Nutrient and Structural Carbohydrate Partitioning in Pearl Millet

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ABSTRACT

Cereal stovers and other crop residues are vital feeds for ruminants during the 6- to 8-mo dry season in mixed farming systems of semiarid West Africa. Reducing the competition between livestock and soil fertility is crucial to the sustained productivity of these farming systems. A 2-yr field study was conducted in Niger on a sandy siliceous isohyperthermic Psammentic Paleustalf to determine the effects of fertilizer N (15 and 45 kg ha^{-1}) and P (4.4 and 17.4 kg ha^{-1}) on dry matter (DM), N, P, and structural carbohydrate distribution in plant parts of pearl millet [*Pennisetum glaucum* (L.) R. Br.]. Fertilizer N increased total millet DM by 13%, N uptake by 63%, and P uptake by 29%. Fertilizer P increased total millet DM by 100%, N uptake by 80%, and P uptake by 140%. Fertilizer N increased millet grain yield only during the year of adequate rainfall, whereas fertilizer P increased yields during both years. Fertilizer N increased and fertilizer P decreased the N concentrations in millet stover. Fertilizer P increased the P concentrations in all upper plant parts. The average total millet DM of 2.75 Mg ha^{-1} was partitioned into grain (18%); animal feed consisting of chaff, immature panicles, upper stover and tillers (41%); and middle and lower stover components for soil conservation (41%). Partitioning was not affected by fertilizer addition. Of the total N (33.4 kg ha^{-1}) and P (5.2 kg ha^{-1}) uptake, 32 and 40% were contained in grain, 41 and 40% in animal feed, and 27 and 20% in components for soil conservation. Results of our study show the importance of N and especially P in increasing grain and forage yield and quality, and that stover can be managed more effectively to raise botb crops and livestock in a more sustainable manner.

In an effort to produce more food for expanding populations, farmers in semiarid West Africa are putting more land into permanent cultivation, are cropping marginal areas, and are abandoning the traditional practices that formerly allowed land to rejuvenate naturally. As a result, nutrient budgets (inputs minus offtakes) are negative, and soil fertility is declining in many farming systems (Stoorvogel and Smaling, 1990). Sustainable increases in agricultural output from these farming systems depend on a much wider use of fertilizers (Breman, 1990; Van Keulen and Breman, 1990), and improved crop residue and livestock management practices (Unger et al., 1991).

Mixed farming systems of semiarid West Africa are characterized by the cultivation of pearl millet, sorghum [*Sorghum bicolor* (L) Moench.], cowpea [*Vigna unguiculata* (L.) Walp.], and groundnut (*Arachis hypogaea* L.) and by the raising of cattle (*Bos indicus* L.), sheep (*Ovis aries* L.), and goats (*Capra hircus* L.). Crop residues are important feeds for ruminants during the 6- to 8-mo dry season. Whereas legume residues are harvested, and either sold or fed to farmers' animals, cereal stovers, the most important of which is pearl millet, are generally left in fields and grazed after grain harvest. Livestock spend 50 to 80% of their total grazing time on cereal stovers during the 2 to 3 mo following grain harvest (Sandford, 1989). Animals initially obtain a high-quality diet from weeds and upper components of millet and sorghum stovers (Powell and Saleem, 1987). In more populated areas where the pressure on land is high, crop residues have a greater economic importance and all cereal stover may be harvested from fields.

Crop residues are grazed and trampled by livestock, degraded by termites (*Macrotermes* spp.), and removed from fields for fuel and construction materials. These practices can deplete soil nutrient reserves and cause high soil surface temperatures, wind erosion, and sand blasting of young millet plants. Research has shown that leaving cereal stovers in fields provides a physical barrier to soil movement, allows soil and organic matter to accumulate, and increases soil pH, cation exchange capacity, total N, and crop yields (Pieri, 1989; Bationo and Mokwunye, 1991; Geiger et al., 1992). Crop residues are, however, vital animal feeds. Animals stabilize food availability during years of low rainfall when crop production is reduced or fails, and provide manure, transport, and traction to the cropping sector.

Given the high potential of fertilizers to increase millet yields in semiarid West Africa (Bationo et al., 1986), the importance and various uses of millet stover, and the possibility of selectively harvesting stover parts based on their chemical composition (Powell et al., 1991), we designed this study to (i) determine the effects of fertilizer N and P on the dry matter, N, P, structural carbohydrate, and lignin distribution in millet stover plant parts and (ii) evaluate management strategies that harvest some stover parts for animal feed while returning other parts to fields for improved soil management. Soil samples were taken at the conclusion of the trial to assess fertilizer N and P effects on soil chemical properties.

MATERIALS AND METHODS

A field study was conducted on a Labucheri soil (sandy, siliceous, isohyperthermic Psammentic Paleustalf; West et al., 1984) at the ICRISAT Sahelian Center (ISC), Sadoré, in the Republic of Niger (13 °15′ N, 2 °18′ E), during the 1989 and 1990 cropping seasons. The 0- to 15-cm soil layer has 940 g kg^{-1} sand, pH 5.4 (1:1 water/soil mixture), organic matter of 2 g kg^{-1} (wet combustion), available P of 2.8 mg kg^{-1} (Bray-1), and CEC of 0.9 cmol$_c$ kg^{-1} (NaOAC). Average annual rainfall at the ISC is ≈560 mm, of which 95% falls during the May to October cropping season. Rainfall was 623 mm in 1989 and 400 mm in 1990. The trials were entirely rainfed both study years.

Two levels of fertilizer N (15 and 45 kg ha^{-1}) and two levels of fertilizer P (4.4 and 17.4 kg ha^{-1}) were used. Previous trials at ISC showed that fertilizer N applications of 30 kg ha^{-1} (Bationo et al., 1990) and fertilizer P of 10 to 15 kg ha^{-1} (ICRISAT, 1991) are sufficient to obtain near-maximum millet yields during years of adequate rainfall. A split-plot design was used, with P levels assigned to main plots and N assigned to subplots of 30 by 50 m. Treatments were replicated three times in a completely randomized block design. All of the P

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Abbreviations: CEC, cation exchange capacity; CIVT, Composite Inter-Varietal de Tarna; DM, dry matter; HI, harvest index; ISC, ICRISAT Sahelian Center.

was broadcast preplant as single superphosphate. Calcium–ammonium nitrate was the N source, with half the N broadcast at approximately 30 d and the other half 60 d after planting.

Pearl millet cultivar CIVT (Composite Inter-Varietal de Tarna) was planted by hand at 70-cm intervals along lines 67 cm apart in late May during both study years. Approximately 10 to 15 seeds were sown into holes 3 to 5 cm deep. Plants were thinned at 2 wk post emergence to three plants per hill. Plant densities of 15 000 to 20 000 hills ha^{-1} have been found to be adequate for achieving good millet yields in average and wet years (Bationo et al., 1990). Plots were kept weed-free by two manual weedings.

Total aboveground vegetation was harvested 2 cm above the soil surface from two randomly placed 10- by 10-m quadrats within each subplot. Grain-producing panicles were detached from stems at the peduncle. The vegetation from two additional stands per subplot were divided into six plant parts: grain-producing panicles; non-grain-producing panicles (mainly vegetative, hereafter referred to as immature panicles); the upper, middle, and lower stover fractions (leaves and stems together) based on equal division of stem height; and non-panicle-producing tillers. Grain-producing panicles were hand-threshed to separate grain from chaff. Chaff was all material remaining after grain was removed from the panicles. Threshing percentages were calculated as percentage grain of total panicle dry matter. Harvest index (HI) values were calculated as percentage grain of total millet aboveground dry matter. Triplicate 150- to 200-g samples of grain from each fertilizer level were milled in a mortar and pestle (the traditional manner) and divided into millet flour and bran.

Subsamples of all millet plant parts were oven-dried for 48 h at 75 °C for DM determination, milled to pass a 1-mm screen, acid-digested (Nelson and Sommers, 1980), and analyzed for total N and P by autoanalyzer (Technicon, 1977). All millet plant parts were analyzed for hemicellulose, cellulose, and lignin (Goering and Van Soest, 1970). These analyses were used to calculate the digestibility of plant parts by the summative equation (Goering and Van Soest, 1970). Dry matter weights were multiplied by respective nutrient, carbohydrate, and lignin concentrations to give nutrient, carbohydrate, and lignin yields on a plant-part basis.

To assess possible treatment effects on soil properties, five soil samples per treatment plot were taken with a stainless steel auger to depths of 0 to 15 cm and 16 to 30 cm after the 1990 cropping season. Samples were composited into one sample per plot, air-dried, sieved to pass a 2-mm screen, and then analyzed for pH (1:1 soil/water and 2 *M* KCl), organic C (Walkley–Black, as modified by Nelson and Sommers, 1982), total N (micro-Kjeldahl), and available P (Bray-1).

An analysis of variance using the general linear model procedure (SAS Inst., 1982) was used to determine treatment effects on soil characteristics. The same procedure was also used to determine effects of year and of fertilizer type and level on millet dry matter yields and nutrient, carbohydrate, and lignin concentrations and yields. Yearly differences in yield and concentrations were determined using the year (Y) by replication (R) error term; differences due to fertilizer P (P) and interactions between Y and P were tested using the $Y \times R \times P$ error term; differences due to fertilizer N (N) and the interactions between Y, P, and N were tested using the residual error term. The probability level of $P \leq 0.05$ was used to delineate significant main and interaction treatment differences unless otherwise stated.

RESULTS

Fertilizer Effects on Soil Chemical Properties

The analysis of variance did not indicate any significant interactions between the effects of fertilizer N and P, and fertilizer N had no effect on soil pH, organic carbon, total N, and available P (Table 1). There were, however, significant interactions between the effects of fertilizer P and soil depth on soil pH (KCl) and available P. Topsoil pH was 4.16 and 4.33 at fertilizer P additions of 4.4 and 17.4 kg ha^{-1}, respectively. Fertilizer P did not affect subsoil pH. Topsoil available P in plots that received annual applications of 4.4 kg P ha^{-1} was 4.01 mg kg^{-1} vs. 11.49 mg kg^{-1} in plots that received annual P applications of 17.4 kg ha^{-1}. Fertilizer P had no effect on subsoil available P levels. Increases in only topsoil available P were probably due to greater P fixation in the more acid subsoil (Brady, 1974, p. 462). At the conclusion of the 2-yr study, soil pH, organic C, and available P levels were greatest in the topsoil, while total soil N was the same in both the top- and subsoil.

Table 1. Chemical characteristics of Psammentic Paleustalf soil at the conclusion of the experiment, ICRISAT Sahelian Center, Sadoré, Niger.

	Soil depth	
	0 to 15 cm	16 to 30 cm
pH (water)	5.25a†	4.84b
pH (KCl)	4.24‡	4.04
Organic C, g kg^{-1}	1.43a	1.17b
Total N, mg kg^{-1}	120.00a	124.08a
Bray-1 P, mg kg^{-1}	7.39‡	2.33

† Within rows, means followed by different letters are significantly different at the 0.05 probability level.
‡ Significant interaction between effects of fertilizer P and soil depth.

Fertilizer Nitrogen and Phosphorus Effects

Grain and Stover Yields and Nutrient Uptake

There were yearly differences ($P \leq 0.05$) in millet total DM yield and partitioning (Fig. 1). Fertilizer N

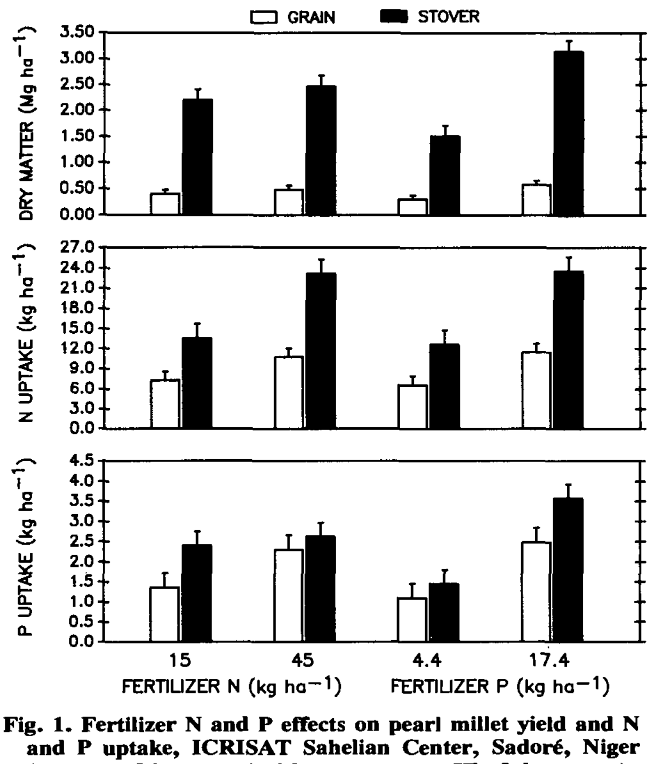

Fig. 1. Fertilizer N and P effects on pearl millet yield and N and P uptake, ICRISAT Sahelian Center, Sadoré, Niger (average of 2 yr; vertical bars represent SE of the means).

Table 2. Fertilizer N effects on dry matter (DM), N, P, hemicellulose (HCL), cellulose (CL), and lignin (LG) concentrations in pearl millet grain, chaff, immature panicles (IP), and upper (UP), middle (MID), and lower (LOW) stover fractions and tillers.

Plant part	DM	N	P	HCL	CL	LG
	% of total	g kg⁻¹				
			Fertilizer N, 15 kg ha⁻¹			
Grain	16	18.8	3.1	200	35	7
Chaff	17	9.9	1.1	358	395	74
IP	5	20.4	3.2	399	230	56
UP	14	9.8b†	1.5	335	330a	63
MID	16	7.2b	0.9	355	318a	71
LOW	24	5.9b	0.8	351	299a	90a
Tillers	7	11.5	1.5	340	250	45
SE		1.5	0.3	13	20	6
			Fertilizer N, 45 kg ha⁻¹			
Grain	17	23.2	3.6	203	46	7
Chaff	13	10.9	1.4	364	375	69
IP	5	22.5	3.6	412	231	43
UP	15	13.6a	1.4	340	307b	63
MID	17	11.1a	1.0	366	299b	67
LOW	26	10.4a	0.9	358	280b	72b
Tillers	7	10.9	1.4	364	245	69
SE		1.6	0.3	16	18	5

† Within columns, mean plant part concentration followed by a different letter are significantly different at the 0.05 probability level.

increased grain yield only during one year, whereas fertilizer P increased yields in both study years. There were no interactions between the effects of fertilizer N and P on either total, grain or stover yields.

Average grain yield in 1989 was 750 kg ha^{-1} vs. 375 kg ha^{-1} in 1990. Total millet DM (3.04 Mg ha^{-1}), HI (25%), and threshing percentage (59%) in 1989 (623 mm rainfall) were greater ($P \leq 0.05$) than total yield (2.47 Mg ha^{-1}), HI (15%), and threshing percentage (46%) in 1990 (400 mm rainfall). Fertilizer N increased grain yield only in 1989: yields at 45 kg N ha^{-1} were 900 kg ha^{-1}, vs. 600 kg ha^{-1} at fertilizer N applications of 15 kg N ha^{-1}. Fertilizer N did not affect millet grain yields in 1990. Lower millet yield and partitioning of total DM into grain in 1990, as well as the lack of millet response to fertilizer N, were probably due to low rainfall and its poor distribution during this study year.

Fertilizer P had a greater positive effect than fertilizer N on millet grain and stover yield and on N and P uptake (Fig. 1). Fertilizer P applications of 17.4 kg ha^{-1} increased total millet DM by 100%, N uptake by 80%, and P uptake by 140%. The addition of 45 kg N ha^{-1} increased total millet DM by 13%, N uptake by 63%, and P uptake by 29%. In contrast to fertilizer N, fertilizer P increased millet grain and stover yields during both study years.

Table 3. Fertilizer P effect on dry matter (DM), N, P, hemicellulose (HCL), cellulose (CL), and lignin (LG) concentrations in pearl millet grain, chaff, immature panicles (IP), and upper (UP), middle (MID), and lower (LOW) stover fractions and tillers.

Plant part	DM	N	P	HCL	CL	LG
	% of total	g kg⁻¹				
			Fertilizer P, 4.4 kg ha⁻¹			
Grain	17	21.9	2.8b†	207	43	6
Chaff	15	11.4	0.8b	352	398	69
IP	5	22.1	2.8b	403	223	51
UP	14	12.7a	1.2b	333	322	63
MID	18	10.1a	0.8	364	304	73
LOW	25	9.6a	0.8	361	287	76
Tillers	6	15.4	1.5	316	253	49
SE		1.5	0.2	15	20	5
			Fertilizer P, 17.4 kg ha⁻¹			
Grain	16	20.1	3.8a	192	38	6
Chaff	16	9.3	1.7a	370	372	74
IP	6	20.7	3.9a	407	237	49
UP	15	10.7b	1.7a	342	314	63
MID	16	8.2b	1.1	357	312	65
LOW	25	6.7b	0.8	348	292	86
Tillers	8	10.4	1.5	321	242	40
SE		1.6	0.3	15	19	5

† Within columns, mean plant part concentration followed by a different letter are significantly different at the 0.05 probability level.

Table 4. Pearl millet uses based on the harvesting pattern and chemical composition of plant parts.

Use	Plant part	DM	N	P	Digest-† ibility	Crude Protein
		kg ha^{-1}			g kg^{-1}	
Food	Grain	500 (382)‡	10.54 (0.87)	2.04 (0.18)	747 (5)	131 (4)
Feed	Chaff	420 (39)	4.38 (0.47)	0.62 (0.05)	485 (7)	65 (9)
	Non-grain panicles	130 (26)	2.79 (0.53)	0.43 (0.06)	518 (10)	134 (6)
	Upper stover	380 (22)	4.45 (0.32)	0.72 (0.06)	516 (5)	73 (4)
	Tillers	190 (21)	2.32 (0.29)	0.31 (0.05)	588 (8)	804 (6)
Soil management	Mid stover	430 (18)	3.80 (0.20)	0.42 (0.04)	482 (7)	57 (3)
	Lower stover	670 (36)	5.11 (0.37)	0.61 (0.06)	446 (11)	508 (5)

† Calculated by the summative equation (Goering and Van Soest, 1970).
‡ SE given in parentheses.

Dry Matter, Nutrient, and Carbohydrate Concentrations in Plant Parts

The partitioning of total millet DM into grain, chaff, and the various stover parts was the same in both study years, and was unaffected by applications of either fertilizer N (Table 2) or fertilizer P (Table 3). There were also no interactions ($P \leq 0.05$) between the effects of fertilizer N and P on millet DM partitioning. Of the average total aboveground millet DM (2.75 Mg ha^{-1}; Fig. 1), approximately 17% was grain, 15% chaff, 5% immature panicles, 15% upper stover, 16% middle stover, 25% lower stover, and 7% tillers. The average threshing percentage of millet panicles was ≈52%.

The nutrient and carbohydrate content of millet plant parts were similar in both study years. There were also no interactions ($P \leq 0.05$) between the effects of fertilizer N and P on the chemical composition of millet. Fertilizer N additions of 45 kg ha^{-1} significantly increased the N concentrations of the upper, middle, and lower millet stover portions (Table 2). Concomitant to these increases in plant N were reductions in cellulose concentrations of these plant parts. Fertilizer N also decreased the lignin concentration of the lower stover component. The P and hemicellulose concentrations in all millet parts were unaffected ($P > 0.05$) by fertilizer N rate.

Fertilizer P additions of 17.4 kg ha^{-1} significantly decreased the N concentrations in the upper, middle, and lower stover parts (Table 3). The P contents of millet grain, chaff, immature panicles, and upper stover parts were increased, however, by this higher fertilizer P level. Fertilizer P had no effect ($P > 0.05$) on either the structural carbohydrate or the lignin concentrations of any millet part. The reduced plant N concentrations due to fertilizer P additions were probably due to N dilution in the greater biomass produced at this fertilizer rate. Total DM production was increased by 100% by fertilizer P applications of 17.4 kg ha^{-1} (Fig. 1).

Upper millet plant parts (grain, immature panicles, and upper stover) contained the highest N and P concentrations of all millet plant parts. Such an enrichment typifies a cereal's translocation of nutrients from vegetative material to grain (Marschner, 1986). The similar N and P concentrations in grain and immature panicles (Tables 2 and 3) was, however, somewhat surprising. Panicles usually accumulate carbohydrates in grain before translocating nutrients from vegetative material (Boyer and McPherson, 1975). Immature panicles contained higher hemicellulose and lower cellulose and lignin concentrations than other stover parts.

DISCUSSION

Most millet operations are done manually in semiarid West Africa. Grain harvesting involves removing panicles with a knife at the upper node. Panicles are stored in granaries and threshed at households when grain is needed. Grain is always used as food and seldom fed to animals in semiarid West Africa. Chaff, being a byproduct of panicle threshing, would be available for feeding directly to animals at the homesteads. The apical concentration of nutrients in millet (Tables 2 and 3), in conjunction with farmers' harvesting techniques, may allow for selective harvesting of millet parts for food and feed, while returning other stover parts to fields for improved soil conservation.

Of the average total millet DM (2.75 Mg ha^{-1}; Fig. 1), 18% was contained in the grain, 41% in animal feed, and 41% in components for soil conservation (Table 4). Of the total N (33.4 kg ha^{-1}) and P uptake (5.2 kg ha^{-1}), 32 and 40% was contained in grain, 41 and 40% in animal feed, and 27 and 20% in components for soil conservation. Harvesting the upper one-third of millet stover and immature panicles in conjunction with the harvest of grain-producing panicles would require additional manual labor, but would provide feed of relatively high quality. Tillers, which had the highest feeding value of all stover components, could be harvested or grazed selectively in situ. All millet feed components, except for chaff, have crude protein content above the minimum 7.0% necessary for ruminant maintenance (Humphreys, 1978) and P contents above 1.2 g kg^{-1} (Tables 2 and 3) sufficient for ruminant growth (Little, 1980).

The seed coat or bran removed from millet grain during milling is also considered a valuable animal feed by farmers. Millet grain contained 77% flour and 23% bran (SE = 1.5%) and was unaffected by fertilizer type or level. Based on this information, the reported average millet grain yield of 500 kg ha^{-1} (Table 4) could be further divided into 385 kg ha^{-1} of food (flour) and 115 kg ha^{-1} feed (bran).

The 1.1 Mg ha^{-1} (Table 4) of millet stover contained in the lower two-thirds of millet stover, which represents 40% of all millet stover, would be best suited for use for soil conservation. The average 8.6 g kg^{-1} N, 350 g kg^{-1} hemicellulose, 300 g kg^{-1} cellulose, and 75 g kg^{-1} lignin indicate that these stover components would decompose in soil more slowly than other stover parts. Organic materials with <15 g kg^{-1} N initially immobilize soil N when applied to soils (Bartholomew, 1972). Soil microorganisms most readily utilize the soluble carbohydrates in stover, followed by hemicellulose, cellulose, and lignin (Van Veen et al., 1984; Paul and Clark, 1989). The resistance of structural carbohydrates and lignin to degradation could stabilize soil organic matter levels in millet-based production systems where only lower stover components are returned to soil.

CONCLUSIONS

The adoption of techniques to selectively harvest stover parts of high-quality feed while leaving other parts for soil management will depend on the relative costs and benefits associated with these practices. Information is required on animal response to feeding millet parts, soil response to field application of millet stover parts, and the additional labor involved to harvest millet parts. Animal and soil responses need to be compared with current practices where animals graze weeds and millet leaves, and most stalks are returned to fields. Farm implements may be needed to reduce manual labor requirements. Although this study has shown that fertilizer N and P can raise food and feed production, the maintenance of appropriate balances between agricultural supply and human and livestock demands remains a critical factor in the long-term sustainability of mixed farming systems of semiarid West Africa.

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