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# Phosphorus application affects the nutritional quality of millet grain in the Sahel

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## Abstract

The application of phosphorus (P) and crop residues (CR) to acid sandy soils of the Sahel has been shown to increase yields of pearl millet (*Pennisetum glaucum* L.) several-fold. Information is lacking, however, about possible detrimental effects of such yield-enhancing amendments on grain quality, in particular the bioavailability of zinc (Zn) as defined by the phytate:zinc molar ratio (PZMR) and the concentrations of calcium, micronutrients, and protein. To determine the effects of CR and P on grain quality, millet seeds taken from the grain stores of 14 farmers and from a 2-yr on-station fertilizer experiment were analyzed for macronutrients, Zn, copper, iron, and phytate-P. The on-station experiment comprised four millet lines, P applied at 0 and 13 kg ha$^{-1}$, and CR applied at 500 and 2000 kg ha$^{-1}$ as surface mulch or ash. Grain from farmers' unfertilized millet had PZMRs ranging from 15 to 30. Application of P increased the concentrations of phytic acid in the grain between 25 and 29% and decreased Zn concentrations between 6 and 11%. The reasons for this were greater P uptake and a dilution of Zn by the large yield increases after P application. Phosphorus application decreased protein concentrations in both years, and increased the PZMRs from 20 to 28 in 1992 and from 21 to 29 in 1993. Although CR markedly increased millet yield, their application had little effect on PZMRs. While PZMRs above 15 are generally considered critical for Zn nutrition of humans, meat consumption and traditional practices of millet processing may increase Zn bioavailability in local dishes. Further studies of full diets are therefore needed, particularly among rural groups at particularly high risk of Zn deficiency such as nursing women and small children before definitive conclusions can be drawn about the effects of P fertilizer application to millet on the nutritional status of farmers in the Sahel. © 1998 Elsevier Science B.V. All rights reserved.

*Keywords:* Human nutrition; Millet grain quality; Phosphorus fertilizer; Phytate:zinc molar ratio; Sahel

## 1. Introduction

The low fertility of acid sandy soils in the Sahel is a major constraint to the production of millet in traditional agro-pastoral farming systems (Bationo and Mokwunye, 1991; Payne et al., 1991; Bationo et al., 1992). A major challenge in the future will be to feed a population with growth rates exceeding 3% per annum. Major changes in the traditional farming systems are required because average millet yields in farmers' fields in the country of Niger have declined from 530 to 345 kg ha$^{-1}$ over the last 25 yrs

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(SEDES, 1987). It is well documented, both on-farm and on-station, that the application of phosphorus (P) fertilizers and millet crop residues (CR) can increase millet grain yields several-fold (Bationo et al., 1993; Rebafka et al., 1994) and enhance the sustainability of the current production system by reducing soil erosion (Michels et al., 1995; Buerkert et al., 1996), increasing the concentration of P in the soil solution (Kretzschmar et al., 1991) and by recycling of potassium (Rebafka et al., 1994). There are growing concerns, however, that the emphasis on increasing cereal yields by the application of macronutrients alone may lead to deficiencies of micronutrients, mainly iron (Fe) and zinc (Zn), and also vitamins, in diets of the poor who rely on a cereal-based food supply (Graham and Welch, 1996).

Given the effectiveness of applied P fertilizers in increasing millet grain yields in the West African Sahel, the degree to which these increases in food quantity may be counterbalanced by a decline in dietary quality is an important issue. In small grain crops such as wheat or oat, from 64 to 80% of grain P is stored as phytate (*myo*-inositol 1,2,3,4,5,6-hexakis dihydrogen phosphate) (Michael et al., 1980; Raboy et al., 1991). Phytate concentration strongly depends on P fertilization (Saastamoinen, 1987) and the total P concentration in the grain (Srivastava et al., 1955). While phytic acid is considered an important antioxidant that suppresses lipid peroxidation in dormant seed (Graf and Empson, 1987) and prevents colon cancer in humans (Shamsuddin et al., 1988), phytate-P is poorly available to monogastrics. Phytates also impair calcium (Ca) uptake in children (Bonner and Harris, 1954) and may severely hamper the bioavailability of Zn (Davies and Nightingale, 1975; Morris and Ellis, 1980), especially in whole-grain cereal-based diets with low levels of vitamin C, fats, and essential amino acids (Sandström et al., 1980; Burk and Salomons, 1985). Early work in Iran with people fed mainly on cereals indicated that Zn deficiency can result in a severe retardation of growth and sexual development (Prasad et al., 1963; Halsted et al., 1972). To predict dietary Zn deficiency in the presence of high phytate concentrations, Oberleas (1975) introduced the concept of a phytate:zinc molar ratio (PZMR), and subsequent studies concluded that a ratio above 15 may lead to Zn deficiencies in humans (Turnlund et al., 1984; Harland et al., 1988).

The few available studies concerned with the quality of the dietary intake of rural populations in West Africa have revealed phytate:zinc molar ratios above 20 (Davies, 1982; Mbofung et al., 1984). Investigations about the effect of soil amendments such as P fertilizers and CR on the concentrations of phytate and micronutrients, particularly Zn, in millet grain are lacking. This study was therefore conducted to determine whether large increases in pearl millet grain yield resulting from CR and P application affect grain quality as defined by the protein and micronutrient concentrations and by the PZMR.

## 2. Materials and methods

### 2.1. On-farm seed collection

#### 2.1.1. Sample collection

To obtain baseline data of nutritional properties of millet in farmers' grain stores, millet seed were collected along a rainfall gradient from 600 mm to 350 mm annual precipitation in southwest Niger (12°52′N, 2°26′E to 14°15′N, 3°26′E, around 250 m a.s.l.) before the onset of the rainy season in 1994. In each of three villages, Sounga–Dossado, Boulkas, and Chikal, seed samples of landraces were taken from farmers' grain stores. At Chikal, one farmer also added seed of the improved short-season cultivar Haini Kiri Précoce (HKP). Additional samples came from two farmers in the villages of Kirtachi (12°48′N, 2°28′E) and Sadoré (13°14′N, 2°17′E). In an attempt to collect representative samples, three to five well-developed millet heads per farmer were taken from air-dried bundles which are usually kept unthreshed in the traditional grass stores, well protected from insect attack and microbial decay.

#### 2.1.2. Chemical analyses

All 14 unwashed samples were dried to constant weight at 65°C, hand-threshed in a wooden mortar, ground to pass through a 2-mm screen and analyzed for nitrogen (N), potassium (K), magnesium (Mg), Ca, Zn, Fe, copper (Cu), total P, and phytate-P. The concentration of total N was determined with a Macro-N-Analyzer (Elementar; Hanau, Germany) and multiplied by 6.25 to obtain the concentration of crude protein. For the analysis of other mineral

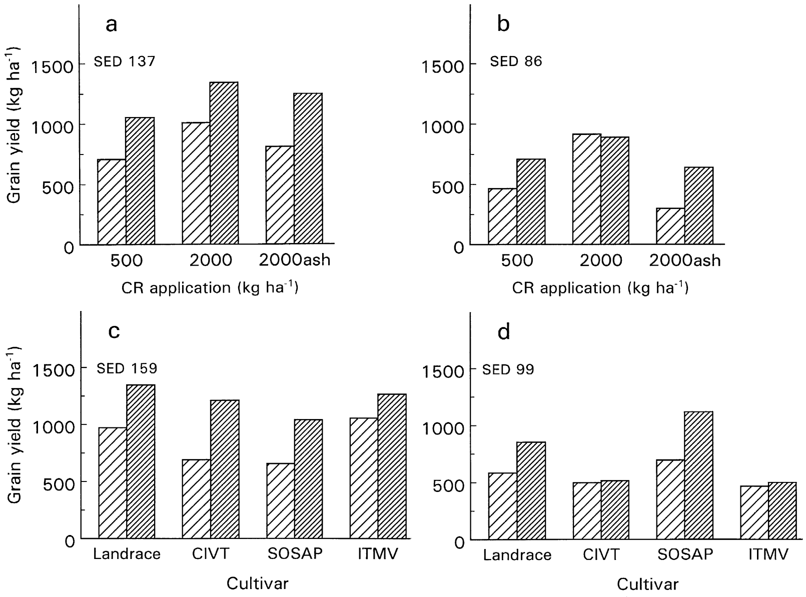
Table 1
Crude protein and mineral nutrient concentrations in millet grain from 14 farmers at five locations in southwest Niger

| | ($mg\ g^{-1}$) | | | | ($\mu g\ g^{-1}$) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Crude protein | $P_{total}$ | $P_{phytate}$ | K | Ca | Zn | Cu | Fe | PZMR[a] |
| Median | 129 | 3.2 | 2.2 | 4.3 | 244 | 32.3 | 5.2 | 79 | 24 |
| Maximum | 158 | 5.5[b] | 4.2[b] | 6.1[b] | 415 | 43.7 | 7.0 | 349 | 40[b] |
| Minimum | 102 | 2.3 | 1.5 | 3.6 | 140 | 25.0 | 3.9 | 36 | 15 |

[a] Phytate:zinc molar ratio.
[b] Outlier from Kirtachi field.

elements, milled grain was ashed for 4 h at 500°C in a muffle furnace and the ash dissolved in 1:30 (v/v) diluted HCl. Potassium and Ca were determined by flame-emission photometry (Eppendorf, Elex 6361; Ismaning, Germany), Mg, Zn, Cu, and Fe with an atomic-absorption spectrophotometer (UNICAM 939 Unicam; Offenbach, Germany), and total P colorimetrically (Hitachi U-3300 spectrophotometer Hitachi Ltd; Tokyo, Japan) according to the vanado-molybdate method (Gericke and Kurmies, 1952).

The vanado-molybdate method for phytate-P employed the following modifications in the anion-ex-

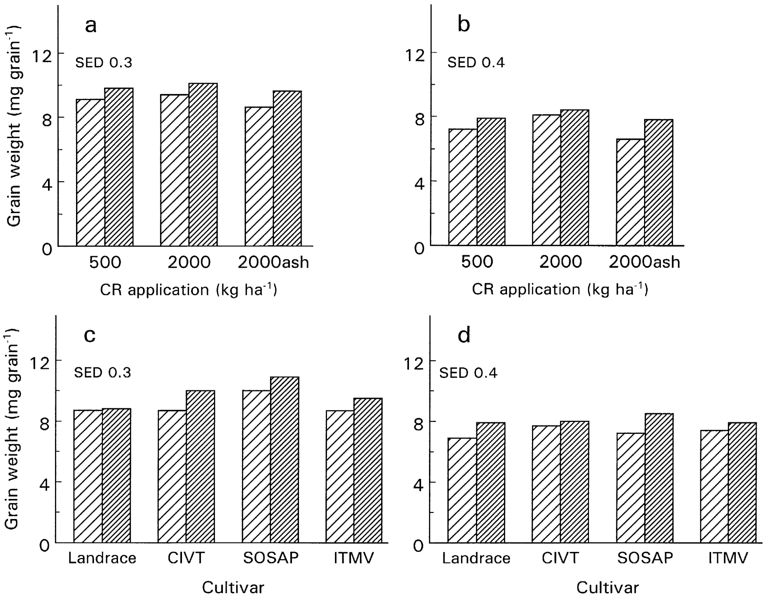


Probability of a treatment effect (significance level)

| | P > F 1992 | P > F 1993 |
|---|---|---|
| CR | 0.015 | <0.001 |
| P | <0.001 | <0.001 |
| CULTIVAR | 0.014 | <0.001 |
| CULT x CR | 0.458 | <0.001 |
| CULT x P | 0.596 | 0.014 |

Fig. 1. Millet grain yield (kg $ha^{-1}$) as affected by crop residues (CR) applied at 500 or 2000 kg $ha^{-1}$ as surface mulch ar ash, by phosphorus (P) at 0 (lightly shaded rectangles), or 13 (darkly shaded rectangles) kg P $ha^{-1}$, and by cultivar in 1992 (a and c) and 1993 (b and d).

change procedure originally proposed by Harland and Oberleas (1986): to retain the phytate, AG1-X8 anion-exchange resin (Bio-RAD Laboratories GmbH; Munich, Germany) was used instead of AG1-X4 and the pH in each flask was adjusted to 6.0 after addition of the $Na_2EDTA$–NaOH reagent and water to the sample aliquot. Comparative studies determining phytate concentrations by HPLC had demonstrated that this pH adjustment improved the reliability of the anion-exchange method considerably (H.J. Lantzsch; Hohenheim University, Germany; personal communication). The phytate from the resin-filled columns was eluted with two flushes of 15 ml 0.5 M NaCl because initial checks had shown that a second flush contained between 10 and 18% of the total recovered phytate. Both extracts of each sample were combined, dried in porcelain dishes on an electric heater, and ashed for 4 h at 500°C. The ash was dissolved in 2.5-ml 5.2 M $HNO_3$, flushed with deionized water into a 25 ml volumetric flask, and filtered with analytical paper. From the P concentration in this 25-ml sample, the concentration of phytic acid in the grain was calculated using a conversion factor of 3.546 (Harland and Oberleas, 1986). To obtain the phytate:zinc molar ratio (PZMR) in the grain, an indicator of grain quality with respect to Zn bioavailability, the phytic acid concentration was divided by 660.3, the molar weight of phytic acid in the purified Na-phytate standard used and by the molar concentration of Ca in the grain. At regular intervals the phytate standard (No. P-5756, Sigma-Aldrich Chemie GmbH; Deisenhofen, Germany) was



Probability of a treatment effect (significance level)

| | P > F | |
|---|---|---|
| | 1992 | 1993 |
| CR | 0.006 | <0.001 |
| P | <0.001 | <0.001 |
| CULTIVAR | 0.001 | <0.290 |
| CULT x CR | 0.041 | <0.154 |
| CULT x P | 0.146 | 0.127 |

Fig. 2. Grain weight (mg $grain^{-1}$) of millet as affected by crop residues (CR) applied at 500 or 2000 kg $ha^{-1}$ as surface mulch or ash, by phosphorus (P) at 0 (lightly shaded rectangles) or 13 (darkly shaded rectangles) kg P $ha^{-1}$, and by cultivar in 1992 (a and c) and 1993 (b and d).

reanalyzed giving a standard deviation of only ±3% of the mean indicating consistency of the procedure across the large number of samples processed. Repeated analyses of the same grain samples also indicated that individual results could be reproduced with measurement errors of less than 5%.

### *2.2. Site description and design of the on-station experiment*

Data on grain yield and grain samples were taken from rainfed millet sown at ICRISAT Sahelian Center, Sadoré, Niger in 1992 and 1993. The chemical characteristics of the reddish acid Lambucheri soil at this site, which had been cleared in 1991 after 8 yrs of fallow, have been described previously (Buerkert et al., 1995). It is classified by West et al. (1984) as a sandy, siliceous, isohyperthermic psammentic Paleustalf (Soil Management Support Services, 1988) and as a luvic Arenosol (FAO, 1988). Annual rainfall, distributed unimodally between mid-May and mid-September, was 586 mm in 1992 and 542 mm in 1993 compared with a 14-yr average of 541 mm.

The 48 treatments applied every year since 1991 to plots of 10 by 10 m in a completely randomized factorial experiment with two replicates were a combination of: (1) four millet lines commonly used on research stations in southwest Niger with growing periods of 90 days (CIVT and ITMV8001), 100 days (SOSAP in 1992 and ICMV89305 in 1993), and 110 days (the landrace Sadoré Local); (2) three levels of millet crop residues (CR), which were broadcast on the soil surface in January of each year as stalks harvested from the corresponding plots at rates of 500 and 2000 kg dry matter ha$^{-1}$ or prior to planting as ash at the rate of 2000 kg burned CR ha$^{-1}$ with a complement of 3 kg ha$^{-1}$ of elemental sulfur to account for volatilization losses; and (3) P fertilizer broadcast at a rate of 0 and 13 kg P ha$^{-1}$ as single superphosphate (SSP) shortly before sowing. Average total mineral nutrient concentrations in millet stalks, determined as above, were 0.65% N, 0.05%

Table 2
Crude protein (mg g$^{-1}$) and potassium (mg g$^{-1}$) concentrations in the dry matter of millet grain as affected by crop residues (CR) applied at 500 or 2000 kg ha$^{-1}$ as surface mulch or ash, by phosphorus (P) at 0 or 13 kg P ha$^{-1}$, and by cultivar in 1992 and 1993

| | 1992 | | | | 1993 | | | |
|---|---|---|---|---|---|---|---|---|
| | Crude protein | | K | | Crude protein | | K | |
| | $P_0$ | $P_{13}$ | $P_0$ | $P_{13}$ | $P_0$ | $P_{13}$ | $P_0$ | $P_{13}$ |
| *CR* | | | | | | | | |
| 500 | 136 | 129 | 3.32 | 3.26 | 140 | 129 | 3.87 | 4.37 |
| 2000 | 136 | 131 | 3.33 | 3.52 | 135 | 119 | 4.05 | 4.42 |
| $2000_{ash}$ | 136 | 126 | 3.22 | 3.44 | 141 | 126 | 4.03 | 4.67 |
| SED[a] | 2.9 | | 0.14 | | 3.8 | | 0.14 | |
| Cultivar | | | | | | | | |
| Landrace | 144 | 132 | 3.74 | 3.94 | 140 | 122 | 4.22 | 4.84 |
| CIVT | 137 | 130 | 3.32 | 3.38 | 139 | 129 | 3.75 | 4.46 |
| SOSAP[b] | 132 | 128 | 3.00 | 3.35 | 140 | 121 | 4.13 | 4.35 |
| ITMV | 132 | 124 | 3.10 | 3.45 | 136 | 128 | 3.83 | 4.29 |
| SED | 3.3 | | 0.16 | | 4.4 | | 0.16 | |
| $P > F$[c] | | | | | | | | |
| CR | 0.555 | | 0.368 | | 0.023 | | 0.081 | |
| P | < 0.001 | | 0.005 | | < 0.001 | | < 0.001 | |
| CULTIVAR | < 0.001 | | < 0.001 | | 0.725 | | 0.001 | |
| CULT × CR | 0.891 | | 0.307 | | 0.065 | | 0.086 | |
| CULT × P | 0.462 | | 0.532 | | 0.181 | | 0.164 | |

[a] Standard error of the difference.
[b] Replaced by cultivar ICMV89305 in 1993.
[c] Probability of a treatment effect (significance level).

P, 2.1% K, and 0.17% Ca. A fourth factor varied in the 2 yrs. It consisted of banded molybdenum (Mo) application (0 and 200 g Mo $ha^{-1}$ as ammonium molybdate) in 1992 and P placement (0 and 500 g P $ha^{-1}$ as SSP) with the seed into the pockets at sowing in 1993. After a germination test, millet was sown at the onset of the rainy season on 25 May 1992 and on 6 June 1993 into the untilled soil at a spacing of 1 m × 1 m by placing 75 viable seeds at about 0.05 m depth in a hole made with a traditional hand hoe of 0.15 m blade width. The pockets were thinned to three plants around 25 days after sowing. A more detailed description of all treatments and management operations such as thinning, weed and pest protection can be found elsewhere (Buerkert and Stern, 1995). In 1993 source–sink relationships were influenced by a heavy attack of the cotton stainer (*Dsydercus voelkeri* Schmidt) at grain formation which led to a much lower grain yield than in 1992.

In 1992 and 1993 at final harvest, four central rows of millet were harvested. Shoots and heads were separated and dried to constant weight at 65°C. Heads were threshed by hand and grain yield determined. Individual grain weight (GW) was calculated after counting and weighing three samples of 500 grains. Two separate sub-samples from each treatment plot were used for the analysis of mineral nutrients which were performed as described above. To estimate the gross energy concentration of millet grain expressed as heat of combustion, 14 samples representing the whole range of treatments were analyzed in a bomb calorimeter according to Naumann et al. (1983). The reported combustion data were expressed as water-noncondensed values as the absolute water contents of the grain samples were < 10%.

### 2.3. Data analysis

Data of grain yield, grain weight, and nutrient concentrations were subjected to analysis of variance

Table 3
Total and phytate–phosphorus (P) concentrations (mg $g^{-1}$) and phytate-P concentration as percent of total P (phytate-P%) in the dry matter of millet grain as affected by crop residues (CR) applied at 500 or 2000 kg $ha^{-1}$ as surface mulch or ash, by phosphorus (P) at 0 or 13 kg P $ha^{-1}$, and by cultivar in 1992 and 1993

| | 1992 | | | | | | 1993 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total P | | Phytate-P | | Phytate-P (%) | | Total P | | Phytate-P | | Phytate-P (%) | |
| | $P_0$ | $P_{13}$ | $P_0$ | $P_{13}$ | $P_0$ | $P_{13}$ | $P_0$ | $P_{13}$ | $P_0$ | $P_{13}$ | $P_0$ | $P_{13}$ |
| *CR* | | | | | | | | | | | | |
| 500 | 2.74 | 3.17 | 1.93 | 2.30 | 70.4 | 72.5 | 2.87 | 3.57 | 1.84 | 2.30 | 63.7 | 64.6 |
| 2000 | 2.82 | 3.29 | 1.87 | 2.42 | 66.4 | 73.1 | 3.09 | 4.16 | 2.03 | 2.68 | 66.1 | 64.4 |
| $2000_{ash}$ | 2.58 | 3.05 | 1.71 | 2.19 | 66.5 | 71.4 | 2.75 | 3.33 | 1.65 | 2.16 | 59.9 | 64.7 |
| SED[a] | 0.13 | | 0.12 | | 2.2 | | 0.13 | | 0.11 | | 1.8 | |
| *Cultivar* | | | | | | | | | | | | |
| Landrace | 2.99 | 3.37 | 2.07 | 2.45 | 69.0 | 72.2 | 2.92 | 3.80 | 1.76 | 2.46 | 60.2 | 64.6 |
| CIVT | 2.69 | 3.14 | 1.80 | 2.21 | 67.0 | 70.7 | 2.88 | 3.71 | 1.82 | 2.26 | 63.0 | 61.2 |
| SOSAP[b] | 2.56 | 3.05 | 1.72 | 2.28 | 67.1 | 74.4 | 2.91 | 3.62 | 1.85 | 2.42 | 63.5 | 66.8 |
| ITMV | 2.61 | 3.13 | 1.76 | 2.27 | 68.0 | 72.1 | 2.90 | 3.63 | 1.92 | 2.39 | 66.4 | 65.8 |
| SED | 0.15 | | 0.14 | | 2.5 | | 0.15 | | 0.13 | | 2.1 | |
| $P > F$[c] | | | | | | | | | | | | |
| CR | 0.039 | | 0.062 | | 0.247 | | < 0.001 | | < 0.001 | | 0.079 | |
| P | < 0.001 | | < 0.001 | | < 0.001 | | < 0.001 | | < 0.001 | | 0.214 | |
| CULTIVAR | 0.005 | | 0.029 | | 0.703 | | 0.772 | | 0.601 | | 0.021 | |
| CULT × CR | 0.239 | | 0.226 | | 0.835 | | 0.546 | | 0.744 | | 0.813 | |
| CULT × P | 0.900 | | 0.794 | | 0.656 | | 0.827 | | 0.475 | | 0.128 | |

[a] Standard error of the difference.

[b] Replaced by cultivar ICMV89305 in 1993.

[c] Probability of a treatment effect (significance level).

within each year using GENSTAT 5 release 3 (Lawes Agricultural Trust, 1993). Tests of residuals with SAS Version 6.06 (SAS, 1991) revealed that in 1992, values of phytate-P and phytate-P relative to total P, and in both years data of Fe, total P, and PZMR values, were not normally distributed. While log-transformations helped to normalize all P data and Fe data in 1992, no suitable transformation could be found for PZMRs and Fe data in 1993. Because data transformation had very little influence on the *F*-values, it seemed more appropriate to present statistics of untransformed data with approximate probabilities.

## 3. Results

### 3.1. On-farm survey

The range of nutrient concentrations in millet seed from farmers' grain stores is presented in Table 1. There was no relationship between nutrient concentrations in farmers' grain samples and the average yearly rainfall of the respective villages. The ranges were small for crude protein and large for Fe.

### 3.2. On-station experiment

There were significant interactions of CR with broadcast P application in 1993 for grain yield ($P < 0.01$) and for total P concentration in the grain ($P < 0.002$). As there were no effects of the fourth treatment factor (Mo or P placement) on any of the measured parameters, results are presented for each CR level and millet line and separated for P.

#### 3.2.1. Gross energy concentration of millet

The mean gross energy concentration of millet grain samples from the on-station experiment in 1992 and 1993 was 20.0 MJ kg$^{-1}$ with a standard deviation of 0.4 MJ kg$^{-1}$. There were no effects of fertility treatments or year on gross energy, but

Table 4
Zinc (Zn), copper (Cu), and iron (Fe) concentrations ($\mu$g g$^{-1}$) in the dry matter of millet grain as affected by crop residues (CR) applied at 500 or 2000 kg ha$^{-1}$ as surface mulch or ash, by phosphorus (P) at 0 or 13 kg P ha$^{-1}$, and by cultivar in 1992 and 1993

| | 1992 | | | | | | 1993 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Zn | | Cu | | Fe | | Zn | | Cu | | Fe | |
| | $P_0$ | $P_{13}$ | $P_0$ | $P_{13}$ | $P_0$ | $P_{13}$ | $P_0$ | $P_{13}$ | $P_0$ | $P_{13}$ | $P_0$ | $P_{13}$ |
| *CR* | | | | | | | | | | | | |
| 500 | 33.0 | 28.0 | 6.3 | 5.2 | 36.2 | 31.6 | 29.4 | 28.8 | 6.4 | 5.7 | 40.5 | 46.9 |
| 2000 | 33.4 | 30.6 | 6.7 | 5.6 | 37.0 | 38.4 | 33.1 | 30.5 | 6.8 | 6.1 | 45.1 | 47.3 |
| $2000_{ash}$ | 30.6 | 27.8 | 5.9 | 5.6 | 37.4 | 36.2 | 29.4 | 27.5 | 6.6 | 5.8 | 45.7 | 47.2 |
| SED[a] | 1.4 | | 0.5 | | 4.0 | | 1.1 | | 0.4 | | 6.8 | |
| *Cultivar* | | | | | | | | | | | | |
| Landrace | 32.0 | 29.6 | 6.8 | 6.1 | 36.1 | 39.9 | 29.0 | 27.7 | 7.2 | 6.0 | 36.5 | 32.1 |
| CIVT | 31.4 | 27.9 | 6.7 | 5.2 | 38.0 | 32.4 | 31.0 | 31.1 | 6.5 | 6.1 | 44.2 | 52.1 |
| SOSAP[b] | 35.1 | 30.3 | 6.1 | 5.8 | 35.2 | 33.2 | 29.4 | 26.6 | 6.3 | 5.8 | 45.0 | 49.0 |
| ITMV | 30.8 | 27.4 | 5.6 | 4.8 | 38.1 | 36.2 | 33.1 | 30.3 | 6.4 | 5.5 | 49.6 | 55.4 |
| SED | 1.6 | | 0.5 | | 4.6 | | 1.3 | | 0.5 | | 7.9 | |
| $P > F$[c] | | | | | | | | | | | | |
| CR | 0.026 | | 0.406 | | 0.370 | | < 0.001 | | 0.375 | | 0.819 | |
| P | < 0.001 | | 0.004 | | 0.532 | | 0.010 | | 0.003 | | 0.400 | |
| CULTIVAR | 0.017 | | 0.014 | | 0.627 | | < 0.001 | | 0.193 | | 0.017 | |
| CULT × CR | 0.495 | | 0.747 | | 0.576 | | 0.282 | | 0.137 | | 0.495 | |
| CULT × P | 0.757 | | 0.431 | | 0.541 | | 0.335 | | 0.539 | | 0.703 | |

[a] Standard error of the difference.
[b] Replaced by cultivar ICMV89305 in 1993.
[c] Probability of a treatment effect (significance level).

samples from the landrace had a gross energy concentration slightly greater than the average, which was most likely due to its higher concentration of protein and possibly lipids (data not shown).

### *3.2.2. Treatment effects on yield and grain weight*

Phosphorus application increased grain yield across lines and CR treatments by 44% in 1992 and by 33% in 1993 (Fig. 1). Only in 1993 was there a significant interaction between cultivar and P application caused by a larger response of the landrace and SOSAP to P application compared with the two other lines. In plots with 2000 kg CR $ha^{-1}$, yields were between 43 and 97% greater than with 500 kg CR $ha^{-1}$. Application of burned CR at 2000 kg $ha^{-1}$ (ash) gave yields comparable with those of 500 kg CR $ha^{-1}$ in 1992, but in 1993, they were 20% smaller.

Phosphorus application increased grain weight (GW) by almost 10% across years and cultivars (Fig. 2). Compared with ash, the mulch of 2000 kg CR $ha^{-1}$ increased GW between 9 and 23% without P, and between 5 and 8% with P fertilization. These effects were consistent and additive regardless of the degree of correlation between GW and grain yield ($r = 0.27$ in 1992, $P < 0.007$; $r = 0.73$ in 1993, $P < 0.001$).

### *3.2.3. Treatment effects on macronutrient and phytate-P concentrations*

Although CR treatments did not affect protein or K concentrations of millet grain, broadcast P application decreased protein concentration in both years by an average of 8% to 127 mg crude protein $g^{-1}$, and increased the K concentration by 9% (Table 2). Calcium concentrations in the grain differed significantly between millet lines. Across fertility treatments, the grain of the landrace contained 186 mg Ca $kg^{-1}$ in 1992 and 178 mg Ca $kg^{-1}$ in 1993 which was 18 and 30% more Ca, respectively than found in ITMV, the line with the lowest concentration of this nutrient. Phosphorus application decreased Ca concentrations by 8% across all other treatments (Ca data not shown).

The application of P increased the P concentration in the grain by 17% in 1992 and 27% in 1993 (Table 3). The effect of P application was even more pronounced on phytate-P, leading to a 5% increase in the phytate-P percentage of total P across lines, CR levels, and years (Table 3). Overall, phytate-P as a proportion of total P was 64% in 1993 and 70% in 1992. Compared with ash, the application of CR at 2000 kg $ha^{-1}$ as a surface mulch led to increases in total P and phytate-P for all cultivars in both years, but relative P was increased only in 1993. The higher concentration of total P in 1993 compared with 1992 was related to a much larger increase in the concentration of phytate-P with mulched CR, the effects of CR applied at 500 kg $ha^{-1}$ were smaller but similar to 2000 kg $ha^{-1}$. In both years, the landrace had higher total P concentrations across all treatments than any other line, but only in 1992 was this also reflected in a significantly higher phytate-P concentration (Table 3). Across treatments, correlations between phytate-P and grain yield were low ($r = 0.51$ in 1992, $P < 0.001$; $r = 0.40$ in 1993, $P < 0.001$).

Table 5
Phytate/zinc molar ratio (PZMR) in millet grain as affected by crop residues (CR) applied at 500 or 2000 kg $ha^{-1}$ as surface mulch or ash, by phosphorus (P) at 0 or 13 kg P $ha^{-1}$, and by cultivar in 1992 and 1993

| | 1992 | | 1993 | |
|---|---|---|---|---|
| | $P_0$ | $P_{13}$ | $P_0$ | $P_{13}$ |
| *CR* | | | | |
| 500 | 21.1 | 28.9 | 21.0 | 28.6 |
| 2000 | 20.0 | 27.9 | 21.7 | 31.1 |
| $2000_{ash}$ | 19.7 | 28.0 | 19.8 | 27.9 |
| SED[a] | 1.6 | | 1.3 | |
| *Cultivar* | | | | |
| Landrace | 23.4 | 29.5 | 21.4 | 31.2 |
| CIVT | 20.2 | 28.0 | 19.4 | 26.0 |
| SOSAP[b] | 17.2 | 26.5 | 22.2 | 32.0 |
| ITMV | 20.1 | 29.1 | 20.3 | 27.7 |
| SED | 1.8 | | 1.5 | |
| $P > F$[c] | | | | |
| CR | 0.538 | | 0.028 | |
| P | < 0.001 | | < 0.001 | |
| CULTIVAR | 0.008 | | < 0.001 | |
| CULT×CR | 0.614 | | 0.886 | |
| CULT×P | 0.589 | | 0.338 | |

[a] Standard error of the difference.

[b] Replaced by cultivar ICMV89305 in 1993.

[c] Probability of a treatment effect (significance level).

### 3.2.4. Treatment effects on concentrations of micronutrients

Phosphorus application decreased Zn and Cu concentrations by 11 and 12% in 1992 and by 6 and 11% in 1993, but Fe concentrations were not affected (Table 4). In contrast, a mulch of 2000 kg CR $ha^{-1}$ increased Zn concentration by about 10% in both years and Cu concentration by an average of 5% compared with ash application. These effects of CR were, with the exception of Cu with P in 1993, consistent across lines, years, and P levels. The analysis of variance also indicated differences between lines in the concentrations of micronutrients (Table 4), but these effects were inconsistent with respect to the specific nutrients and years.

### 3.2.5. Treatment effects on the phytate:zinc molar ratio (PZMR)

Across years, CR levels, and lines, broadcast P application increased PZMR in millet grain by 40% (Table 5). Compared with ash, the application of 2000 kg CR $ha^{-1}$ increased PZMR by 10% in 1993 but not at all in 1992. Differences in the PZMR between lines were detected, but in both years, correlations between PZMR ratios and grain yield were low ($r = 0.39$ in 1992, $P < 0.001$; $r = 0.38$ in 1993, $P < 0.001$).

## 4. Discussion

### 4.1. On-farm survey

The wide range of concentrations in macro- and micronutrients and in phytic acid found in millet grain from farmers' grain stores along the transect in southwest Niger (Table 1) most likely reflected a combination of differences in the soil nutrient status as affected by the farmer's short- and long-term soil productivity management strategy and genotypic differences in nutrient acquisition and nutrient-use efficiency of the millet landraces (Saric and Loughman, 1983). For Fe, the particularly high variation in the on-farm survey and the non-normal distribution in the on-station experiment may be partly due to surface contamination of the grain with dust containing soil particles at threshing as seeds were not rinsed with deionized water before analysis. The large variation in the protein concentration of the grain from the on-farm survey was likely caused by differences in the nitrogen status of the soils as influenced by manure application. The low Ca concentrations are typical for the acid sandy soils of the Sahel and may decrease the risk of lower Zn bioavailability in the presence of the high concentrations of phytate-P (Davies et al., 1985).

With the exception of the millet from Kirtachi, the measured phytate concentrations of all grain samples are within the range of those reported by Simwemba et al. (1984) for different millet cultivars grown in the United States and by McKenzie-Parnell and Guthrie (1986) for whole-grain flakes of millet in New Zealand. The latter authors also found comparable concentrations of Zn and Cu but only half as much Fe. The farmer at Kirtachi claimed to have applied considerable amounts of manure to his field leading to an average dry matter yield of 4200 kg $ha^{-1}$. Under these circumstances, other factors such as a heavy attack of the cotton stainer (*Dysdercus voelkeri* Schmidt) during flowering in 1993 may have affected the P sink in the millet grain and led to the increase of grain P concentrations.

### 4.2. Effects of P-fertilizer and crop residue mulch on grain quality

In the on-station experiment, the rise in total P and phytate-P concentrations in millet grain despite the increase of grain yield with applied P (Fig. 1) reflected not only an improved P availability in the soil, but may also be the result of other growth-limiting factors. Nitrogen has been found to be the second growth-limiting nutrient for millet on acid sandy soils in the Sahel (Bationo et al., 1995). With additional nitrogen from rotations between cowpea (*Vigna unguiculata* Walp.) and millet, grain yields can be further increased (Buerkert et al., 1997) most likely leading to a dilution of P and at the same time higher protein concentrations.

It has been known that $P_{Bray}$ (Olsen and Sommers, 1982) is a good indicator of soil-P availability to millet in the Sahel (Bationo et al., 1991). When separated for lines, both total P and phytate-P concentrations in the 1993 millet grain (Table 3) reflected the concentrations of available soil-P in the topsoil (0 to 0.2 m) of the experimental plots at the end of the growing season (data not shown). These results are similar to those found by Srivastava et al. (1955) for field-grown wheat from a long-term fertility experiment although the phytate concentrations in the millet grain reported here were slightly higher. After 3 yrs of an annual application of 13 kg P $ha^{-1}$, $P_{Bray}$ in the upper 0.2 m of the experimental plots in our study has increased from an initial average value of 2.8 mg P $kg^{-1}$ to 5.4 and 7.8 mg P $kg^{-1}$ in plots with 500 and 2000 kg CR $ha^{-1}$, respectively, and to 5.6 mg P $kg^{-1}$ with ash application. This makes it unlikely that the increase of grain-P was the result of enhanced P uptake caused by Zn-deficiency, which is usually observed at much higher P levels in the rooting medium (Cakmak and Marschner, 1986). For the same reason, it is also unlikely that the decrease in Zn concentrations with P application was the result of P-induced Zn deficiency such as reported by Takkar et al. (1976) in a field trial with maize (*Zea mays* L.) fertilized at very high rates of P. The fact that broadcast P application led to a decrease in grain protein concentration, and to an increase in the total Zn accumulation in millet grain of 28% in 1992 and 25% in 1993, indicates that the decreased Zn concentrations after P application are probably due to dilution effects caused by growth promotion (Loneragan et al., 1979). The increases in grain Zn concentrations at much higher yield levels with CR application indicate increased Zn acquisition through enhanced root growth of millet with CR mulching (Hafner et al., 1993).

In 1992, the year with higher grain yields, there were significant differences in phytate concentrations between lines (Table 3). Genotypic differences in phytic acid concentrations have previously been found in faba bean (*Vicia faba* L.; Griffiths and Thomas, 1981), soybean (*Glycine max* L. Merr.; Raboy et al., 1984), lupin (*Lupinus* ssp.; Trugo et al., 1993), and pearl millet (Simwemba et al., 1984). Studies in 20 $F_6$ lines from double-crosses of winter wheat indicated, however, that with a given environment and level of soil fertility, phytic acid is highly and positively correlated with protein concentration and to a lesser degree also with grain yield (Raboy et al., 1991). Thus, selection for low phytate concentrations in millet grain may not be advisable in the Sahel where food shortages are a threat to subsistence farmers.

### *4.3. Implications of changes in millet grain quality for human nutrition*

In view of the periodic food shortages in the Sahel, any discussion of possible negative effects of P-fertilizer application on the nutritional quality of millet grain, as defined by the protein concentration or the bioavailability of micronutrients such as Zn, may appear of minor importance. This seems particularly true if one considers the large benefits in terms of grain yield increases after the application of this single mineral nutrient and the fact that with larger grain consumption also the total Zn intake increases. A more detailed examination of the food supply in the West African Sahel, however, suggests that in most regions and years, the total caloric intake of rural subsistence farmers is just sufficient, even if it may be occasionally supplemented by purchased grain or food aid. With this and the high infant mortality among rural populations in mind, the contribution of the micronutrient concentration in traditional staples to the food quality and welfare of subsistence farmers needs more attention.

Although information about critical PZMRs in human diets is limited, threshold values seem to depend on other factors such as Ca intake (Davies et al., 1985), the protein source (Cossack and Prassad, 1983), and the amount of vitamins in the diet (Graham and Welch, 1996). Detailed studies with vegetarians in the United States indicate that ratios above 15 are likely to induce Zn deficiency, especially in people with high Zn demands such as nursing mothers and children (Ellis et al., 1987; Harland et al., 1988). Similarly, Malawian school children (Ferguson et al., 1989) and pregnant Guatemalan periurban women (Fitzgerald et al., 1993) were thought to be at risk of Zn deficiency with PZMRs exceeding 15 in diets dominated by cereals and high in plant fiber. Given the already high PZMRs in the millet seed from the survey (Table 1) and from the unfertilized plots of the on-station trial (Table 5), the observed increases in PZMRs after P application seem potentially serious.

Symptoms usually related to Zn deficiency in humans such as retarded growth, diarrhea, and high infant mortality (Anonymous, 1990) are widespread among millet farmers and their families in sub-Saharan Africa. It remains to be determined, however, whether these symptoms are related to the high PZMRs found in our grain samples as PZMR values alone may be a poor indicator of Zn bioavailability in the real dishes of farmers in Niger because meat consumption can prevent Zn deficiency in high PZMR diets (Thompson, 1988; Harland, 1989). Given the recent decline in meat intake in Niger from the already low level of 3.2% of the daily energy intake of 9400 kJ $d^{-1}$ and 10.5% of the protein intake of 64 g $d^{-1}$ (1978 to 1983) by 39% for the daily energy and 34% for the protein intake (1984 to 1990; FAO, 1993), however, meat consumption may have become less effective in alleviating Zn deficiency. Likewise grain processing such as shelling can influence Zn bioavailability. Reductions of phytic acid concentrations in cereals after fermentation have been reported for rye (*Secale cereale* L.) and wheat (*Triticum aestivum* L.; Khan et al., 1986; Fretzdorff and Brümmer, 1992), for rice (*Oryza sativa* L.; Toma and Tabekhia, 1979), and even for pearl millet (Dhankher and Chauhan, 1987; Kheterpaul and Chauhan, 1991). Thus, the impact of changes in grain nutritional quality with P fertilizer application as found in the present study needs to be evaluated in relation to a complete dietary analysis including the effects of grain shelling and food preparation such as the traditional fermentation methods in millet processing for 'Tô' or 'Boule' by Sahelian women.

## 5. Conclusions

The data presented here reveal that the often-reported large increases in millet grain yield with the application of mineral P fertilizers on acid sandy soils of the West African Sahel may detrimentally affect the nutritional quality of millet grain by decreasing protein concentrations and increasing the PZMR. To draw a more definitive conclusion, however, studies of Zn bioavailability in local dishes need to be undertaken, which examine the role of traditional food-processing techniques in hydrolyzing phytate-P in millet grain. If the deleterious side effects of an unbalanced mineral P application on the quality of millet dishes can be verified, more efforts should be made to simultaneously improve the N nutrition of pearl millet through an increased use of legumes in rotations or mineral N application. Alternative approaches to improve the Zn nutrition of rural subsistence farmers would be the addition of Zn to mineral P fertilizers or in much smaller amounts to commonly traded goods such as sugar. For areas with a more commercial agriculture and likely adoption of improved varieties, existing breeding programs should strive for cultivars with higher micronutrient densities in the grain (Graham et al., 1997).

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