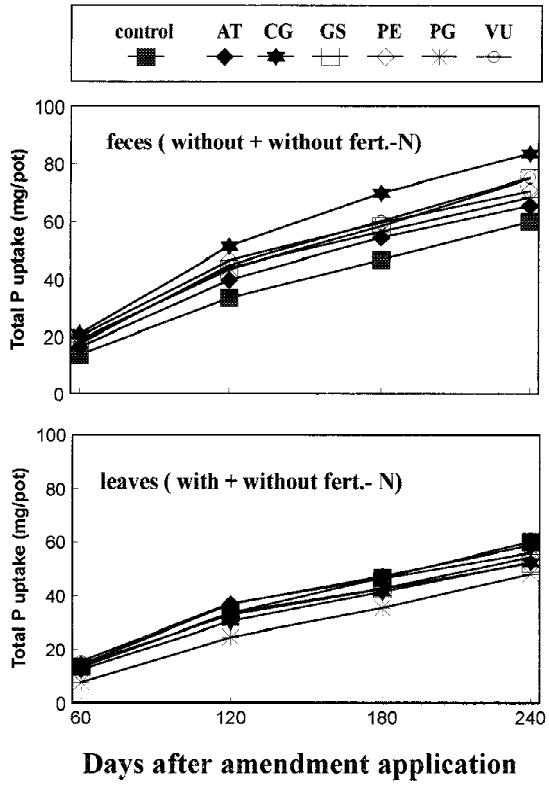

Figure 3. Cumulative P uptake by millet

0.81) and between the water holding capacity of feces (y, g H_2O g^{-1} DM) and lignin content (x, g kg^{-1}) as described by the equation $y = 2.30 - 0.0245x$ (r^2 = 0.68). Higher P concentration in applied feces improved millet N and P uptake during 2nd, 3rd and 4th millet growing cycles.

Nitrogen use efficiency

An analysis of variance showed that the use efficiency of organic-N (ONUE) and total-N (TNUE) varied (P <0.01) with plant species and amendment (Table 5). Leaves of CG, GS and especially of PG apparently continued to immobilize N up to the trial's end (120 d). All feces, except those from VU, had greater ONUE than their companion leaves. TNUE (i.e. NUE in pots receiving organic- plus fertilizer-N) was, on average, slightly greater in pots amended with feces (20 $\pm$ 4.5%) than in pot amended with leaves (17 $\pm$ 8.6). The principal interactive effects of Specie$*$Amendment on TNUE can be summarized as follows: whereas feces derived from CG, GS and PG provided greater TNUE than the leaves of the same species, the feces derived from PE and VU had lower TNUE than leaves of the same species (Table 5).

Table 5. Organic-N use efficiencies (%) and total-N use efficiencies (%) by millet

Plant species	Organic-N use efficiencies		Total-N use efficiencies	
	Feces	Leaves	Feces	Leaves
AT	10	4	18	17
CG	5	−1	24	15
GS	6	−3	22	15
PE	14	9	15	20
PG	7	−23	20	16
VU	12	24	23	30
(SEM)	(1.75)	(3.10)	(0.99)	(1.77)

Pots without fertilizer-N (i.e. organic-N only added to pots).
Pots with fertilizer-N (organic- plus fertilizer-N added to pots).

Soil analysis

At trial's end, total soil-N levels depended on interactions between amendment type and plant species, and on interactions between amendment type and fertilizer-N (Table 2). Whereas soil amended with AT, CG, GS and VU leaves or feces had similar total-N, soil amended with PE or PG leaves had significantly greater total-N than with PE or PG feces (Table 6). Total-N in soil of control pots that received fertilizer-N (190 mg kg^{-1}) was significantly greater than in control pots that received no fertilizer-N (165 mg kg^{-1}). Ammonium-N was unaffected by any treatment type or combination.

SOM levels were affected solely by fertilizer-N (Table 2). SOM levels were greater ($P < 0.05$) in pots that received fertilizer-N (9.5 mg kg^{-1}) than in pots that received no fertilizer-N (9.2 mg kg^{-1}). Amounts of heavy SOM depended on plant species and amendment type (Table 6). Soil amended with AT leaves had significantly more heavy SOM than with AT feces, whereas pots containing CG, PE, PG and VU leaves had significantly less heavy SOM than pots containing feces derived from these species.

The amount of N associated with the heavy SOM fraction was most affected by amendment type, being greater in soil that received feces (217 mg pot^{-1}) than with leaves (138 mg pot^{-1}), or in pots that received no amendments (9 mg pot^{-1}). Fertilizer-N increased the N content of heavy SOM by 33% in pots amended with feces, by 19% in pots amended with leaves, and by 66% in control pots. Fertilizer-N increased the N content of light SOM in soil that received leaves and decreased the N content of light SOM in soil that received feces.

Table 6. Effects of amendment and plant species on soil total-N and heavy fraction of SOM at the end of the trial

Plant species	Feces				Leaves			
	Total-N (mg kg^{-1})	Heavy SOM			Total-N mg kg^{-1}	Heavy SOM		
		Ash-free OM (g pot^{-1})	N (mg pot^{-1})	P (mg pot^{-1})		Ash-free OM (g pot^{-1})	N (mg pot^{-1})	P (mg pot^{-1})
AT	199	4.7	205	7.4	196	6.2	250	7.9
CG	190	5.9	210	11.2	195	4.3	187	10.3
GS	197	6.0	201	10.0	201	5.6	197	8.6
PE	185	6.6	240	11.8	209	2.0	78	3.7
PG	193	7.5	265	16.6	217	3.0	99	5.2
VU	201	5.0	184	11.6	198	1.1	31	2.6
Mean	194	5.9	217	11.4	202	3.7	138	6.4
SEM	2.4	0.14	7.2	0.48	2.2	0.31	13.2	0.54
Control	178	0.4	9	1.8	178	0.4	9	1.8

At trial's end, measures of the P remaining in pots were related almost exclusively to amendment type. Bray1-P levels were greater in soil receiving feces (5.2 mg kg^{-1}) than in soil receiving leaves (4.5 mg kg^{-1}) or no amendments (4.3 mg kg^{-1}). The P contained in heavy SOM was significantly greater in soil that received feces (11.4 mg pot^{-1}) than in soil that received leaves (6.4 mg pot^{-1}) and soil that received no amendments (1.8 mg pot^{-1}). However, the P content of light SOM was greatest ($P < 0.05$) in pots amended with leaves (1.75 g kg^{-1}), followed by pots receiving no amendments (0.97 g kg^{-1}) and feces (0.88 g kg^{-1}).

Discussion

Fertilizer-N was added as a treatment principally to evaluate its effectiveness in reducing net N immobilization in pots amended with leaves of low N content. When no fertilizer-N was added, millet pots amended with the leaves of PE and VU had greater N uptake than in control pots, indicating net N mineralization. Fertilizer-N enhanced N mineralization as indicated by the smaller negative relationships between leaf DM, NDF and NDF:N applications, and nutrient uptake by millet (Table 3). Fertilizer-N at the selected application rate (60 kg ha^{-1}) however, was apparently insufficient to totally offset N and P immobilization in pots containing the leaves of PG (Figures 2 and 3).

The chemical composition of feces, especially concentrations of total-N, P and NDF were more uniform than the chemical composition of leaves (Table 1). It was perhaps for this reason that in pots amended with feces only (no fertilizer-N) there were no significant relationships between fecal chemical components and millet yield and nutrient uptake (Table 4). Millet response to feces in pots receiving fertilizer-N were inhibited by the amount of undigested feed-N in feces (NDIN) and cell wall content (NDF). This result indicates that during the later part of the study, after the readily available fraction of N in feces had been mineralized and removed by millet, these recalcitrant fecal components may have immobilized fertilizer-N. The almost two-fold increase in N content of heavy SOM in feces- than leaf-amended pots (Table 6) supports this view.

The efficiency of fertilizer use, which is key to the future sustainability of these production systems (Breman, 1990; Van Keulen and Breman, 1990) can be enhanced greatly when combined with organic amendments (Fussell et al., 1987; Bationo and Mokwunye, 1991). The results of this study showed fertilizer N use efficiency was, in most cases, higher in pots amended with feces than in pots amended with leaves (Table 5). The exception to this trend can be summarized as follows: the N content of VU and PE leaves was greater than their feces (Table 1) and exceeded the threshold level of 20 g kg^{-1} for net mineralization (Stevenson, 1986). Dilution of N in feces occurred during the feeding trial when VU and PE leaves were fed with PG

leaves. Less VU and PE leaves than feces were needed to achieve equivalent organic-N applications. For this reason, less fertilizer-N apparently was immobilized in pots containing VU and PE leaves than feces. The opposite effect can be described for PG leaves and feces. Much greater amounts of PG leaves than feces were needed to attain equivalent organic-N applications. For this reason there was a three-fold difference in ONUE in pots amended with PG leaves than in pots amended with PG feces.

Differences in the N content of the light and heavy SOM fractions indicated more residual fertilizer-N may be available in pots amended with feces than in pots amended with leaves. Pots amended with feces plus fertilizer-N had much more N in the heavy (recalcitrant) SOM fraction (248 mg pot^{-1}) than pots amended with leaves plus fertilizer-N (150 mg pot^{-1}). Average N content of light SOM, the most active fraction of SOM having a half life of 1–5 years (Anderson and Ingram, 1989) was similar in feces- and leaf-amended pots. These results indicate that more N was mineralized, and at the same time more N was stored (in the heavy SOM fraction) in pots amended with feces than in pots amended with leaves. Feces, therefore, appear to be much better providers of N to crops than leaves, perhaps through N mineralization in synchrony with plant-N demands, and at the same time providing a sink for fertilizer-N that can be remineralized slowly for subsequent crop use.

Almost all of the P fed to ruminants is excreted in feces and, therefore, potentially available for recycling. Pots amended with feces had much greater P uptake (Figure 3) and higher Bray1-P than pots amended with leaves. The P associated with light SOM was lower in pots amended with feces than leaves, indicating that most fecal-P (albeit applied in higher amounts than leaf-P) had been mineralized and taken up by millet. Also, the N associated with the light SOM fraction was lower in pots amended with feces than leaves indicating that most fecal-N had mineralized.

Average P uptake in pots amended with leaves was lower than control pots, indicating P immobilization. Although fecal-P likely mineralized more rapidly than leaf-P, observed differences in millet response to the application of fecal- versus leaf-P was also likely due to higher P application rates in feces treatments. The wide range in N content of the leaf material used in this study necessitated that a wide range of P be added to pots to achieve equal N applications. It was perhaps for this reason that the highest accumulation of P by millet was in pots amended with feces having the highest P content (PE, VU and GS). The amount of fertilizer-P applied uniformly to pots (20 kg ha^{-1} equivalent) at the beginning of each cropping cycle apparently was insufficient to satisfy millet's P requirement. As a result, millet apparently responded to the readily mineralizable-P in feces.

Lignin:N, polyphenol:N, or NDF:N ratios in this biomass (Table 1) could be used to predict total N excretion and amounts of N voided in feces and urine in sheep (Powell et al., 1994). When incubated with soil, the polyphenol:N ratio of biomass can be used to estimate N mineralization (Palm and Sanchez, 1991; Oglesby and Frownes, 1992). The lignin:polyphenol:N ratio of applied organic amendments can be used to predict N uptake by plants (Fox et al., 1990). In contrast to these findings, neither polyphenol nor lignin concentrations of applied biomass, nor their ratios with N were related to the N or P uptake by millet in our greenhouse experiment (Tables 3 and 4). This may have been due to the complexity of phenolic chemistry and wide range of assays used to determine phenolic contents in organic materials (Myers et al., 1994). Rumen microorganisms readily degrade and transform phenolic compounds (Martin, 1978). These compounds were, therefore, not present in feces (Table 1).

The results of this study must be viewed within the inherent limitations of using a pot experiment to study complex nutrient cycling interactions. In many cases there were no statistical differences between treatments (Figures 1–3) even though the applied amendments varied considerably in their chemical composition. Treatment effects on pearl millet yield, N and P uptake, and on soil extractable nutrients and SOM may be different under field conditions where rooting is less constricted.

Conclusions

Assessing the costs and benefits associated with the direct land application of plant biomass as a soil fertility amendment versus feeding plant biomass first to livestock then using feces (and urine) to fertilize the soil requires information on both crop and livestock production and associated impacts on nutrient cycling. For example, gains in crop production due to the direct land application of plant biomass need to be evaluated in relation to foregone gains in livestock production, plus forgone gains in crop production due to the application of feces (and urine) rather than plant biomass.

Likewise, gains in livestock production due to feeding biomass need to be evaluated in terms of foregone gains in crop production if biomass were applied directly to soil, plus the value of nutrient losses due to feeding. About one-half of the N consumed by ruminants is excreted as urine, much of which may be lost via volatilization and leaching. However, if livestock are managed to capture and recycle urine, nutrient cycling and crop yields can be enhanced greatly. For example, after daytime grazing, corralling livestock overnight on cropland returns both feces and urine to soil and results in much greater crop yields than when only feces are applied (Powell et al., 1998). The residual effects on yield increases may last 2–3 years after corralling.

A principal challenge facing agriculture in SAWA is how to maximize the efficient use of scarce sources of nutrients towards achieving more sustainable production systems. Critical assessments must be made of the key factors which affect nutrient flows and how improved nutrient management in one production component (e.g. feed) may affect nutrient cycling in other production components (e.g. soils and crops) and the relative impact of each component's management on overall system productivity, profitability and environmental impact. Such evaluations should be of particular importance for agricultural systems, such as those in SAWA, which rely principally on internal nutrient sources for producing crops and livestock and soil nutrient depletion is a major concern.

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