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Millet response to microdose fertilization in south–western Niger: Effect of antecedent fertility management and environmental factors

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ABSTRACT

Soil fertility is a major constraint to agricultural development in most of the Sahel, with P being the most limiting nutrient for millet production on acid sandy soils. To address this issue, microdose applications of P fertilizer have been widely advocated in recent years. However, little is known regarding the effect of farmer management practices and environmental factors on millet's yield response to this technique. For this purpose, 276 farmer demonstrations were setup across a 3-year period in the Fakara region, western Niger. Five strata were considered based on antecedent organic manure management (corralling or transported manure). At each demo site, conventional management was compared to basal microdose fertilizer application of DAP (2 g hill^{-1}), NPK (6 g hill^{-1}), or DAP (2 g hill^{-1}) with urea (1 g hill^{-1}) applied at tillering. Millet grain yields on control plots were low (84% < 400 kg ha^{-1}), reflecting the unfavorable environmental conditions of the area. On average, the application of DAP, NPK and DAP + urea increased grain yields by 43, 46 and 69 kg ha^{-1} (2001–2002). A positive response to microdose fertilization was observed for 92% of the sites where yields on control plots were <100 kg ha^{-1} but only for 32% of the sites where yields on control plots were >500 kg ha^{-1}. In particular, the positive response to microdosing increased with later sowing given that late sowing tended to reduce yields on control plots. Higher rainfall during the early growing season favored a positive response to microdosing. On average over DAP and DAP + urea, 36% of the demonstrations had value-cost ratios (VCR) < 1. However, for low yielding control plots (<200 kg grain ha^{-1}), 26% of the demonstrations had VCR < 1, whereas for high yielding plots (>400 kg grain ha^{-1}), 55% had a VCR < 1. Not accounting for labor, DAP and DAP + urea had similar economic returns. The use of NPK could not be recommended as the cost per unit P is 3 times higher than DAP. It appears that, for the Fakara study area, microdosing may best be targeted to areas with low expected yields. In particular, it may serve as a famine mitigation strategy in case of late sowing. Nevertheless, for poorly endowed areas such as the Fakara, the economic risk associated with microdosing (2 g DAP hill^{-1}) appears higher than has hitherto been reported and widespread adoption may not be warranted without institutional support.

1. Introduction

Due to a high population growth rate (approx. 3.7% per annum for the 2000–2012 period), agricultural land in many areas of Niger has become a limiting factor to sustain the rapidly increasing food demand. Agricultural systems are now in transition (Cour, 2001; Raynaut, 2001), leaving to rural populations the option to either intensify and increase the productivity of the land, or to complement their needs through contracted farm labor, off-farm activities and seasonal migration.

Agricultural production in Niger is predominantly rainfed. Subsistence farming, which is still practiced by the vast majority of farmers, is often confronted with low and declining soil fertility (Bationo and Mokwunye, 1991; Sanchez et al., 1997). Traditional soil fertility restoration practices are no longer sufficient to maintain soil fertility. Fallow periods and fallow/cropland ratios have been drastically reduced. Animal manure, which constitutes a major source of nutrients for staple crops such as sorghum and millet in these mixed crop-livestock systems, is not available in quantities large enough to fertilize all fields at appropriate levels, such that only a small fraction of the cropped area benefits from it (Powell et al., 1996). Other sources of organic amendments

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(e.g., crop residue) are in short supply and suffer from competing uses such as cattle feed, fuel or construction material (Achard and Banoin, 2003; Baidu-Forson, 1995; Valbuena et al., 2012).

Given this situation, the recourse to external nutrient inputs to complement the traditional soil fertility management practices appears inevitable in order to increase or simply to maintain system productivity. Whereas more densely populated areas in south-central Niger with access to the large Nigerian market have to some extent already intensified their cereal production through the use of mineral fertilizer (Mortimore et al., 2001), a majority of rural households do not rely on mineral fertilizers to increase cereal yields (World Bank, 2014). Broadcast application of fertilizer in combination with organic amendments has shown its effectiveness at increasing yields in controlled experiments as well as on-farm demonstrations (Bationo and Mokwunye, 1991; Bationo et al., 1993), but this technique has not been widely adopted by farmers. Reasons for this include low fertilizer availability, high cost of fertilizers relative to millet price, limited market access for the produce, limited cash availability for buying inputs and high risk of low or even negative returns on investment (Abdoulaye and Lowenberg-DeBoer, 2000; Abdoulaye and Sanders, 2005). Consequently, researchers have investigated alternative fertilization techniques which rely on smaller quantities of placed mineral fertilizers targetting in priority the most limiting element, i.e., phosphorus (Buerkert et al., 2001; Payne et al., 1991).

Also referred to as 'microdosing', 'microfertilisation' or 'point placement', hill-placed application of small quantities of mineral fertilizer at sowing, typically 0.3 to 6 g hill^{-1} of NPK or 0.3 to 2 g hill^{-1} of DAP, has shown promising results in both on-station and on-farm trials conducted in Niger (Aune et al., 2007; Bationo et al., 1998; Buerkert and Hiernaux, 1998; Buerkert et al., 2001; Muehlig-Versen et al., 2003; Rebafka et al., 1993). Besides reducing the quantity of fertilizer to be applied and hence the financial investment, the microdose technique inherently adjusts application rates to sowing densities, as opposed to broadcast fertilization. This is important in the Nigerien context as sowing densities in farmer's fields can be highly variable (1300 to 12,500 hills ha^{-1}; Bationo et al., 1992). Compared to broadcast fertilizer applications, P use efficiency is greatly increased with microdosing. Because various trials demonstrated strong positive effects on yields and high returns on investments (Pender et al., 2008), the microdose technique has been referred to as the second of a 4-step agricultural intensification pathway for Sub-Saharan Africa (Aune and Bationo, 2008; Twomlow et al., 2008), and has been promoted accordingly.

The first results of large scale on-farm fertilizer microdose trials in the Sahel were reported by Buerkert et al. (2001). Hill-placed applications of 0.4 g P hill^{-1} in the form of NPK (15–15–15; 6 g hill^{-1}) or DAP (18–46–0; 2 g hill^{-1}) were tested over a 2-year period on a total of 199 field demonstrations in the Maradi, Dosso and Say regions (south west Niger). The average yield increase was 120% over the unfertilized control for both DAP and NPK. In subsequent studies, millet grain yield increases ranging from an average of 4% (Camara et al., 2013) to an average of 144% (Aune et al., 2007) have been reported as a result of microdose fertilization demonstration trials in Mali, Niger and Burkina Faso. In Niger, mean yield increases of up to 320 kg ha^{-1} have been reported from demonstration trials (Bationo et al., 2005).

Although most existing studies reported substantial increases in mean millet grain yields, few studies actually reported on the variability of crop response to microdose fertilizer applications within a given region. This is surprising as such information is crucial with respect to evaluating risk, a central criterion in famers' decision making in rainfed subsistence farming in the Sahel. Mean responses, however good, do not convey this information. Buerkert et al. (2001) analyzed the distribution of millet responses to microdosing. Yields in microdose fertilized plots were almost always higher than in control plots. Yield increases ranged from 0 to 2000 kg ha^{-1} depending on the demonstration plot. Buerkert et al. (2001) reported that the probability of achieving lower net returns on microdose plots than on control plots decreased as the yield on the control plots increased. On low productivity plots, there was a >50% probability to achieve lower net returns on the microdose plots than on the control plot. Tabo et al. (2011) also plotted yield distributions, with responses varying from slightly negative to yield increases of the order of 900 kg ha^{-1}. Bationo et al. (2005) reported an even larger variability in millet responses to microdosing, from 0 to 1500 kg grain ha^{-1} in excess of yield on control plots. However, neither Tabo et al. (2011) nor Bationo et al. (2005) analyzed the economic risk of microdosing per se.

It is apparent from the above-mentioned studies that even for control plots with very similar productivity levels (e.g., Fig. 9 in Buerkert et al., 2001), the response to P microdose fertilization can be highly variable. This variability may stem from different combinations of environmental (such as soil type, rainfall distribution, pest and disease) and management factors (such as antecedent fertility management, sowing density, plant variety, sowing date, and weeding dates), yet this has hitherto not been investigated. Understanding the sources of variability would be highly desirable when defining the recommendation domain of the technology within a given agro-ecological zone. Questions such as "Should the technology be applied preferentially to low/high fertility plots within a farm?", "How does the technology respond to differences in climatic conditions within the same agro-ecological zone?", "How does the technology interact with farmer management practices?" remain largely unanswered. The interaction between microdosing and manure management is of particular importance. Indeed, manure application has become the principal means for soil fertility restoration applied by farmers in western Niger (Powell et al., 1996). This is achieved through transportation of manure to the fields, or through direct corralling of livestock in the fields with residual effects extending over several years (Gandah et al., 2003; Powell et al., 1996).

The objectives of the present study were therefore (1) to investigate whether the performance of microdose fertilization is affected by the farmer's organic manure management in previous years; (2) to determine to what extent locally variable environmental and management factors affect the response to microdose fertilization; and (3) to evaluate the economic risk associated with P fertilizer microdosing based on the distribution of value-cost ratios. For this purpose, on-farm demonstration trials of microdose fertilization were monitored across a 3-year period in the Fakara region of Niger. Besides millet grain yield, information was collected regarding soil, daily rainfall and farmer management practices.

2. Materials and methods

During three consecutive rainy seasons (2000–2002), a series of simple demonstrations were established in collaboration with voluntary farmers spread across an area of approx. 500 km^2 in the Fakara region of south–western Niger, 80 km east of the capital Niamey (Fig. 1). The region was selected because of the abundance of bio-physical and socio-economic data available in various spatial databases (Hiernaux et al., 2009; La Rovere et al., 2005; Schlecht et al., 2004).

The climate is tropical semi-arid with a single rainy season occurring between mid-May and early-October. The mean annual rainfall for the zone is 470 mm with high inter-annual variability and possible dry spells of a few weeks during the season. The soils are sandy, with low water holding capacity and low inherent soil fertility (Table 1).

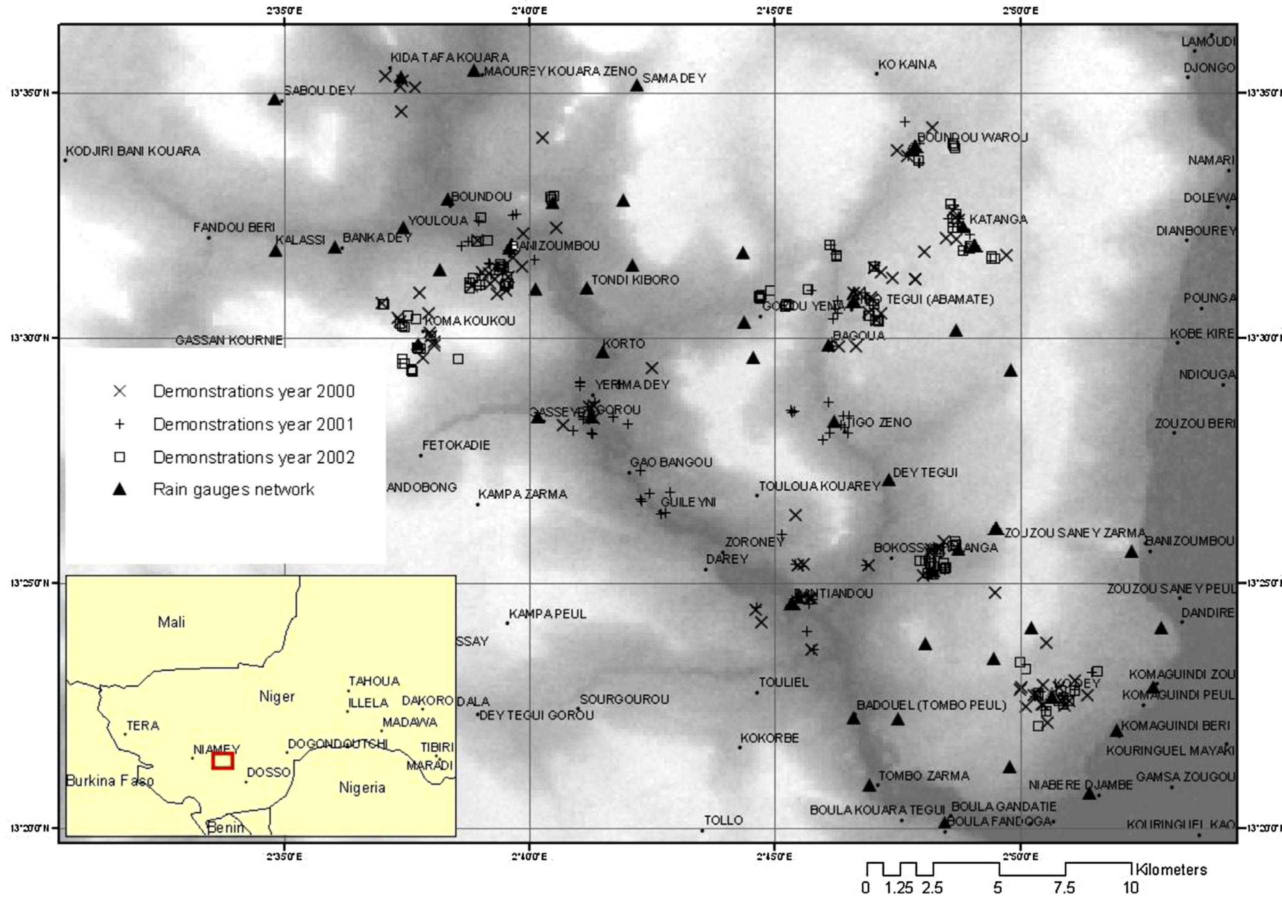

Fig. 1. Location of the Fakara in western Niger, major villages and distribution of rain gauges and demonstration sites.

2.1. Set-up of demonstrations

Field selection for the demonstrations was performed to cover a range of organic manure management practices (MANURE) followed by farmers in the area. Five antecedent manure management conditions were considered: (1) no manure (No-MAN); (2) manure transported to the field and applied in the previous dry season (Tr-MAN); (3) manure applied through night corralling during the preceding dry season (COR-0); manure applied through night corralling (4) one (COR-1) or (5) two years (COR-2) before the demonstration was established. Not all levels were present in all years. Distribution of demonstrations across the various management practices is given in Table 2.

In 2000, each demonstration consisted in 3 plots with the following fertilizer treatments (FERT): control, application of NPK fertilizer (15–15–15; 6 g of fertilizer per hill) or DAP (18–46–0; 2 g of fertilizer per hill) at sowing. Starting in 2001, an additional treatment consisting in the application of 2 g DAP per hill at sowing and 1 g urea (46–0–0) per hill at tillering was added. The rates of DAP and NPK were calculated so as to supply an equivalent quantity of P per hill (0.4 g P hill^{-1}). For a mean planting density of 6500 hills ha^{-1}, these microdose fertilization rates

Table 1
Soil types of the Fakara and their main characteristics.

Soil type	Arenic gleysol	Gleyic arenosol	Leptic lixisol	Arenic cambisol	Arenic lixisol	Ferralic arenosol	Skeletic leptosol
Topography	Valley	Valley	Down-slope	Flats	Mid-slope	Up-slope	Plateau
Landform	River bed	Alluvial deposit	Erosion surface	Colluvial fan	Sand deposit	Eroded deposit	Plateau cliff
Depth (cm)	>300	>300	20–80	>300	>300	10–50	0–10
Texture 0–30 cm (%)							
Coarse sand	2–5	45–48	40–50	45–50	40–50	34–36	32–35
Fine sand	35–40	40–45	35–40	38–42	40–50	50–53	32–38
Silt	30–35	2–3	5–8	3–5	2–3	4–7	5–8
Clay	15–25	6–12	7–12	5–10	2–5	4–8	12–17
Chemical properties							
pH	5.5–6.3	5.0–5.3	5.0–5.5	4.5–5.5	5.2–6.2	5.0–5.9	5.0–6.0
CEC (cmol$_c$ kg^{-1})	5.0–7.0	1.5–2.0	2.0–2.5	1.0–2.0	0.8–1.2	1.0–1.2	2.0–2.5
SOM (%)	0.4–0.8	0.1–0.25	0.25–0.35	0.2–0.7	0.12–0.17	0.15–0.30	0.1–0.5
Total P (mg kg^{-1})	2.5–5.0	1.5–2.0	1.2–2.5	1.5–2.0	1.5–3.5	0.7–1.5	2.5–5.5

Sources: Hiernaux and Ayantunde (2004).

Table 2
Number of field demonstration sites per MANURE treatment.

	2000	2001	2002	Total
No-MAN	69	28	22	119
Tr-MAN	7	30	19	56
COR-0	12	22	17	51
COR-1	N/A	22	15	37
COR-2	N/A	N/A	16	16
Total	88	102	89	279

No-MAN: no manure, Tr-MAN: transported manure, COR-0: manure applied through corralling in the previous dry season, COR-1 and COR-2: manure applied through corralling 1 and 2 years before, respectively. N/A: not applicable.

correspond to 2.3 kg N and 2.6 kg P ha^{-1} for DAP; 5.9 kg N, 2.6 kg P and 4.9 kg K ha^{-1} for NPK; and 5.3 kg N and 2.6 kg P ha^{-1} for DAP + urea. Plots were contiguous and had dimension of $20 \times 30\ m^2$. None of the previous year demonstrations were selected the following year to avoid possible residual effects of mineral fertilizer.

Voluntary farmers were identified through local farmer organizations, and training on hill-placed application of fertilizer was given each year by FAO-Projet Intrants staff before the onset of the rainy seasons. Research assistants and farmers jointly performed the delineation of demonstration plots to have demonstrations of uniform plot size. The demonstrators (farmers) managed fully their demonstrations from planting to harvesting, and the role of research was limited to the monitoring of the management practices and the measurement of grain yield at harvest. The choice of sowing, weeding, thinning and harvest dates as well as sowing density were left to each individual farmer demonstrator. For a given demonstration, sowing, weeding and harvest dates were identical across FERT treatments but sowing densities could vary since sowing is done manually and farmers do not use a fixed spacing between planting holes. All plots were sown with the local millet variety known as Haini Kiré.

2.2. Crop data collection

The data collected for each demonstration were: sowing and harvesting dates, sowing density, first and second weeding dates, and grain yields. Grain yields were estimated from the total air-dried weight of harvested millet heads per plot and millet grain/millet head ratio derived from a 2 kg air-dried millet head sub-sample per plot. From these data two additional indicators were calculated: time between sowing and first weeding and time between first and second weeding.

2.3. Rainfall and weather monitoring

Depending on the year, 49 to 62 geo-located rain gauges were installed throughout the landscape to monitor and record individual rainfall events (Akponikpè et al., 2011). Rainfall was measured by voluntary villagers recording water levels from gauges on paper tapes, which were later collected and encoded by a technician as rainfall amounts in a spreadsheet. To each demonstration site, rainfall from the nearest rain gauge was attributed (Fig. 1). Besides total rainfall during the growing period (sowing to harvest), different indicators of rainfall were used: cumulative rainfall (1) prior to sowing, (2) between sowing and 1st weeding, (3) between sowing and flowering, set at 80 DAS, (4) between flowering and harvest, (5) during the 1st third, (6) 2nd third, and (7) 3rd third of the growing period.

2.4. Spatial data processing

The objective of the spatial data processing was to explain grain yield variability and millet response to microdose fertilization as a function of spatially variable environmental factors. For that purpose, demonstrations were georeferenced. Analysis in ArcGIS 9.1 allowed obtaining the following spatial variables for each demonstration: distance from the nearest village, altitude and slope derived for SRTM Digital Elevation Model (www.srtm.usgs.gov), landscape position, and soil status.

Landscape position was assessed using the geomorphological map of Hiernaux and Ayantunde (2004) and visual interpretation of satellite images (Google Earth, 15/01/2010), distinguishing between plateaus, mid- and down-slope sandy skirts, up-slope glacis and valley bottoms. Soil status referred to three conditions: leached, which refers to whitish sands (as opposed to brownish or reddish) generally but not exclusively found in valley bottoms; degraded, referring to severe signs of erosion or tramping; and brownish or reddish soils neither leached, nor degraded.

2.5. Risk analysis

Risk was assessed on the basis of the probability of achieving a certain value-cost ratio (VCR) for a given type of fertilizer. VCR was computed as the difference in grain yield between the fertilized and the control plot multiplied by the unit market price of grain, divided by the cost of applied fertilizer. Cost of fertilizer was taken as 13,500 FCFA per 50 kg bag irrespective of the type of fertilizer (Réseau régional des chambres d'agriculture du Niger, 2011). These prices are fixed by the Nigerien government. For the millet price, we used the 5-year average (2008–2013) market price of millet in Niamey (FEWS NET, 2014). Prices are provided on a monthly basis and fluctuate between a minimum of 200 FCFA kg^{-1} in October and a maximum of 270 FCFA kg^{-1} in July–August. Mean yearly price is 240FCFA kg^{-1} (1 euro = 655 FCFA).

2.6. Statistical analysis

Statistical analyses were performed using R version 2.15.2 (R Development Core Team, 2012) in several steps:

Prior to analysis, data were carefully checked using descriptive statistics, boxplots and correlation analysis. Square root transformations were applied to yield and sowing density data to ensure normality. Only complete datasets (no missing data) were retained. Some very poorly represented combinations of factors were discarded as well (demonstrations on plateaus; demonstrations on non-leached, non-degraded valley sites).

First, an analysis of variance was performed to assess the effect of FERT and MANURE on millet grain yield. The model explicitly took into account between-demonstration site variation (i.e., MANURE) and within-demonstration variation (i.e., FERT). Because the DAP + urea treatment was only applied in 2001 and 2002 and because not all MANURE treatments were present in all years, the analysis was carried out on a year by year basis. Analyses were performed using the 'Anova' commands in package 'car' in R. Given the unbalanced design, both type II (no interactions) and type III (in case of interaction) Anova were considered. Both approaches lead to the same interpretation of results.

In order to further elucidate the relationship between yield data on one hand, and FERT, MANURE and other management or environmental variables on the other hand, statistical analysis was performed using the Generalized Linear Model (GLM) approach. The 'glmulti' command in package 'glmulti' was used to identify through stepwise multiple regressions the combination of variables leading to the highest Akaike information content index

Table 3
Descriptive statistics of major variables used in statistical analyses (2000–2002, all data).

Variable	Units	Median	Mean	SD	Min	Max
Yield	kg ha^{-1}	260	295	192	0	1145
Density	hills ha^{-1}	6350	6530	1703	1950	15,670
Sowing date	DOY	160	166	14.4	126	199
Interval between sowing and first weeding	Days	21	21	7.1	3	45
Interval between sowing and 2nd weeding	Days	56	57	11.4	27	91
Length of growing period	Days	108	108	9	71	134
Slope	%	1.45	1.57	0.92	0.20	5.44
Annual rainfall	mm	410	417	80	267	580

(AIC). A similar regression analysis was performed using millet yield response to microdose fertilization (mean of NPK and DAP plots) as independent variable. Both regressions were based on the 2000–2002 No-MAN, Tr-MAN and COR-0 data.

3. Results and discussion

3.1. General characteristics of the dataset

During the 3 experimental years, cumulative rainfall during the growing period (sowing to harvest) ranged from 219 mm to 559 mm (Table 3). This range covers the low to medium range of rainfall conditions observed in the region. Most of the variability in rainfall resulted from spatial rather than temporal variability. Spatial patterns were strongly variable from year to year (Akponikpè et al., 2011).

Millet was generally grown on land with gentle slopes (1.6 ± 0.9%, mean ± SD) and across a narrow range of altitudes (230 ± 15 m; Table 3). On average, plots were distant from 1050 ± 790 m from the nearest village. Two hundred and eleven demonstrations were located on sandy skirts, 36 on glacis, and 29 in valleys. This is consistent with the fact that the sandy skirts are predominantly used for millet cropping.

Sowing occurred on average around mid-June, but ranged anywhere between end of May and mid-July (Table 3). In 2000, sowing occurred on average 30 days later (DOY 188) than in 2001 (DOY 159) and 2002 (DOY 158). This reflects the high spatial and temporal variability in rainfall at the start of the rainy season. In addition, farmers may not always have the manpower to sow all their fields at the first suitable event, and hence may have to delay sowing for certain fields. Resowing due to seedling emergence failure was observed in only a few cases.

The first weeding occurred on average 21 ± 7 days after sowing (Table 3). It did not differ across years and was not correlated to the date of sowing. The second weeding took place on average 57 ± 11 DAS (Table 3). The interval between sowing and second weeding decreased significantly with later sowing (P < 0.001). Neither interval (sowing to 1st weeding, sowing to 2nd weeding) was significantly affected by MANURE treatment, indicating that the date of weeding was not influenced by prior fertility management. Weeding is the main constraint for farmers in terms of manpower requirement (10 person day ha^{-1}). As a result, the weeding dates are spread over a rather wide period, with potentially negative effects on crop productivity because of weed competition when weeding is undertaken late. The length of growing period (sowing to harvest) was 108 ± 9 days on average (Table 3), independently of the year and consistent with the planted variety. Later sowing resulted in significantly shorter length of growing period (P < 0.001).

Sowing density averaged 6500 hills ha^{-1}, ranging from approx. 2000 to 15,000 hills ha^{-1} (Table 3). The sowing density recommended by research is 10,000 hills ha^{-1}, with 3 plants per hill. The low average sowing density compared to the recommended densities are consistent with previous studies in the region and most likely reflects the overall low fertility of the soils of the Fakara. Anova revealed that there was no MANURE or FERT effect on density, i.e., there was no indication that farmers systematically adjusted planting density either to the FERT treatment, or to the MANURE level. In general, differences in mean density across FERT treatments in a given demonstration did not exceed 450 hills ha^{-1}. There was, however, a significant interaction between these two factors (P = 0.02). In the COR-0 plots, densities were significantly higher in the control plots (6900) than in the NPK plots (6170), with intermediate values for DAP (6550). As this was not observed in any other MANURE treatment, it seems unlikely that this resulted from a deliberate strategy. In spite of this interaction, one may conclude that there were no systematic and sufficiently large differences in planting density across treatments (FERT or MANURE) that could have confounded the results given the limited differences in densities within a given demonstration. It must be noted, however, that low planting densities never led to high yields, irrespective of the MANURE or FERT treatment. It appears that a minimum density of 5000 hills ha^{-1} was needed to achieve the highest observed yields (>800 kg ha^{-1}; not shown).

3.2. Millet yield

The combined effects of the MANURE and FERT treatments as well as the wide range of environmental and management conditions resulted in a wide range of grain yields (Table 3). Average yield was 295 kg ha^{-1}, which is low but consistent with national statistics (FAO, 2012). In 84% of the plots, yields were <400 kg ha^{-1}.

Anova of the millet grain yield data revealed significant MANURE and FERT effects for all years separately (Table 4). Yields consistently increased in the following order: No-MAN < Tr-MAN < COR-2 < COR-1 < COR-0. There was no interaction between

Table 4
Effect of organic manure (MANURE) and microdose fertilization (FERT) on millet grain yield. Anova was performed on square root transformed yield data.

	Millet grain yield (kg ha^{-1})		
	2000	2001	2002
MANURE[*]			
No manure	226a	174a	193a
Transported manure	287ab	279b	265b
COR-0	430b	401c	481c
COR-1	N/A	298b	435cd
COR-2	N/A	N/A	390d
P value	<0.01	<0.001	<0.001
FERT[*]			
No fertilizer	184a	240a	301a
DAP	309b	285ab	341ab
NPK	282b	288ab	344ab
DAP + urea	N/A	309b	370b
P value	<0.001	<0.001	<0.001

[*] Treatments followed by the same letter in the same year are not significantly different at P = 0.05. N/A = not applicable.

Table 5
Optimal linear regression model using the square root of millet grain yield as independent variable. (Data are from 2000–2002.).

Model: sqrt(yield) = f(MANURE + FERT* SowDate + sqrt(PlDens):LastSow + IntSowW1 + year + distance + slope + Rain_before_sow + Rain_Sow_Weed + village)

Coefficients

	Estimate	Std. Error	*t* Value	Pr(>|*t*|)
(Intercept)	9.117e+01	8.455e+00	10.783	<0.001***
COR-0	6.943e+00	4.503e-01	15.419	<0.001***
Tr-MAN	2.877e+00	4.374e-01	6.577	<0.001***
DAP	−1.614e+01	4.269e+00	−3.780	<0.001***
NPK	−1.163e+01	4.273e+00	−2.722	<0.01**
SowDAte	−5.088e-01	5.032e-02	−10.111	<0.001***
IntSowW1	−1.539e-01	3.361e-02	−4.579	<0.001***
2001	−1.112e+01	1.431e+00	−7.770	<0.001***
2002	−1.053e+01	1.461e+00	−7.205	<0.001***
Distance	−1.158e-03	3.207e-04	−3.609	<0.001***
Slope	5.173e-01	1.883e-01	2.747	<0.01**
Rain_before_sow	7.858e-02	1.499e-02	5.242	<0.001***
Rain_Sow_Weed	1.349e-02	6.360e-03	2.122	<0.05*
Village Banizoumbou	3.909e+00	1.518e+00	2.575	<0.05*
Village Boundou	5.868e+00	1.631e+00	3.599	<0.001***
Village Dantiandou	3.881e+00	1.546e+00	2.511	<0.05*
Village Falla	4.737e+00	1.674e+00	2.831	<0.01**
Village Gorou	6.998e+00	2.238e+00	3.127	<0.01**
Village Guill	1.070e+01	2.208e+00	4.848	<0.001***
Village Katanga	8.912e+00	1.739e+00	5.124	<0.001***
Village Kodey	3.484e+00	1.453e+00	2.398	<0.05*
Village Komakokou	7.208e+00	1.608e+00	4.482	<0.001***
Village Tchigo Tegui	6.239e+00	1.602e+00	3.895	<0.001***
Village TigoZ	2.072e+00	1.662e+00	1.247	>0.05
Village Yerim	5.475e+00	1.577e+00	3.471	<0.001***
DAP:SowDate	1.115e-01	2.499e-02	4.461	<0.001***
NPK:SowDate	8.327e-02	2.501e-02	3.330	<0.001***
SowDate:sqrt(Density)	6.285e-04	8.815e-05	7.130	<0.001***

Adjusted R-squared: 0.47

F-statistic: 23.27 on 27 and 644 DF, *P*-value: <0.001

* MANURE = No-MAN, Tr-MAN and COR-0; FERT = DAP and NPK.
SowDate = sowing date (DOY), PlDens = planting density (hills ha^{-1}), IntSowW1 = interval between sowing and 1st weeding (days), distance = distance from nearest village (m), slope = local slope (%), Rain_before_sow = cumulative amount of rainfall prior to sowing date (mm), Rain_Sow_Weed = cumulative amount of rainfall between sowing and 1st weeding (mm), village = nearest village to the demonstration.

MANURE and FERT, and no significant difference between DAP and NPK.

Across MANURE treatments, compared to unfertilized control plots, the response to microdose fertilization (NPK and DAP) was stronger in 2000 (+112 kg ha^{-1} = +61%) than in 2001 (+46 kg ha^{-1} = +19%) and 2002 (+41 kg ha^{-1} = +14%).

Since Anova revealed no significant difference between NPK and DAP microdose (Table 4), the mean yield of DAP and NPK plots was used to analyze the yield response to fertilizer microdose. Furthermore, since the GLM and linear model (LM) analyses led to identical results, results of the LM analysis are shown for convenience (Table 5). Overall, the linear model explained 47% of the total variance. Besides MANURE and FERT (27% of the total variance), a large number of management and environmental factors contributed to explain overall yield (20% of the total variance). The unexpected negative coefficients for DAP and NPK result from the significant interaction between FERT and sowing date (Table 5). On average, late sowing resulted in a decrease in grain yield, but this effect was noticeable only for the control plots (Fig. 2). Yields on microdose plots were insensitive to late sowing.

Besides late sowing, delayed weeding also negatively affected yields (Table 5), which is easily understood because of the strong competition between millet and weeds for water and nutrients. Yields tended to decrease with increasing distance from the village, which may reflect the fertility gradient around Sahelian villages. Yields also tended to increase with increasing slope but no sensible explanation could be found for this unexpected result. Sowing density interacted with sowing date. The negative impact of late sowing was stronger at low planting densities than at high planting densities, i.e., it appears that higher sowing densities were able to compensate in part for the yield loss expected from late sowing. Cumulative rainfall before sowing had a positive impact on yields. Finally, location ('Village') had a significant influence on yields. The latter seems to indicate that there were factors strongly influencing yields at the meso-scale that were not captured by the biophysical components of the regression model. Land use intensity and settlement dynamics are spatially contrasted in the studied area, partly reflecting the ease of access to groundwater. The cluster of villages around Kodey (South East Fakara) were established earlier and have a larger population density, leading to a higher land use pressure from crops and so lower proportion of fallow

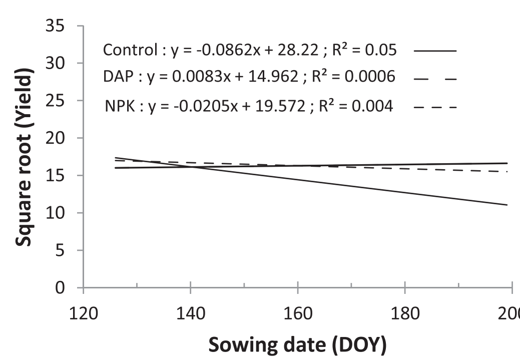

Fig. 2. Illustration of the Sowing date by FERT interaction on millet grain yield (see Table 4). Late sowing leads to lower yields only on control plots. (Data are from 2000–2002.) DOY = day of year.

Table 6
Optimal linear regression model using millet grain yield response to microdose fertilization as independent variable. (2000–2002 data).

Model: Δ(yield) = f(Sqrt(yield) + Rain_1third + Sqrt(PlDens))

Coefficients

	Estimate	Std. Error	*t* Value	Pr(>|*t*|)
(Intercept)	−6.1894	53.6288	−0.115	0.91 ns
Sqrt(yield)	−6.8497	1.3188	−5.194	<0.001***
Rain_1third	0.2207	0.1005	2.196	<0.05*
Sqrt(PlDens)	1.6176	0.6705	2.412	<0.05*

Adjusted R-squared: 0.14
F-statistic: 13.31 on 3 and 220 DF, *p*-Value: <0.001

* Δ(yield) = difference between millet grain yield in microdose plots (mean of DAP and NPK) and control plots. PlDens = planting density (hills ha^{-1}), Rain_1third = cumulative rainfall during the 1st third of the growing season at each demonstration site. Sqrt = square root.

fields leading to more nutrient depleted soils. The cluster of villages/hamlets around Bagoua–Tchigo Tegui (north east) have the lowest population density with somewhat longer and more frequent fallows and better access to manure and higher fertility soils. The Banizoumbou cluster of villages/hamlets (north west) has an intermediate situation.

Given that only 47% of the total variance could be explained, there appears to be additional factors varying across years which had a significant effect on yields which were not included explicitly in the model. These may be biotic factors affecting millet yield such as *Striga hermontica*, stemborrer, and heads bugs, but also climate-driven factors (e.g., drought stress) not well represented by the simple rainfall indices used here.

GLM and LM regression analysis of millet yield response to microdose (difference between microdose plots and control plots) revealed only three parameters of influence: square root of millet yield of control plot, square root of planting density, and rainfall during the 1st third of the growing season (Table 6). Rather than the type of manure management, it was the productivity of the control plot which best explained millet response to microdose fertilization (Fig. 3).

Microdose fertilization led to a wide range in yield responses (Fig. 3). Between 19% (DAP + urea) and 23% (NPK, DAP) of the microdose plots yielded less than the control plots. Furthermore, millet response to microdose tended to be systematically positive for low

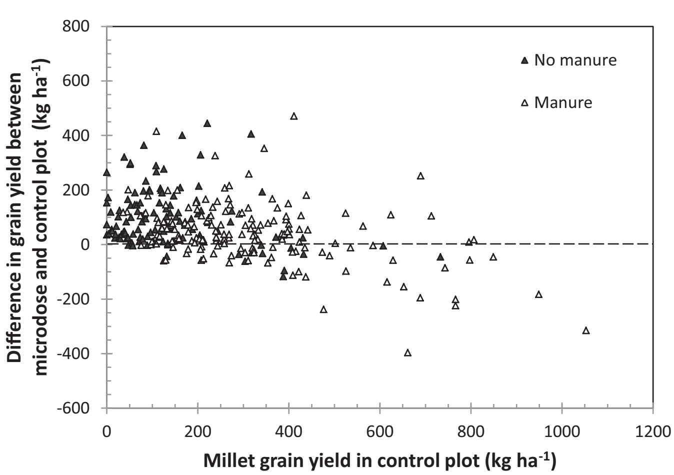

Fig. 3. Difference in grain yield between DAP or NPK microdose plots and the control plots, as a function of yield in control plots. Because yields in DAP and NPK microdose plots were not significantly different, the mean yield of these two treatments was used. (2000–2002, all data.) A distinction is made between no manure plots and plots having received manure in the previous seasons through corralling or transportation.

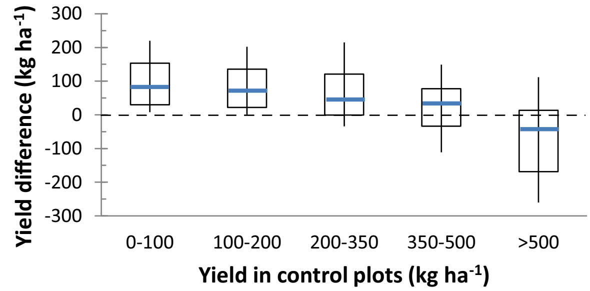

Fig. 4. Distribution of grain yield difference between microdose plots and control plots, as a function of yield in control plots. Yields in control plots are grouped by class. Because yields in DAP and NPK microdose plots were not significantly different, the mean yield of these two treatments was used. Boxes correspond to 10th, 25th, 50th, 75th and 90th percentile. (2000–2002, all data).

yielding control plots (<100 kg ha^{-1}), but for high yielding control plots (>800 kg ha^{-1}) the reverse was observed (Fig. 4). Sahelian agricultural fields are known to be characterized by high within field spatial variability (Stein et al., 1997). A negative response to microdose may thus occasionally result from high spatial variability among plots within the same demonstration. However, plot sizes were large (600 m^2), which should have limited the extent of between-plot variability. Furthermore, in the absence of response to fertilizer, one would expect the distribution of yield responses to be centered on 0. However, except for the 350–500 kg ha^{-1} class, the mean yield difference of all classes was significantly different from 0 at the 5% probability level (Fig. 4). This confirms that yields in low-yielding control plots significantly increased whereas yields in high-yielding control plots significantly decreased following microdose application of DAP or NPK.

3.3. Agronomic efficiency of fertilizers

Given that both the quantity of P applied and the yields were similar for the DAP and NPK treatments, the agronomic efficiency of P was similar. On average, the agronomic efficiency of P from DAP microdose was equal to 48 kg grain kg^{-1} P in 2000 and 16 kg grain kg^{-1} P in 2001 and 2002. For DAP + urea, P agronomic efficiency was higher, with 26 kg grain kg^{-1} P in both 2001 and 2002.

On a unit N basis, the agronomic efficiency of N was evidently much higher for DAP than for NPK since the amounts of N applied were lower for DAP yet yields were similar. N agronomic efficiency was 49, 20 and 17 kg grain/kg N for DAP in 2000, 2001 and 2002, respectively. For NPK, it was on average 19, 8 and 7 kg grain kg^{-1} N, respectively. The higher agronomic efficiency of N from DAP may in part result from the form of N fertilizer used. According to Rebafka et al. (1993), ammonium stimulates early root growth, which helps the plants make better use of available resources (water and nutrients, especially P). Even though NPK and DAP + urea supplied equivalent amounts of N and P, the N agronomic efficiency of DAP + urea (13 kg grain kg^{-1} N in 2001 and 2002) was higher than that of NPK. Besides the positive effect of ammonium on early root growth, the split application (DAP at sowing and urea at booting) may have resulted in smaller N losses by leaching compared to the one-time application of NPK at sowing.

3.4. Economic analysis

More important than yield increases are the financial returns and risk associated with the adoption of a technology. Because the quantity of microdose fertilizer applied depends on the planting density, the minimum yield increase required to compensate for the financial investment (VCR = 1) depends on planting density.

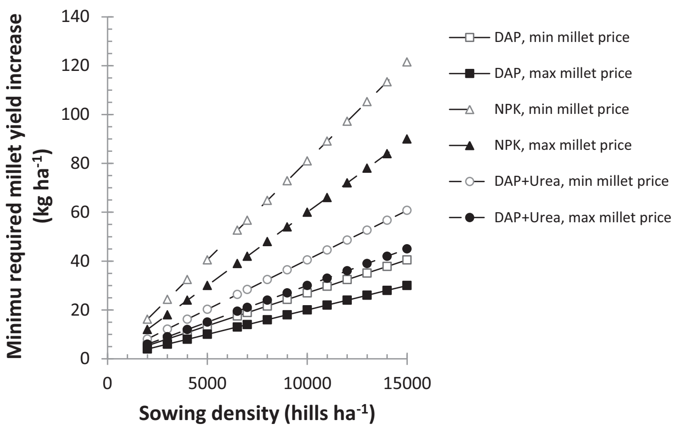

Fig. 5. Minimum millet grain yield increase needed to achieve a value-cost ratio of 1 following microdose applications of DAP (2 g hill^{-1}), NPK (6 g hill^{-1}) or urea (1 g hill^{-1}), as a function of planting density. Min. and max. millet prices are 200 and 270 FCFA kg^{-1} millet. Fertilizer price is 13,500 FCFA per 50 kg bag irrespective of fertilizer type.

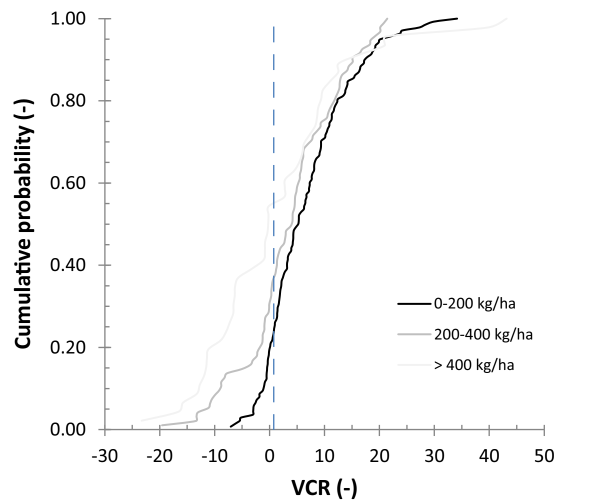

Fig. 6. Cumulative probability distribution of DAP microdose value-cost ratios (VCR) for three different classes of millet grain yields in control plots, based on a millet price of 240 FCFA kg^{-1}.

Depending on the millet price (Fig. 5), for an average planting density of 6500 hills ha^{-1}, DAP microdose would require a minimum yield increase of 13 to 17.5 kg ha^{-1}, NPK microdose would require 39 to 52.5 kg ha^{-1}, and DAP + urea would require a yield increase of 19.5 to 26.5 kg ha^{-1}. The required yield increase for VCR = 1 would evidently be higher for the recommended planting density of 10000 hills ha^{-1}.

In practice, one generally considers that the VCR should be at least 2 for adoption in developing countries, but VCR values of 3–4 may be required in risky environments (CIMMYT, 1988). This means that yield increases following microdose application should be at least twice, but ideally 3 to 4 times, the values reported in Fig. 5.

Table 7 and Fig. 6 present the distribution of VCRs for the entire datasets as well as for subsets as a function of grain yield in the control plots. Given that yield response to NPK was similar to that for DAP but the cost of NPK microdose fertilization per unit P was 3 times higher, the use of NPK for microdose fertilization cannot be recommended and the distribution of VCRs for NPK was not studied in detail.

It is apparent from Table 7 that 34 and 38% of the demonstration sites have a VCR < 1 both for DAP and DAP + urea, respectively. Between 40 and 51% of the demonstration sites had a VCR > 4. After ranking demonstration sites as a function of the yield of the control plots, it became apparent that the risk of having low VCR values strongly depended on the yield of the control plot. For low yielding control plot (grain yield <200 kg ha^{-1}), between 25% (DAP + urea) and 26% of the plots experienced a VCR < 1. Only between 48 and 56% of the plots had a VCR > 4. For higher yielding control plots, the risk of achieving a VCR < 1 increased, reaching between 54 and 56% for yields >400 kg ha^{-1}. For control plots yielding >400 kg ha^{-1}, only between 26 and 38% of fields presented a VCR > 4.

Table 7
Proportion of fields with value-cost ratios <1, 2 or 4 following DAP or DAP + urea microdose fertilization, for different millet grain yield classes in control plots. Millet price was 240 FCFA kg^{-1}.

Grain yield	Value-cost ratio			Nb of plots
	<1	<2	<4	
DAP	%	%	%	
All plots	34	41	49	279
0–200 kg ha^{-1}	26	34	44	138
200–400 kg ha^{-1}	38	44	50	95
>400 kg ha^{-1}	55	56	62	46
DAP + urea				
All plots	38	46	60	191
0–200 kg ha^{-1}	25	38	52	82
200–400 kg ha^{-1}	44	51	64	74
>400 kg ha^{-1}	56	58	74	35

4. General discussion

All three microdose fertilization strategies tested in this study supplied equivalent quantities of P, corresponding to 2.6 kg P ha^{-1} at a planting density of 6500 hills ha^{-1}. However, all treatments also supplied small quantities of N, and in the case of NPK, potassium. Regarding the latter, potassium is generally not considered a limiting nutrient for commonly encountered millet productivity levels in the Sahelian zone of Niger, in part because of substantial K inputs from Harmattan dust (Fofana et al., 2007; Herrmann et al., 1996).

In western Niger—where P is the most limiting element and the price per bag is the same for DAP and NPK—DAP should be largely preferred over NPK in microdose fertilization tests because yields were equivalent yet the cost per unit P of DAP is three times lower than that of NPK. Buerkert et al. (2001) also tested DAP and NPK. Though not explicitly analyzed, their results did not show any comparative advantage of one fertilizer over the other in terms of millet grain yield. The same conclusion was also reached by Bationo et al. (2005).

Not considering labor costs related to fertilizer application nor possible differences in weeding and harvesting time, DAP and DAP + urea appeared to bear similar financial risks (Table 7). On average, the somewhat higher yields observed on DAP + urea plots compared to DAP alone just about compensated for the higher financial investment. The probability of achieving VCR < 1 was similar for both fertilization strategies (Table 7). Hence, it would seem preferable to work with DAP rather than DAP + urea as it requires a smaller initial financial investment on behalf of the farmer. Furthermore, the split application of urea requires additional labor at a time of peak demand for weeding, which is not compensated for by the small additional yield increase.

The mean millet yield response to microdose fertilization in the present study (Table 3) was substantially lower than what has been reported previously for on-farm demonstrations in Niger for the same fertilizers at the same rates. Bationo et al. (2005) reported a millet yield increase from 400 kg ha^{-1} in control plots to 720 kg ha^{-1} after application of fertilizer microdose (2 g DAP or 6 g NPK). Hayashi et al. (2008) and Bagayoko et al. (2011) reported similar increases for similar yields in control plots. Tabo et al. (2009) reported that grain yield was increased on average by 44% (+300 kg ha) following the application of NPK or DAP + urea. However, planting densities in the latter study where 2 to 4 times lower in control plots than in microdose plots such that the yield increase may not solely reflect fertilizer microdosing. In the present study, average yield increases ranged between 40 and 125 kg ha^{-1} depending on the year and fertilizer used (Table 4). The reasons for the lower response to microdosing in our study (Fig. 4) are unclear and would require further investigation.

For the first time, it has been observed that millet's yield response to microdose fertilization may be dependent on the plot's productivity level (Fig. 3). Indeed, on low productivity plots, yields can easily be doubled on average, whereas on high productivity plots no or even negative responses were observed (Fig. 4). Previous studies did not explicitly investigate this aspect but data presented by Buerkert et al. (2001), Bationo et al. (2005) and Tabo et al. (2011) do not provide any clear indication that this was the case in their studies. This discrepancy between the present study and previous studies may possibly partly result from the choice of demonstration sites. Indeed, previous studies did not explicitly consider different antecedent manure management strategies in the selection of demonstration sites. As shown in Table 4, previously manured demonstration sites, especially recently corralled sites, had higher yields on average than unmanured demonstration sites. Fig. 3 confirms that high yielding control plots are mostly manured demonstration sites. Though not measured in the present study, mean manure application rates through corralling are of the order of 10 t dry matter ha^{-1} with maximum values up to 30 t ha^{-1} (Brouwer and Powell, 1998; Michels and Bielders, 2006). It has been shown that such quantities supply many times the nutrient requirements of millet, with residual effects lasting for several years (Brouwer and Powell, 1998; Esse et al., 2001; Powell et al., 1998; this study). In addition, the application of urine during corralling increases P availability to millet. It is therefore to be expected that on manured plots, millet P requirements would be largely satisfied by the previous manure application, such that the addition of a small quantity of P through microdose fertilization would have little impact. The more manure has been added (corralling > transported manure), and the more recent the application, the less one expects a response to P microdose fertilization. It remains unclear, however, why high yielding plots in previous studies responded well to P microdose fertilization since P deficiency is not expected on such plots.

Based on Table 6 and Fig. 4, P microdose fertilization should not only be targeted preferentially to low fertility fields or parts of fields, but to all fields or parts of fields where low yields are expected. Low yields may result not only from low soil fertility, but also from the use of inadequate quantities or poor quality manure, from low planting densities, or from late sowing, for instance (Table 5 and Fig. 2). This strategy is consistent with farmer's current soil and crop management strategies, that aim at reducing the risk of crop failure and which target organic amendments preferentially to low fertility spots (Buerkert et al., 2000).

The latter finding has interesting implications for a region such as the Sahelian zone of Niger that is affected by large inter-annual fluctuations in millet production and frequent food insecurity. Indeed, when low millet production can be traced to factors that are known before sowing occurs, such as late sowing (Fig. 2), microdose fertilization could prove to be a more cost effective and less market-destructuring strategy for famine mitigation than conventional post-harvest food aid. At the national scale, regions affected by late sowing can easily be identified in real time through existing networks, including farmer associations. At those locations, large scale distribution of P fertilizer for microdose application would be a much cheaper alternative to food aid as each kg of fertilizer increased millet grain yields on average by 3.3 (2001 and 2002) to 9.6 kg (2000). In financial terms, at market price, this means that investing in 1 kg of DAP fertilizer (270 FCFA) can save the equivalent of 792 to 2304 FCFA in food distribution (240 FCFA kg^{-1} millet), with additional savings expected from food aid transport, handling and distribution costs. By targeting low fertility plots not previously manured, the returns could be even higher.

Despite such promising applications of P microdose fertilization, it is apparent from the present study that under the environmental conditions of the Fakara region this fertilization strategy still bears a high risk for farmers. On high productivity plots (yield > 400 kg ha^{-1}), more than 50% of the demonstrations experienced VCR values <1 (Table 7). Including labor costs in VCR calculations would make the technology appear even more risky. Blanket recommendations of 2 g DAP hill^{-1} microdose fertilization may therefore prove counterproductive in the study region, and site specific recommendations should be preferred based on expected yields. However, even on low productivity plots (yield < 200 kg ha^{-1}) on which the response to microdosing is expected to be highest, negative returns on investment (VCR < 1) were observed in 26% of demonstrations for DAP and 25% of demonstrations for DAP + urea (Table 7). These results are not in accordance with the results of Buerkert et al. (2001) who reported that the risk associated with microdose fertilization was highest for demonstration sites with a low environmental mean yield, which warrants further investigation. Based on the present results, institutional support may be required to push adoption of microdose fertilization (2 g DAP hill^{-1}). Alternatively, lower rates of microdose fertilization could be tested. Better economic returns of microdosing have been obtained in Mali (Aune et al., 2007) or Sudan (Aune and Ousman, 2011) with 0.3 g fertilizer per hill, which can be achieved by mixing seeds and fertilizer in a 1:1 ratio before sowing. In addition, the latter practice saves on labor costs at sowing, since seed and fertilizer can be applied simultaneously, something that is not feasible with the rate of 2 g fertilizer per hill. The technique can be further enhanced through seed priming (Aune and Ousman, 2011).

On the basis of the dataset, 27% of the variance in millet grain yields could be explained by the experimental treatments (MANURE and FERT), and 20% by environmental and management factors, some of which are proxies that are most likely related to the status of soil fertility or degradation (e.g., 'Distance from village', 'Village'; Table 5). Hence, although management and environmental factors did help explain a non-negligible fraction of the total variance in yields, large sources of unexplained variation remain. Among these are climatic factors not well captured by cumulative rainfall amounts, insufficient characterization of soils as well as poor control over the rates of manure applied in manured plots.

5. Conclusions

The 279 demonstrations carried out over a three-year period for a wide range of manure management conditions revealed a very large variability in millet yield response to P microdose fertilization. P microdosing was most effective at demonstration sites with low yielding control plots, but even at such sites the technique bears a non-negligible financial risk. For control plots yielding >400 kg ha^{-1}, more than 50% of plots had negative returns on investment and the technique should therefore not be recommended at such locations. Based on the results of this study, the application of 2 g of DAP at sowing should be the preferred choice of microfertilization, as NPK is three times more expensive per unit P with no yield benefit compared to DAP, and the addition of 1 g of urea at tillering bears a similar financial risk than DAP but requires more labor and a larger initial financial investment.

At sites were low yields are expected, as for instance in the case of late sowing due to a late start of the rainy season, DAP microdose fertilization could prove to be a valuable, cost-effective addition to conventional famine mitigation strategies. In general, farmers would be well advised to target microdosing preferentially to fields or parts of fields that have low fertility, which is consistent with their traditional soil fertility management strategies.

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