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RESEARCH ARTICLE

# Millet nutrient use efficiency as affected by natural soil fertility, mineral fertilizer use and rainfall in the West African Sahel

**B. Fofana · M. C. S. Wopereis · A. Bationo ·**
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**Abstract** Field experiments were designed to investigate the effectiveness of integrated soil fertility management (ISFM), comparing fertilizer use efficiency and its impact on millet, cultivated close to the homestead ("infields") and away from the homestead ("outfields"). Millet yields and response to N (0, 30, and 60 kg ha$^{-1}$) and P (0, 15, and 30 kg ha$^{-1}$) were determined on nine infields and nine outfields over a period of 3 years (from 1999 to 2001) in the southern Sahel of Niger. Rainfall was 650, 470, and 370 mm during the three successive years, interaction between decreasing rainfall and millet yield performance was also analyzed. While soil organic carbon (1.5 g kg$^{-1}$ on outfields and 1.6 g kg$^{-1}$ on infields) and pH-$H_2O$ (4.8 on outfields and 5.1 on infields) were comparable, total-N, plant available P (measured as P-Olsen and P-Bray), and exchangeable Ca, K, and Mg levels were higher on infields as compared to outfields. Without fertilizer, average grain yield (GY) and stover yield obtained on infields were three times as high as on outfields. GY across years and fertilizer treatments was higher on infields as compared to outfields ($P < 0.001$). Average yield was 800 kg ha$^{-1}$ on outfields and 1,360 kg ha$^{-1}$ on infields ($P < 0.001$). On outfields, average GY was stagnant over the 3-year experimental period. Despite declining rainfall, millet GY across all treatments gradually increased over time on infields ($P < 0.001$). P fertilization alone resulted on both field types to steadily and substantial yield increases while yield response to N fertilization was only obvious when fertilizer P was applied. With no fertilizer applied, N uptake on infields (19 kg N ha$^{-1}$) was more than twice as high as on outfields (7 kg ha$^{-1}$), and P uptake was four times higher on infields (3 kg ha$^{-1}$) than on outfields (0.8 kg ha$^{-1}$). Indigenous soil N supply was on average 24 kg N ha$^{-1}$ on outfields and 46 kg N ha$^{-1}$ on infields. Average value for indigenous soil P supply was 4 kg P ha$^{-1}$ on infields and 2 kg ha$^{-1}$ on outfields. Apparent recovery of fertilizer N applied varied considerably among treatments and ranged from 17 to 23% on outfields and 34 to 37% on infields ($P < 0.001$). Average apparent recovery of fertilizer P applied was significantly higher ($P < 0.001$) on infields (31%) than on outfields (18%) over the 3-year growing period, illustrating ISFM-induced positive effect on millet

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nutrient N and P use. Results indicate higher inherent soil fertility, underline ISFM-induced drought tolerance of soils on infields as compared to outfields, and highlight the crucial role of fertilizer P (especially on outfields) for millet production. These call for site-specific nutrient management and support, even under low rainfall conditions, the potential value of fertile infields for efficient and productive external input use and sustainable millet production in West African Sahel.

**Keywords** Infield · Outfield · Millet · Fertilizer · Nutrient use efficiency · Integrated soil fertility management · Nitrogen · Phosphorus · pH · Organic matter · Calcium · Rainfall · Niger

## Introduction

Soils in the West African Sahel (WAS) are generally low in organic matter, nitrogen (N) and phosphorus (P) (Pieri 1989). Spatial variability of soil fertility is however high, due to considerable variability in soil management practices in space and time. Prudencio (1983) observed a soil fertility gradient with increasing distance from the homestead, with zones of higher soil fertility near the household. Many authors observed centripetal concentration of nutrients when calculating nutrient balances of crop-livestock farming systems at different distance from compounds (Sédogo 1993; Samaké 2003).

Traditionally, farmers in WAS have enriched soil fertility in the compound fields or "infields" close to the homestead through regular application of household waste, crop residues, and animal manure. Continuous cropping and grazing on fields further away from the homestead "outfields" with little or no inputs and use of crop residues as building materials and fuel leads to nutrient depletion and decline in soil fertility. Under farmers' conditions in the Sahelian zone of Niger, increases of millet grain yield (GY) per ton dry matter of applied manure vary between 15 and 86 kg (McIntire et al. 1992), suggesting that crop production on sandy soils is largely dependant on plant nutrients.

Although it is often assumed that rainfall, and hence soil moisture availability is the primary constraint to production in semi-arid areas, research in West Africa has demonstrated that the potential production resulting from any given rainfall is limited by nutrient availability (Breman et al. 2001; Mapfumo and Giller 2001). Analysis of nutrient balances of four mixed farming systems in Mali (Powell and Coulibaly 1995) and two in Niger (Buerkert et al. 2000) showed that croplands lack an internal capacity to replenish N removal with grain and crop residues. And farmers in western Niger annually apply manure on 30–50% of their millet fields at rates of about 1,300 kg ha$^{-1}$ (Powell and Williams 1993).

Breman (1990) noted that livestock movement, and therefore farmers' lack of access to the manure of transhumant herds, greatly increases the need for external nutrient inputs such as fertilizers to prevent declines in soil fertility and crop yields. Irrespective of this, the use of external inputs by farmers remains inadequate, due to lack of purchasing power, high prices and limited availability of fertilizer and other inputs, and a generally unconducive policy environment for the use of such inputs (Keatinge et al. 2001). Beneficial effects of integrated use of organic soil amendments and fertilizers, the "so-called" integrated soil fertility management (ISFM), on soil fertility have been shown, and increased nutrient use efficiency was associated with combined nutritional and no-nutritional effects compared to inorganic fertilizer applied alone (Fofana et al. 2005; Wopereis et al. 2005).

It is hypothesized that the use of mineral fertilizers on infields will lead to improved nutrient use efficiency, attributable to ISFM-induced soil drought tolerance, and result in increased soil fertility and crop production on the sandy and fragile soils in WAS. The experiment was designed to test the above hypothesis and draw site-specific recommendations on soil fertility management practices.

## Materials and methods

### Experimental site

Field experiments were conducted near Karabédji (13°26′E, 14°14′N, 80 km south of Niamey), Niger in 1999–2001. Soil was acid, contained 94% sand, 3% clay and 3% silt, and is classified as Psamentic Paleustalfs (Soil Survey Staff 1975). Its extremely course texture favors water infiltration, but the relatively high air temperature and low relative humidity most of the year and the soil texture are unfavorable for soil organic matter accumulation. The last three properties make the soil very marginal for crop production, a characteristic that is still reinforced by the low rainfall. Karabédji is located in the southern Sahel, characterized by a 5-month rainy season lasting from June to October, and a 7-month dry season from November to May. In 1999, 2000, and 2001, cumulative rainfall amounted to 638, 470, and 370 mm, respectively (Fig. 1). While the soil is too sandy to be representative for the Sahel, its extreme properties make validation of ISFM of particular interest.

The region is traditionally dominated by a mixed crop-livestock farming system, including pearl millet, sorghum, cowpea and groundnut. In 1999, three farmers volunteered to collaborate in a field experiment. Each farmer selected one of his infields and one outfield. These infields typically received household waste throughout the year and animal manure during the dry season and were located at 10–50 m from the homestead. The outfields were located at >500 m from the homestead and had not received any organic inputs, except for animal droppings of grazing cattle. Prior to the experiments, infields had been traditionally cropped with millet (without application of mineral fertilizers). The outfields had been left fallow for about 5 years.

## Treatments and crop and soil management

On the outfields, a weedy fallow was hand-cleared and incorporated into the field during land preparation in 1999. On the infields, feed refusal from stall-fed animals, millet stover and household waste were incorporated into the soil. Soil tillage was performed with a two-oxen drawn plow creating a plow depth of about 0.1 m. Pearl millet (*Pennisetum glaucum* (L.) R.BR) was planted at about 10,000 hills ha$^{-1}$ in all growing seasons in June after the first rains. The crop was harvested early November and the land left fallow and opened to grazing during the dry season. Crop residues were left on the soil surface.

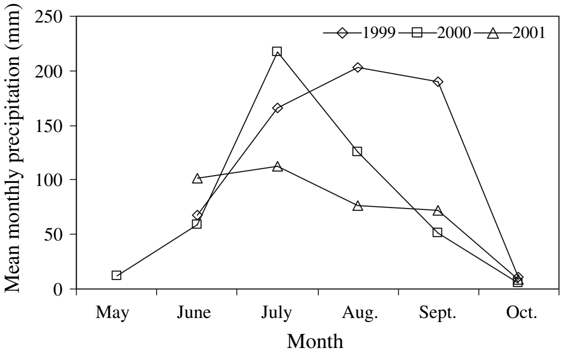

**Fig. 1** Rainfall distribution during growing season in 1999, 2000, and 2001, Karabédji, Niger

The experimental set up was a randomized complete block design with nine replicates and nine treatments for both infield and outfield. Individual plot size was 10 × 10 m$^2$. Mineral fertilizer was applied as urea (0, 30, and 60 kg N ha$^{-1}$) and single super phosphate (SSP, 0, 15, and 30 kg P ha$^{-1}$) on both field types. Urea N was top-dressed with 50% at 21 and 50% at 45 days after planting. SSP was applied during land preparation. Potassium (K) is generally not considered a growth-limiting factor for cereals in the Sahel. Atmospheric deposition enriches Sahelian soils in K (Buerkert and Hiernaux 1998). K was, therefore, not applied in the experiments.

## Plant and soil analyses

Soils samples were taken prior to land preparation to 0.2 m depth, ground to pass through a 2 mm sieve, prior to chemical analysis of organic carbon, total N, available-P, pH-$H_2O$, pH-KCl and exchangeable Ca, K and Mg (IITA 1982).

The central 36 m$^2$ area of each plot was harvested at maturity. Grain and stover sub-samples were oven-dried at 60°C, weighed and ground to pass 0.5 mm and then analyzed for total N and P (IITA 1982). Indigenous soil N supply (INS) was calculated as the amount of N uptake by millet at harvest at the highest P application rate with no N fertilizer applied. Similarly, indigenous soil P supply (IPS) was calculated as millet N uptake at harvest at the highest N application rate with no fertilizer P applied.

Increased N absorption per kg P applied was calculated as the difference between aboveground millet N uptake at harvest between plots with and without P application at constant N rates. Increased P absorption per kg N applied was calculated as the difference between aboveground millet P uptake at harvest between plots with and without N application at constant P rates.

The apparent recovery fraction of applied fertilizer N (RFN) was based on the difference in aboveground millet N uptake at harvest between plots with and without N application, at constant P rates. Similarly, the apparent recovery fraction of applied fertilizer P (RFP) was based on the difference in aboveground millet P uptake at harvest between plots with and without P application, at constant N rates.

### Statistical procedures

Analysis of variance (ANOVA) was carried out for each site on GY, stover yield (SY) and nutrient uptake and recoveries. When a significant treatment effect was found, comparison of treatment means were carried out using the least significant difference (LSD) test at 5% probability level (Gomez and Gomez 1984). Regression analyses were performed to estimate the response in GY to soil and fertilizer N and P uptake, and to explore the relationship between GY gains due to fertilization and apparent fertilizer nutrient recovery fractions.

## Results and discussion

### Soil chemical properties

Organic carbon (C org) and pH (water) were similar for both field types while N, P, Ca, Mg, and K content were different (Table 1). In Mali, Samake (2003) reported organic C and pH (water) values of 5.4 g kg$^{-1}$ and 8.5 on infields and 1.0 g kg$^{-1}$ and 5.2 on outfields. In Burkina Faso, Sedogo (1993) reported pH (water) values of 7.5 on infields and 6 on outfields, and organic C contents ranging from 11–20 g kg$^{-1}$ on infields to 2–5 g kg$^{-1}$ on outfields.

The equal organic C and pH (water) values observed between both field types in this study may illustrate the beneficial effect of the fallow vegetation on outfields. However, total-N (CV = 9%), plant available P measured as P-Olsen (CV = 16%) and P-Bray (CV = 15%), and exchangeable Ca, K, and Mg levels were higher on infields as compared to outfields. This may be linked to rapid mineralization of organic matter and/or manure, enriching topsoil of infields with more Ca, K, and Mg as compared to outfields. There is strong evidence that, even under the conditions of low rainfall in WAS, most of the manure applied mineralized quickly during the rainy season (Esse et al. 2001). The properties observed on both field types indicate that infields are more fertile than outfields, and could be ascribed to the continuous accumulation of mineral plant nutrients from organic amendments including all kinds of animal manure and household waste applied in the small ring directly surrounding the villages. Results indicate spatial variability in soil fertility between infields and those far away (outfields), attributed to different fertility management strategies of farmers.

**Table 1** Soil characteristics (0–20 cm, N - 9) of the experimental site in Karabedji, Niger (1999)

| Characteristics | Field type | | SE (±) |
|---|---|---|---|
| | Bush field | Compound field | |
| pH-$H_2O$ | 4.8 | 5.1 | 0.21 |
| pH-KCl | 4.3 | 4.9 | 0.19 |
| Organic C (g kg$^{-1}$) | 1.5 | 1.6 | 0.04 |
| Total-N (mg kg$^{-1}$) | 118 | 135 | 6.36 |
| P-Olsen (mg kg$^{-1}$) | 1.6 | 2.5 | 0.19 |
| P-Bray$^{-1}$ (mg kg$^{-1}$) | 4.4 | 6.2 | 0.47 |
| $Ca^{2+}$ (mmol kg$^{-1}$) | 2.41 | 3.67 | 0.56 |
| $K^{+1}$ (mmol kg$^{-1}$) | 2.06 | 3.48 | 0.55 |
| $Mg^{2+}$ (mmol kg$^{-1}$) | 1.35 | 1.95 | 0.34 |

N number of farmers per field type

### Millet yield

The highest millet yield was observed on infields. GY was 60% and SY 30% higher on infields as compared to outfield. Likewise, with no fertilizer applied, average GY and SY obtained on infields were three times as high as on outfields (Table 2).

The GY across years and fertilizer treatment averaged 800 kg ha$^{-1}$ on outfields and 1,360 kg ha$^{-1}$ on infields (Table 2) and field type was a significant factor ($P < 0.001$). Samake (2003) and Sedogo (1993) reported greater millet yield performance on infields in Mali and Burkina Faso. On outfields, average GY was stagnant during the 3 years of experimentation. On infields however, GYs gradually increased over time despite declining total cumulative rainfall (Fig. 1), leading to a year × field type

**Table 2** Millet grain and stover yield (kg ha$^{-1}$) on outfields (OF) and infields (IF) during three years and N application (0, 30 and 60 kg ha$^{-1}$) and P application (0, 15 and 30 kg ha$^{-1}$). Data from 1999 (Yr1) to 2001 (Yr 3)

| | Yr1 | | | | | | Yr2 | | | | | | Yr3 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | OF | | | IF | | | OF | | | IF | | | OF | | | IF | | |
| | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 |
| *Grain yield* | | | | | | | | | | | | | | | | | | |
| N0 | 182.8 | 772.9 | 660.4 | 565.2 | 969.2 | 1601.3 | 166.9 | 666.7 | 814.8 | 493.9 | 1314.8 | 1654.2 | 148.3 | 691.4 | 913.4 | 512.2 | 1333.3 | 1654.3 |
| N30 | 367.9 | 738.2 | 1324.8 | 762.9 | 1284.0 | 1611.1 | 351.9 | 728.4 | 1061.6 | 611.1 | 1475.3 | 2129.7 | 364.1 | 895.2 | 1284.0 | 654.2 | 1604.9 | 2092.8 |
| N60 | 260.6 | 1145.6 | 2086.6 | 600.1 | 1448.0 | 1864.1 | 413.7 | 734.7 | 1500.0 | 648.1 | 1568.0 | 2703.6 | 500.0 | 1098.8 | 1728.4 | 789.9 | 1901.1 | 2851.9 |
| LSD $_{(0.05)}$ | 372.1 | | | | | | 210.3 | | | | | | 170.5 | | | | | |
| *Stover yield* | | | | | | | | | | | | | | | | | | |
| N0 | 1074.0 | 2938.3 | 3117.3 | 2876.6 | 3305.4 | 3849.9 | 481.4 | 1500.0 | 2043.3 | 1499.9 | 2975.2 | 3438.2 | 320.9 | 1370.4 | 1709.8 | 1160.4 | 2228.4 | 2605.0 |
| N30 | 1888.9 | 3197.6 | 3469.0 | 2851.9 | 3438.2 | 3999.9 | 919.7 | 1932.1 | 2765.3 | 1882.6 | 3320.8 | 3802.4 | 808.7 | 1691.4 | 2209.8 | 1506.1 | 2586.4 | 3117.3 |
| N60 | 1290.3 | 3164.1 | 4104.9 | 2975.3 | 3691.1 | 4012.3 | 1031.1 | 1907.2 | 3432.0 | 2105.0 | 3426.1 | 4493.8 | 1024.6 | 2012.2 | 2623.4 | 1716.1 | 2993.7 | 3648.1 |
| LSD $_{(0.05)}$ | 498.2 | | | | | | 210.3 | | | | | | 216.8 | | | | | |

interaction ($P < 0.001$). Similarly, Samaké (2003) found decreasing GY on outfields in continuous millet mono-cropping systems. Without N and P fertilization, average GY was 520 kg ha$^{-1}$ on infields and 170 kg ha$^{-1}$ on outfields. This suggests that infields are more adapted for continuous millet cropping than are outfields. The consistent GY increase throughout the 3-year millet mono-cropping despite decreasing rainfall quantity indicates the potential role of ISFM to support continuous millet mono-cropping on infields.

The SY across years and fertilizer treatments averaged 2,950 kg ha$^{-1}$ on outfields and 2,000 kg ha$^{-1}$ in infields (Table 2), and field type was a significant factor ($P < 0.001$). Indeed, average harvest index value was 32 on infield and 28 on outfield (*data not shown*), suggesting an ISFM—induced improvement of the harvest index. SY responded to both fertilizer N and P if applied in isolation, contrary to GY. Combined use of fertilizer N and P resulted in the highest values for SY. The results suggest production-specific fertilization as P nutrition seems to be very crucial for millet grain production on infield, and combined N and P nutrition for both millet grain forage production.

P fertilization alone led on both field types to steadily and substantial grain and SY increases. With only fertilizer P applied (30 kg P ha$^{-1}$), GY on infields (1,640 kg ha$^{-1}$) across years was three times as high as obtained with no fertilizer P and N applied (520 kg ha$^{-1}$). The same trend was observed on outfields where GY with only P applied (800 kg ha$^{-1}$) was almost five times as high as compared to treatment with no fertilizer P and N applied (170 kg ha$^{-1}$). The highest GY (2,850 kg ha$^{-1}$) was obtained on infields at highest N and P application rates. These indicate that both N and P are key factors to millet production with P being the most limiting, especially on outfields (Table 2). The above is confirmed by millet response to N fertilization that was only obvious when fertilizer P is applied. Many authors support the view that P availability is key for millet production on weakly buffered, acid, sandy Sahelian soils (Pichot and Roche 1972; Bationo et al. 1985; Pieri 1986; Manu et al. 1991; Bationo et al. 1992). The larger increase in millet yields with P fertilization in outfields indicates that P is more limiting on outfields than in infields, reflecting the P gradient observed between infields and outfields (Table 1).

Although P fertilization was the key element for millet yield formation on both field types, N uptake via fertilization accounts for much of the yield response on outfields as compared to infields. This points out the need for combined application of fertilizer N and P for increased millet yield on outfields. Indeed, contrary to infields, both P (30 kg ha$^{-1}$) and N (30 kg ha$^{-1}$) fertilization were needed to meet the nutrient requirement for 1,500 kg ha$^{-1}$ millet grain and 3,000 kg ha$^{-1}$ SY building, suggesting greater nutrient requirement on outfields as compared to infields. Studies conducted in Niger by Bationo and Ntare (2000) demonstrated that traditional millet-cowpea rotation in WAS on outfields does not increase millet yields unless inorganic N and P fertilizers and/or manure are added and suggested a cropping system that integrates millet-legume rotation and a mixture of N and P fertilization as an appropriate alternative for restoring soil fertility on outfields.

## Millet grain yield in relation to rainfall quantity

Millet GY across treatments varied considerably over the 3-year cropping seasons, and fluctuation was almost independent of rainfall quantity (Fig. 2). With no fertilizer applied, GY evolution was unaffected by rainfall quantity. However, fertilization led to significant rainfall-induced GY fluctuation. These demonstrate that the potential millet production resulting from any given rainfall is limited by nutrient availability, and suggest the prevailing effect of plant nutrient on millet GY evolution.

Contrary to outfields, GY on infields when highly fertilized increases with decreasing rainfall quantity. These results show an ISFM-induced soil drought tolerance on infields. There is strong evidence that nutrient concentration on infields through active and passive deposition of organic matter (e.g., manure and other organic wastes) contributes to millet drought tolerance, attributed to soil fertility build up via residual effect of 3-year N and P application, leading to increased millet root growth, soil permeability, and water-holding capacity (Hafner et al. 1993; Affholder 1995). This indicates that the integrated use of soil amendments and mineral fertilizers (ISFM) can contribute significantly to sustainable improvement of soil fertility to reduce drought-induced yield losses in WAS. Under the conditions of our field experiments conducted near Karabédji, soil infertility, rather than water shortage, seems to have been the main factor impeding yield

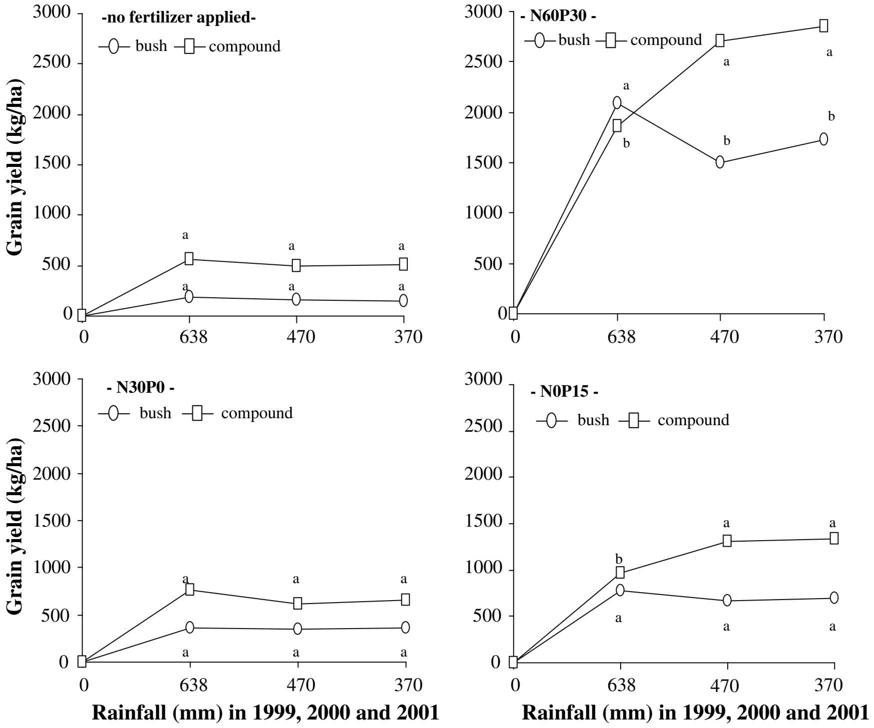

**Fig. 2** Millet grain yield as a function of yearly rainfall and fertilizer N and P applied. *Circle symbols* refer to outfields; *square symbols* refer to infields. The graph includes data from 1999 to 2001. Mean in each curve (outfields and infields) followed by the same letter do not differ significantly, Karabédji, Niger

increases of millet. Similar cases in the Sahel have been reported by Penning de Vries and Ditèye (1991) and Breman et al. (2001).

## Natural soil fertility

The long-term increase of soil fertility of infields was evident in greater indigenous nutrient N and P supply and increased recoveries of N and P associated with higher yield performance, as compared to outfields. Thus, with no fertilizer applied, N uptake of infields (19 kg N ha$^{-1}$) was more than twice as high as of outfields (7 kg N ha$^{-1}$). A similar trend was observed for P with uptake of infields (3 kg ha$^{-1}$) being four times as high as of outfields (0.8 kg ha$^{-1}$) (Table 3). For both N and P uptake, field type was a significant factor ($P < 0.001$), in accordance with differences in total N and P contents of the soil (Table 1).

The INS was, on average, 24 kg N ha$^{-1}$ on outfields and 46 kg N ha$^{-1}$ on infields. Average value for IPS was 2 kg ha$^{-1}$ on outfields and 4 kg P ha$^{-1}$ on infields. These data indicate that more N and P were mineralized in infields than in outfields, which provides a partial explanation of the higher yield performance on infields (Table 2). Other factors which could explain the higher yields in the infields could be the accumulation of secondary and micronutrients in the infield soils. Yield observed with only fertilizer P applied suggests that P is the most limiting factor of the variables of our experiments when aiming at higher millet performance on both field types. This confirms findings by Palm (1995) showing that organic amendments when applied contain sufficient N that might be able to match crop yield but could not contain enough P to meet crop requirement.

With no fertilizer N and P applied, total N uptake steadily decreased over the 3-year cropping period on both field types. The decreasing N and P uptake with continuous millet cropping without fertilization suggests nutrient depletion in the soil, indicating that sustainable, continuous millet mono-cropping could not be achieved without external nutrient inputs.

## Nutrient uptake and use efficiency

Averaged over year and fertilization, total N uptake ranged from 7 to 26 kg ha$^{-1}$ on outfields, and from 19 to 43 kg ha$^{-1}$ on infields. Total N uptake by millet steadily increased up to the highest fertilizer N rate (60 kg N ha$^{-1}$) on both field types and was further greatly improved when fertilizer P was applied, leading to field type × N × P interaction ($P < 0.01$). With no fertilizer P applied, highest N rate did not significantly increase total N uptake on both field types, and P fertilization increased N uptake more than did N fertilization. These suggest, once more, that of the two essential plant nutrients, N and P, which were studied as variables in the field experiments we conducted near Karabédji, P was the most limiting element to millet growth.

Total P uptake steadily increased for both field types with P fertilization, but the increase in total P uptake was highest if N was applied as well. Average total P uptake on infields (8 kg ha$^{-1}$) was twice as high as on outfields (4 kg ha$^{-1}$) and field type was a significant factor ($P < 0.001$). With no fertilizer N applied, substantial gains in P uptake were obtained on outfields at P-rates of up to 15 kg ha$^{-1}$ and on infields up to the maximum rate of 30 kg P ha$^{-1}$. Best millet performance seems to be markedly related to N and P combined application. At low fertilizer N and P rates, increase in total P uptake per kg fertilizer N applied was higher on infields as compared to outfields. Applying fertilizer P on infields resulted, especially in the third cropping season (with the lowest rainfall), in a better N uptake by millet. Total N and P uptake on infields seems hardly affected by decreasing rainfall, suggesting more effective use of rainwater on infields. This may also be due to greater availability macronutrient in the infields, compared to the outfields.

Apparent recovery of fertilizer N applied (RFN) varied considerably among treatments and ranged on average from 17 to 23% on outfields and from 34 to 37% on infields ($P < 0.001$), suggesting a better nutrient use efficiency on infields as compared to outfields. With no fertilizer P applied, RFN values for both field types were almost identical (Table 4). Application of P resulted in significant improvement in RFN, especially on infields, leading to P × field type interaction ($P < 0.001$). With P application, RFN increased from 21 to 39% on outfields and from 23 to 48% on infields. Changes in total N uptake per kg fertilizer P applied were more pronounced on infields (1.2 kg ha$^{-1}$) than on outfields (0.8 kg ha$^{-1}$) (Table 3). N use efficiency seems, particularly on infields, to be closely linked to P fertilization.

**Table 3** Millet nutrient uptake (kg ha$^{-1}$) on outfields (OF) and infields (IF) during three years and N application (0, 30 and 60 kg ha$^{-1}$) and P application (0, 15 and 30 kg ha$^{-1}$). Data from 1999 (Yr1) to 2001 (Yr 3)

| *Above-ground N uptake* | | | | | | | | | | | | | | | | | | | Mean increase kg N uptake/ kg P applied | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Yr1 | | | | | | Yr2 | | | | | | Yr3 | | | | | | g kg$^{-1}$ | | | | | |
| | OF | | | IF | | | OF | | | IF | | | OF | | | IF | | | OF | | | IF | | |
| | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 |
| N0 | 10.3 | 36.3 | 25.1 | 25.0 | 34.9 | 48.0 | 6.6 | 22.7 | 24.1 | 16.6 | 39.3 | 46.2 | 5.1 | 22.9 | 24.0 | 15.5 | 36.8 | 42.4 | – | 1331 | 569 | – | 1198 | 883 |
| N30 | 20.9 | 27.7 | 40.6 | 34.7 | 47.9 | 49.2 | 14.1 | 22.5 | 33.1 | 25.2 | 50.1 | 58.3 | 13.2 | 23.9 | 33.9 | 24.3 | 48.3 | 53.3 | – | 580 | 660 | – | 1380 | 851 |
| N60 | 16.8 | 37.6 | 61.8 | 34.3 | 51.0 | 61.3 | 17.9 | 23.2 | 47.8 | 28.7 | 51.8 | 82.1 | 19.5 | 30.9 | 47.3 | 29.7 | 55.3 | 80.3 | – | 833 | 1141 | – | 1453 | 1456 |
| LSD $_{(0.05)}$ | 11.6 | | | | | | 8.2 | | | | | | 6.7 | | | | | | | | | | | |

| *Above-ground P uptake* | | | | | | | | | | | | | | | | | | | Mean increase kg P uptake/kg N applied | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Yr1 | | | | | | Yr2 | | | | | | Yr3 | | | | | | g kg$^{-1}$ | | | | | |
| | OF | | | IF | | | OF | | | IF | | | OF | | | IF | | | OF | | | IF | | |
| | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 |
| N0 | 1.0 | 4.9 | 4.3 | 4.0 | 7.0 | 10.5 | 0.7 | 3.5 | 4.2 | 2.8 | 7.9 | 10.4 | 0.6 | 3.5 | 4.4 | 2.6 | 7.2 | 9.2 | – | – | – | – | – | – |
| N30 | 2.1 | 4.4 | 7.4 | 5.6 | 9.0 | 9.9 | 1.5 | 3.7 | 6.0 | 3.9 | 9.5 | 11.7 | 1.5 | 4.1 | 6.4 | 3.9 | 9.1 | 10.8 | 31.0 | 3.3 | 76.7 | 44.4 | 61.1 | 25.6 |
| N60 | 1.4 | 5.6 | 12.5 | 4.6 | 8.8 | 11.4 | 1.9 | 3.5 | 9.2 | 3.9 | 9.0 | 15.8 | 2.1 | 4.8 | 9.3 | 4.1 | 9.7 | 15.6 | 17.0 | 11.1 | 100.6 | 17.8 | 30.0 | 70.6 |
| LSD $_{(0.05)}$ | 2.3 | | | | | | 1.9 | | | | | | 1.1 | | | | | | | | | | | |

**Table 4** Nutrient fertilizer N and P recoveries (kg kg$^{-1}$) on outfields (OF) and infields (IF) during three years and N application (0, 30 and 60 kg ha$^{-1}$) and P application (0, 15 and 30 kg ha$^{-1}$). Data from 1999 (Yr1) to 2001 (Yr 3)

| | Yr1 | | | | | | Yr2 | | | | | | Yr3 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | OF | | | IF | | | OF | | | IF | | | OF | | | IF | | |
| | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 | P0 | P15 | P30 |
| *N recovery* | | | | | | | | | | | | | | | | | | |
| N0 | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – |
| N30 | 0.22 | –0.28 | 0.42 | 0.22 | 0.54 | 0.31 | 0.25 | –0.01 | 0.30 | 0.29 | 0.36 | 0.40 | 0.27 | 0.04 | 0.33 | 0.29 | 0.38 | 0.36 |
| N60 | 0.12 | 0.02 | 0.53 | 0.17 | 0.26 | 0.56 | 0.19 | 0.01 | 0.40 | 0.20 | 0.21 | 0.60 | 0.24 | 0.13 | 0.39 | 0.24 | 0.31 | 0.63 |
| LSD $_{(0.05)}$ | 0.30 | | | | | | 0.25 | | | | | | 0.18 | | | | | |
| *P recovery* | | | | | | | | | | | | | | | | | | |
| N0 | – | 0.23 | 0.11 | – | 0.27 | 0.21 | – | 0.19 | 0.12 | – | 0.34 | 0.25 | – | 0.19 | 0.13 | – | 0.31 | 0.22 |
| N30 | – | 0.16 | 0.17 | – | 0.37 | 0.21 | – | 0.15 | 0.15 | – | 0.38 | 0.26 | – | 0.17 | 0.16 | – | 0.35 | 0.23 |
| N60 | – | 0.23 | 0.31 | – | 0.31 | 0.34 | – | 0.11 | 0.25 | – | 0.34 | 0.40 | – | 0.18 | 0.24 | – | 0.38 | 0.38 |
| LSD $_{(0.05)}$ | 0.11 | | | | | | 0.11 | | | | | | 0.10 | | | | | |

Average apparent recovery of fertilizer applied P (RFP) across years and treatments was significantly higher on infields (31%) as compared to outfields (18%) (Table 4) and field type was a significant factor ($P < 0.001$). Contrary to outfields, average apparent P recovery on infields increased in time despite decreasing rainfall quantity and increase was more pronounced at highest fertilizer N and P rate applied.

Results indicate, despite drought occurrence, better soil drought tolerance on infields as compared to outfields. This could be ascribed to better water retention capacity of soil and root growth attributed to the centripetal concentration of nutrient through corralling manure application on infields. The high Ca content observed on infields (Table 1) could have contributed to increased Ca uptake, leading to millet root elongation and drought tolerance (Marschner 1995). The above is confirmed by studies conducted in WAS, revealing that manure application was associated with increased root density, improved soil structure and water-holding capacity (Maurya and Lal 1981; Affholder 1995; Buerkert et al. 2000).

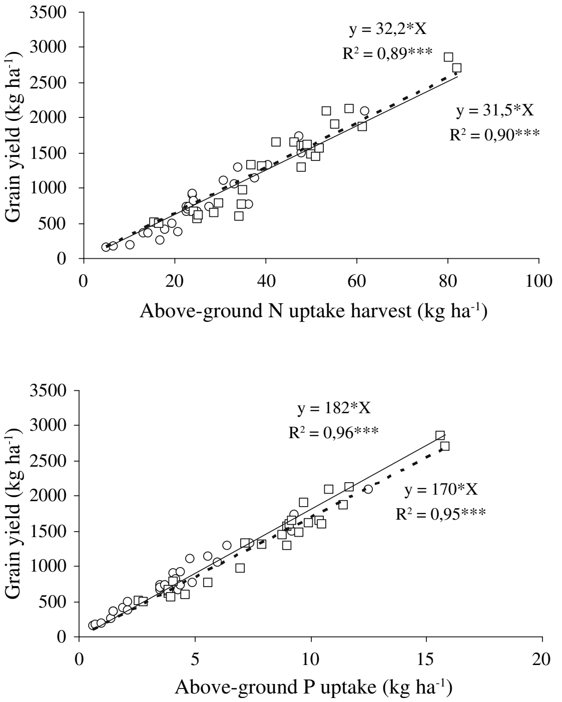

**Fig. 3** Millet grain yield as a function of above-ground N and P uptake at harvest. *Circle symbols* refer to outfields; *square symbols* refer to infields. *Solid line* is the regression line for outfields, the *dotted line* is the regression line for infields. The graph includes all data for 1999–2001

## GY versus nutrient uptake

Regression lines for total N uptake versus GY were almost identical for both field types (Fig. 3). The slope obtained from the regression analysis was 32.2 kg grain kg$^{-1}$ plant N for infields and 31.5 kg grain kg$^{-1}$ plant N for outfields. Regression analysis of GY and total P uptake resulted in slopes of 170 kg grain kg$^{-1}$ plant P for infields and 182 kg grain kg$^{-1}$ plant N for outfields. GY gain was

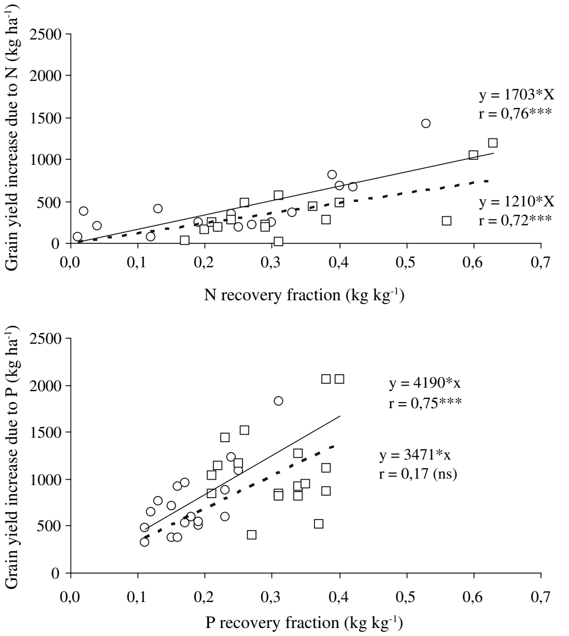

**Fig. 4** Millet grain yield increase as a function of aboveground N and P recoveries at harvest. *Circle symbols* refer to outfields; *square symbols* refer to infields. *Solid line* is the regression line for outfields, the *dotted line* is the regression line for infields. The graph includes all data for 1999–2001

calculated using yield difference between two given fertilizer rates (N and P), keeping fertilizer N or P constant, and separately correlated with fertilizer (N and P) nutrient recoveries. GY gain was highly correlated with increased nutrient uptake per unit nutrient applied and the effect was more pronounced on outfields than on infields. These confirm lower soil fertility and suggest greater fertilizer requirement for millet growth on outfields as compared to infields. Slopes obtained from the regression analysis were 1,703 and 1,210 for N, 4,190 and 3,471 for P apparent recovery, on outfields and infields, respectively (Fig. 4). Results indicate that obtained higher apparent nutrient recovery on infields could not be expressed in higher GY.

Nutrient N and P uptake accounted equally for the millet yield response to fertilization. The almost identical association between GY versus total N and P found on infields and outfields is not in line with the higher nutrient recoveries observed on infields as compared to outfields. One could have expected closer association between GY and nutrient N and P on infields as compared to outfields.

These suggest that other factors not related to N and P nutrients (e.g., potassium, soil moisture content, and micronutrients) impaired greater millet performance at highest fertilizer nutrient rates. This is supported by the potassium deficiency observed by Hafner et al. (1993) after a 2-year continuous millet cropping in a trial with a long-term application of crop residues and/or mineral fertilizers in Niger. Apparently, potassium supply through atmospheric deposition (Buerkert and Hiernaux 1998) and application of crop residues/compost were not sufficient to meet millet potassium requirement for higher GY formation.

## Conclusion

The present study shows great spatial variability in soil fertility, and indicates that soils close to the homestead "infields" are more fertile and productive than their counterparts away from the homestead "outfields." The consistent GY increase and the fertilizer use efficiency obtained on infields, despite the occurrence of drought, underline the crucial role of the integrated use of soil amendments and mineral fertilizers (ISFM-strategy) in mitigating drought-induced yield losses for sustainable crop productivity in the Sahel. This yield performance confirms the potential value of ISFM-strategy on infields for continuous millet mono-cropping on very sandy Sahelian soils, having extremely low levels of organic matter and weak buffering capacity. The practical implication of this result would be more advantageous to farmers in WAS, having better access to livestock and manure but limited area of cultivable land.

Results provide evidence that for Sahelian farmers targeting up to 1,500 kg ha$^{-1}$ millet grain and 3,000 kg ha$^{-1}$ SY, continuous soil amendment in combination with compound fertilizer P application (for instance NPK 14-23-14) at 15 kg ha$^{-1}$ rate might be enough to meet millet P requirement on a typical infield in WAS. Although it remains clear that combined P and N fertilization can (especially on outfields) contribute to greater GY and SY, fertilization should nevertheless be managed with caution, taking into account factors which limit millet growth, such as water shortage, genetic potential, and availability of all essential, mineral nutrients, in WAS.

It is certainly not feasible to rely solely on infields to produce enough food and fodder to feed the increasing density of WAS population, cattle and small ruminant, because their surface are relatively small, compared to the outfields. Therefore, there is a need to add to the confined fertile area of infields by developing mechanisms that enable the application of manure on outfields through, for instance, corralling livestock overnight directly on outfields and/or gathering manure from stalls.

There is a need to promote widespread use of ISFM in WAS. To this end, policy instruments are required to help farmers to have easily access to both soil amendments (e.g., compost, manure, etc.) and mineral fertilizers. The availability and accessibility of organic soil amendments is mainly dependent on animal traction. Policy measures to extend fertile but confined infields should therefore include for instance micro credits allowing farmers to invest in animal traction and soil fertility through mineral fertilizers.

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