Field Crops Research 230 (2019) 139–150

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Variability in maize yield and profitability following hill-placement of reduced mineral fertilizer and manure rates under smallholder farm conditions in northern Benin

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ARTICLE INFO

Keywords:
Microdose fertilization
Maize yield response
Management and environmental factors
Northern Benin
Profitability

ABSTRACT

Whereas the decision to promote a given agricultural intensification technology has hitherto been largely based on its average agronomic or economic performance, it is increasingly being recognized that the variability in the performance must also be taken into account in order to develop more meaningful and flexible recommendations. This is true in particular for microdose fertilization which is being actively promoted in sub-Saharan Africa as a means to increase crop productivity, profitability and fertilizer use efficiency. To this end, a total of 51 on-farm maize trials were carried out in northern Benin in 2014 and 2015. The performance of two microdose fertilization options (MD1 = 23.8 kg N, 4.1 kg P, and 7.8 kg K ha^{-1}; MD2 = 33.1 kg N, 8.2 kg P, and 15.6 kg K ha^{-1}) applied alone or combined with hill-placed manure (FYM) at 3 t ha^{-1} was compared to an unfertilized control and a broadcast fertilizer treatment at the recommended rate (RR; 76 kg N, 13.1 kg P, and 24.9 kg K ha^{-1}). On average, microdose fertilization alone increased maize grain yields by 1145 kg ha^{-1} (+105%), compared to the unfertilized control (1096 kg ha^{-1}). There was no significant difference in yields between MD1, MD2 and RR in both years. Combining microdose fertilization with manure further increased yields by 848 kg ha^{-1} (+40%) on average. There was a large variability in yields among farmers, from 420 to 1687 kg ha^{-1}, 1419 to 3418 kg ha^{-1} and 1834 to 4475 kg ha^{-1} for the control, sole microdose (MD1 and MD2) and microdose + FYM treatments, respectively. Variability tended to be lowest in the control treatment. Absolute yield response to microdose fertilization tended to decrease with increasing yields in the control plots and was well explained by the combination of some measured soil parameters (clay and/or silt, total carbon, exch-Mg, pH) and weed pressure. Based on the value-cost ratio (VCR), the economic performance of the RR treatment was less than that of the microdose treatments (alone or combined with manure) despite the higher labor cost associated with the latter treatments. MD1 should be favored over MD2 because yields were not significantly different yet the risk of achieving low VCRs was lower in MD1. Despite the greater variability compared to the control, the risk of no return on investment was nearly nil for MD1 (6%) and MD1 + FYM (2%) as a result of the strong increase in yield. Despite the overall good performance of fertilizer microdosing, more effort is needed to better understand crop response to microdose fertilization for a broader range of environmental conditions in Benin in order to fine tune recommendation domains.

1. Introduction

Microdose fertilization was introduced less than two decades ago as a means to increase crop productivity in the low-input, rainfed cropping systems of Sub-Saharan Africa (SSA) where farmers face severe challenges related to the low inherent soil fertility, limited availability of organic amendments, low capacity to invest in external inputs and high production risk (Buerkert et al., 2001; Tabo et al., 2007). As compared to the blanket fertilizer application rates hitherto recommended by agricultural research and extension services, microdose

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https://doi.org/10.1016/j.fcr.2018.10.018
Received 22 May 2018; Received in revised form 29 October 2018; Accepted 31 October 2018
0378-4290/

fertilization is characterized by a much higher fertilizer use efficiency and requires smaller financial investment, thereby making this technology more suitable to smallholder farmers. This has been well documented for cereal crops (sorghum, millet, maize and rice) in the semi-arid zones of West Africa (e.g, Aune et al., 2007, 2012; Tabo et al., 2007; Hayashi et al., 2008; Palé et al., 2009; Bagayoko et al., 2011; Camara et al., 2013; Ibrahim et al., 2015a, b;Bielders and Gérard, 2015; Okebalama et al., 2016; Vandamme et al., 2018). More recently, on-station trials also demonstrated the potential benefits of microdose fertilization for maize and rice under sub-humid climatic conditions in Benin (Tovihoudji et al., 2017a). This is of particular interest since, contrary to millet and sorghum for which market opportunities are limited, maize is increasingly grown as a cash crop in northern Benin which constitutes an additional incentive for farmers to invest in this technology.

Though field studies have consistently established the benefits of microdose fertilization in low input farming systems when considering the average agronomic or economic performances, there is a growing concern that such average responses are insufficient to properly assess a technology considering the diversity of smallholder farming environments and practices (e.g. Tittonell et al., 2005, 2010, 2011; Zingore et al., 2007, 2011; Giller et al., 2011; Chikowo et al., 2014). Indeed, several studies in SSA have documented high variability in yield response to microdose fertilization, even within the same agro-ecological zone. For example, previous studies reported a large variability in millet responses to microdose fertilization in Niger, with yield increases ranging between 0–2000 kg grain ha^{-1} (Buerkert et al., 2001), 0–1500 kg grain ha^{-1} (Bationo et al. (2005) and 0–900 kg grain ha^{-1} (Tabo et al., 2011). Such variability is large considering that average millet yields in unfertilized farmer's fields were of the order of 400-500 kg ha^{-1}. Also in low input millet farming systems in south-western Niger, Bielders and Gérard (2015) showed that a value-cost ratio (VCR) > 2 for microdose fertilization was achieved in only 59% of farmer's plots (n = 279) even though a VCR of 2 is often considered as a lower limit justifying investment in risky environments. Similarly, in southern Zimbabwe, Twomlow et al. (2010) reported a large variability in maize response to microdose fertilization, from slightly negative values to about +2000 kg grain ha^{-1} across a broad range of soil, farmer management, and seasonal climatic conditions. According to these authors, 25% of farmers did not achieve a yield gain that would translate into acceptable net returns.

The causes of the large variability in response to microdose fertilization are expected to relate both to environmental conditions (e.g., rainfall and soil) and crop management practices (e.g., planting density, weeding intensity) for a given cultivar within the same agro-ecological zone. For instance, Bielders and Gérard (2015) showed that sowing date, rainfall-related variables and planting density affected crop response to microdose fertilization in the Sahelian conditions of western Niger. They further demonstrated that microdose fertilization should be targeted preferentially to all fields or parts of fields where low yields are expected. Although the typology of factors affecting yield variability may be broadly similar across regions, the extent to which they affect yield response will undoubtedly differ depending on soil characteristics, climatic conditions, crop type and agricultural practices (e.g. Falconnier et al., 2016; Ronner et al., 2016). Characterizing the extent of the yield response variability and its causes thus remains an important step to develop meaningful and flexible recommendations that allow farmers to use scarce fertilizer and organic resources efficiently (Giller et al., 2011). With such understanding, site-specific recommendations with known levels of risk may be issued to smallholder farmers, which would greatly benefit the credibility of the technology and ultimately help its rapid diffusion.

Because mineral fertilizers mostly supply macronutrients, it has been advocated to combine microdose fertilization with manure applications along the principles of integrated soil fertility management (ISFM) (Vanlauwe et al., 2011, 2015). Indeed, besides supplying macro and micronutrients, manure is essential for maintaining soil physical, chemical and biological quality in the long run (e.g. Bationo et al., 2007; Liu et al., 2010; Kihara et al., 2011). In environments where manure availability is limited, hill-placement of farmyard manure appears especially promising (e.g. Ibrahim et al., 2015a, b, 2016; Tovihoudji et al., 2017b). Furthermore, the manure may in some cases alleviate soil-related constraints (e.g., supply of micronutrients, improved soil water retention) that restricted crop response to microdose fertilization. Hence, combining microdose fertilization with manure may result in reduced variability in crop response, thereby making the technology more predictable and possibly less risky for smallholder farmers.

The specific objectives of the present study were therefore (1) to quantify the variability in maize yield response to microdose fertilization alone or in combination with manure in smallholder farmers' fields in northern Benin; (2) to identify the main agronomic management and environmental factors that govern such responses and (3) to evaluate the economic profitability and risk associated with each treatment.

2. Materials and methods

2.1. Study sites and farm characteristics

During two consecutive rainy seasons (2014 and 2015), a series of demonstration trials were established in collaboration with farmers across an area of approx. 600 km^2 in the Ina district (North-eastern Benin), 70 km north of Parakou (Fig. 1). Ina is located in the agro-ecological region III (Tovihoudji, 2018) where annual rainfall ranges between 900 and 1200 mm. The annual rainfall for the last 30 years at Ina was 1148 ± 184 mm (mean ± standard deviation) and the average temperature was 27.5 °C (CRA-Nord Climate Database, 1982–2015). The rainfall distribution is unimodal, characterized by a rainy season that occurs between May and October, and a dry season that prevails during the rest of the year. July and August are the wettest months. The soils have low inherent fertility and are classified as ferruginous tropical soils in the French soil classification system which corresponds to Acrisols or Lixisols according to the World Reference Base (Youssouf and Lawani, 2002).

2.2. Study design and management

During the 2014 and 2015 rainy season, a series of on-farm demonstration trials were established in collaboration with 18 farmers in 2014 and 33 in 2015 across five administrative villages (Supplementary Table S1). Each farmer hosted one single, non-replicated trial with six treatments randomly arranged. Each farmer trial was considered as a replicate. The treatments consisted of: i) a control (no fertilizer, no manure), ii) a microdose option 1 (MD1): 2 g NPK 15–15–15 per hill after plant emergence (10–14 days after sowing, DAS) + 1 g urea per hill at 45–50 DAS; iii) a microdose option 2 (MD2): 4 g NPK 15–15–15 per hill after plant emergence + 1 g urea per hill at 45–50 DAS; iv) MD1 + farmyard manure 3 t DM ha^{-1} after plant emergence (MD1 + FYM), v) MD2 + farmyard manure 3 t DM ha^{-1} after plant emergence (MD2 + FYM) and vi) a recommended rate (RR): 200 kg ha^{-1} of NPK 15–15–15 after plant emergence + 100 kg urea ha^{-1} at 45–50 DAS. These treatments are equivalent to 23.8 kg N, 4.1 kg P and 7.8 kg K ha^{-1} for MD1; 33.1 kg N, 8.2 kg P and 15.6 kg K ha^{-1} for MD2; and 76 kg N, 13.1 kg P, and 24.9 kg K ha^{-1} for RR. The two microdose fertilization rates are identical to the rates tested previously in on-station experiment by Tovihoudji et al. (2017a). The RR treatment is the blanket fertilizer rate recommended by the National Agricultural Research System in the study area. The rate of manure used in the trials (3 t ha^{-1}) is 2–3 times lower than the rate recommended by extension services because of the limited availability of manure to farmers. To compensate for these lower application rates, and based on recent evidence (Ibrahim et al., 2015a, b; Tovihoudji et al., 2017b), the

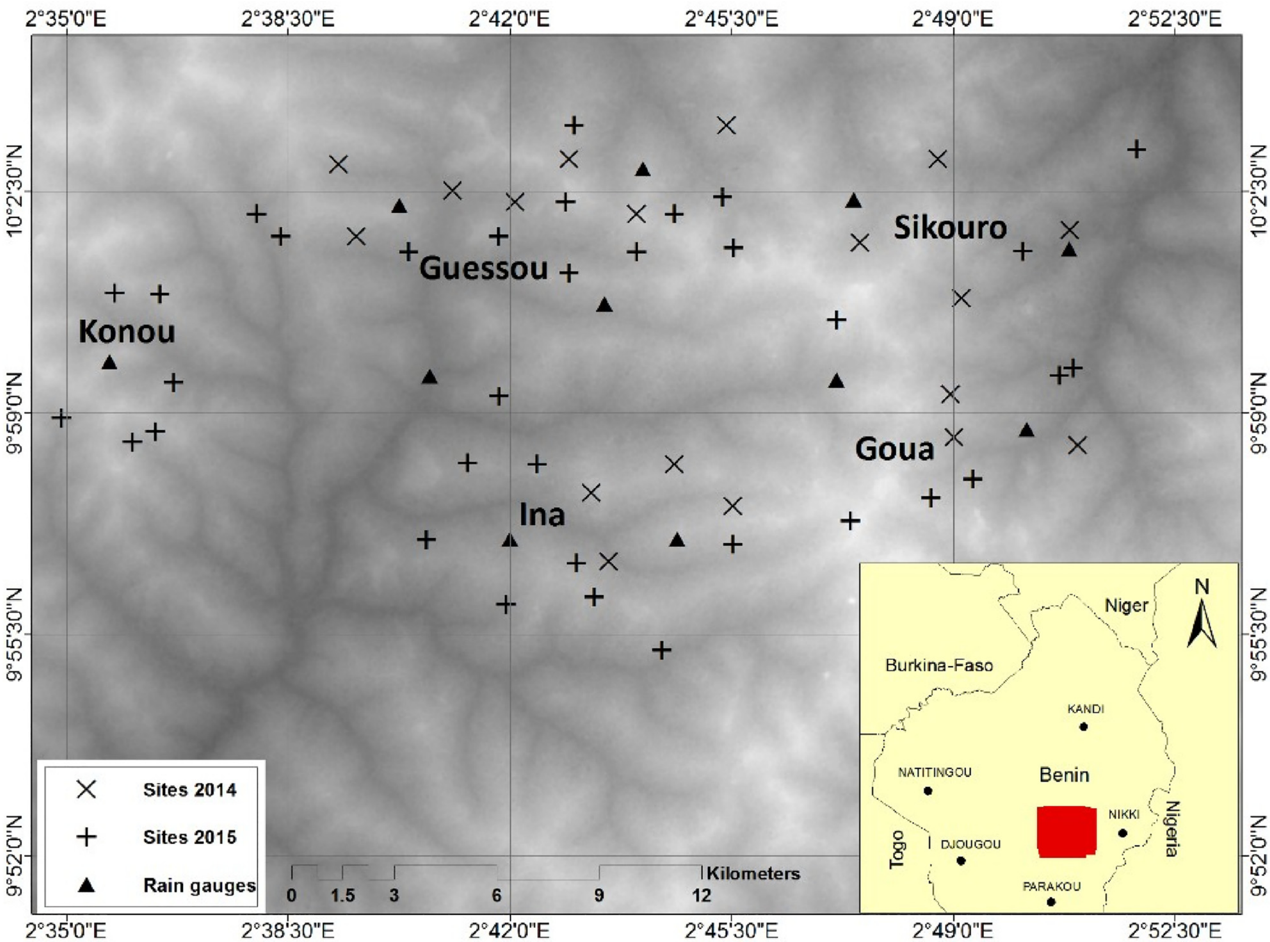

Fig. 1. Location of Ina district (Municipality of Bembèrèkè) in northern Benin and distribution of rain gauges and demonstration sites.

manure was hill-placed at 96 g manure hill^{-1} to increase its efficiency.

To apply microdose fertilization (both NPK and urea), small pits (approx. 0.05-m diameter and 0.05-m depth) were dug on one side of each planting hill at approximately 0.1 m from the planting hill and closed after application. The NPK and urea fertilizer in the RR treatment were spot-broadcasted at approximately 0.10 m from each planting hill and not incorporated into the soil, in accordance with farmer's practice in the study area. For both the microdose fertilization and RR treatments, urea application was immediately followed by weeding-ridging as done by farmers. In case of combined application of microdose fertilization and manure (MD1 + FYM and MD2 + FYM), small pits (approx. 0.1-m diameter and 0.1-m depth) were dug on both sides of each planting hill at approx. 0.1-m from the planting hill and closed after the application of both amendments.

In these trials, unwanted sources of variability were controlled by ensuring that all farmers participating in the trial used the same maize variety, planting density, and inorganic fertilizer type and manure source. Farmyard manure was taken from the barn of the Agricultural Research Centre of Northern Benin located in Ina district. Each season, the collected manure was thoroughly mixed, sampled for nutrient content, and measured and bagged for each plot before it was brought to the demonstration sites. A composite manure sample was analyzed for organic C as well as total N, P and K at the soil and plant analysis laboratory of the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT, Sadoré, Niger). Manure characteristics were slightly different in 2014 (1.27% N; 0.48% P; 0.66% K; 14.3% organic C) and 2015 (1.30% N; 0.41% P; 0.62% K; 18.9% organic C), corresponding on average to 38.6 ± 0.6 kg N, 13.4 ± 1.5 kg P and 19.2 ± 0.8 kg K ha^{-1} for the application rate of 3 t ha^{-1}. The manure C/N ratio was 11.3 in 2014 and 14.5 in 2015. On each farmer's field, six contiguous plots measuring 4 m x 5 m were delimited, separated by a 1 m alley. Fields were ploughed by farmers, and planting was done under the control of technicians. Maize variety DMR-ESR (90 day-maturity) was planted at a spacing of 0.80 m × 0.40 m in all plots and thinned to two plants per hill at 10–14 DAS, giving a plant population density of 62,500 plant ha^{-1}. Different plots were used in 2014 and 2015 to avoid interaction of residual effects.

Participating farmers were identified through local farmer organizations and extension agents based on their experience in maize cultivation, willingness and consent to participate, and the accessibility of the field. The farmers were trained each year regarding the microdose application technique by research staff before the onset of the rainy seasons. The 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 measurements. The choice of sowing, fertilizer application, weeding, thinning and harvest dates was left to each individual farmer. But sowing dates, weeding and harvest dates were identical across treatments at any given farmer field.

2.3. Monitoring and measurements

Depending on the year, 7 to 11 geo-located manual rain gauges were installed from May to record individual rainfall events (Fig.1). 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. Rainfall from the nearest rain gauge was attributed to each demonstration site (each site was located within 0.5 to 3 km of a raingauge). From this data, total rainfall from the beginning to the end of the rainy season (May to October) and the cumulative rainfall from sowing to physiological maturity were calculated.

For each experimental plot, field history was collected, including previous crops grown and the amount of mineral fertilizer or organic fertilizer applied. Also, the distance from the village to the trial field was calculated.

The farmers received a manual (including record sheets) outlining the agreed experimental protocols. The farmers were assisted by a field assistant to fill in the record sheets. Information recorded included the timing of the different operations (sowing, fertilizer application, weeding, harvesting). Farmers could also record other observations such as the problems encountered (pests and diseases). Weed pressure was scored visually by the two field technicians who regularly visited the fields on a scale from 1 (< 25% of the plot surface covered with weeds) to 4 (> 75% of the plot surface covered with weeds) at 30 and 60 DAS. Scores were compared and debated until there was a consensus among the 2 technicians regarding each level. Farmers did not always remember exactly the amount of mineral fertilizer previously applied. Since we could not assign reliable quantities of fertilizer, it was used as a categorical factor (yes/no).

At crop maturity, maize plants were sun dried in the plot for two weeks (farmers' common practice). Thereafter, farmers and researchers jointly harvested maize cobs from the three middle rows of each plot. Cobs were weighed in the field, transported to the laboratory and oven-dried at 60 °C for 48 h to determine moisture content. After threshing, maize grain yields were then calculated and expressed in kg ha^{-1} on a dry weight basis. Yield response to any given fertilized treatment was calculated using the following ratio:

Yield response $= \frac{Yf - Yc}{Yc}$ (Eq. 1) where Y_f and Y_c are the grain yield (kg ha^{-1}) from the fertilized and control treatments, respectively.

2.4. Baseline soil and manure analyses

To assess the nutrient status of the soils before sowing and amendment application, soil samples (0–20 cm soil depth) were taken at randomly selected points in each treatment plot and bulked as a composite sub-sample per plot. The sub-samples from each plot were then mixed and one composite sample per field was sent for analysis. The samples were air-dried, passed through a 2-mm sieve, and stored at room temperature prior to analysis. Particle size distribution was determined using the pipette method (Gee and Or, 2002). pH (H_2O) was measured potentiometrically in a 1:2.5 soil:water suspension (van Reeuwijk, 1993). Organic carbon was determined by the method described by Walkley and Black (1934), total N by the Kjeldahl method (Houba et al., 1995) and available phosphorus by the Bray 1 method (van Reeuwijk, 1993). Exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were determined after extraction by the ammonium acetate solution at pH 7 using the method described by van Reeuwijk (1993). All chemical analyses were carried out at the ICRISAT laboratory in Sadoré, Niger.

2.5. Economic and risk analysis

An economic analysis of the profitability of microdose fertilization alone or in combination with hill-placed manure was conducted by calculating the partial gross margin (PGM) and the value-cost ratios (VCR). The PGM was calculated by subtracting the sum of the costs of fertilizer and manure and the labor costs for application (not including the other operations costs) from the total revenue (grain yield multiplied by the price of grain). 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 variable costs. Prices of maize grain and mineral fertilizer were obtained from a market survey carried out in the study area in 2015. The fertilizer acquisition cost included the price of purchasing and the transportation cost (Table 1 A).

Table 1
Input and output prices (a), and description of scenarios (b) used in the economic and risk analysis.

(A) Input and output prices	Unit**	Min	Max	Average
Inputs				
NPK and urea fertilizer purchasing	US$ per 50 kg bag	23	35	26.5
NPK and urea fertilizer transport	US$ per 50 kg bag	1	2	1.5
Manure	US$ per 100 kg bag	0.4	1.2	0.8
Labor costs				
Hole digging	US$ ha^{-1}	14	28	20
Microdose fertilization (NPK + urea)*	US$ ha^{-1}	18	37	28
RR (NPK + urea)	US$ ha^{-1}	12	24	18
Manure application*	US$ ha^{-1}	24	48	36
Output prices				
Maize grain	US$ kg^{-1}	0.2	0.4	0.3

(B) Scenarios	Codes	Description
Scenario 0	S0	Average grain and average fertilizer and/or manure + labor prices
Scenario 1	S1	Minimum grain and minimum fertilizer and/or manure + labor prices
Scenario 2	S2	Minimum grain and maximum fertilizer and/or manure + labor prices
Scenario 3	S3	Maximum grain and minimum fertilizer and/or manure + labor prices
Scenario 4	S4	Maximum grain and maximum fertilizer and/or manure + labor prices

* Applying fertilizer and closing the holes; RR = recommended rate.
** the local currency in Benin is XOF or FCFA; 1 US$ = 500 F FCFA.

Fertilizer transportation costs can range between 1.0 and 2.0 US$ per 50 kg bag, with an average of 1.5 US$ (Table 1 A), depending on several factors such as the distance, availability, accessibility of farmer's home and the period of the year and/or the day etc (the local currency in Benin is XOF or FCFA, this study considered 1 US$ = 500 FCFA, although fluctuations are observed). The maize grain prices fluctuate between 0.2 and 0.4 US$ kg^{-1} during the year, with an average of 0.3 US$ kg^{-1} (Table 1 A). Since there is still no market for manure in the study area and farmers consider it as a free input, the value of farmyard manure was estimated to be equal to the costs required for collecting manure and transporting it to the fields and ranged between 0.4 and 1.2 US$ per 100 kg bag, with an average of 0.8 US$ (Table 1 A).

The cost of application of amendments included the labor for digging the holes, applying fertilizer or manure and incorporating into the soil. The time required for the remaining management practices (sowing, weeding or harvesting) did not vary significantly across farmer fields and treatments and were not included in the calculations. Labor requirements were estimated each year by direct observation for each treatment plot with 2–3 farmers per village. For each treatment and activity, the duration and the number of people were recorded. The labor times for each task per treatment were calculated and converted into costs (Table 1 A). Casual labor in the study area at the time of study was paid about 4.0 US$ per day, corresponding to 0.5 US$ h^{-1} on the basis of 8 h work per day. For the combined fertility management treatments (MD1 + FYM and MD2 + FYM), labor costs for applying manure and fertilizer were summed.

Risk was assessed on the basis of the probability of achieving a certain value-cost ratio (VCR) for a given treatment. In economic terms, a VCR value greater than 1 means that the cost of investment in fertilizer and additional labor costs are recovered, while a VCR of 2 represents 100% return on investment (Kihara et al., 2015; Ronner et al., 2016). In addition to calculations based on the mean cost of inputs and outputs, four scenarios were evaluated to assess the effects of fluctuations on the VCR on the basis of the minimum and maximum values of inputs (fertilizer and/or manure and labor) taking into account the variation in input and output prices and labor times (Table 1B).

2.6. Statistical analysis

Prior to analysis, data were carefully checked for outliers using descriptive statistics, boxplots and correlation analysis. Yield was square root transformed to ensure homoscedasticity of residuals, while soil Exch-Na and P-Bray 1 were log10 transformed. Pearson's correlation was used to characterize the relationships among soil parameters on the one hand, and rainfall and related variables on the other hand. Scatter plots of the distributions of yields and VCRs for the different treatments were constructed for more informative understanding of the variability (Vanlauwe et al., 2016).

Yield stability was analyzed by plotting treatment yields vs. the environmental mean, i.e., the mean yield of all treatments at a given site (Guertal et al., 1994). The slope of the linear regression was thereafter used to evaluate yield stability (smaller the slope, greater the yield stability; Guertal et al., 1994).

The effects of treatment on maize grain yield, PGM and VCR was first assessed with a linear mixed model (LMM) using the Restricted Maximum Likelihood (REML) for variance estimation of slope. Farm site and year were considered as random factors and treatment as a fixed factor. The Tukey-Kramer post-hoc test ($p < 0.05$) was used for mean separation when the analysis of variance showed a significant treatment effect.

With the same LMM approach, the relation between treatment yields and different environmental and management variables, and their interactions by treatment were assessed. First, the strength of each variable in explaining yield variability was explored in separate analyses. Subsequently, a final combined analysis over the two years was made by backward selection of variables using the Akaïke Information Criterion (AIC). Since there were significant correlations between the cropping year and related factors (rainfall, sowing date) on the one hand and distance, soil total carbon and nitrogen on the other hand, they were not combined in the same model to avoid confounding effects. Hence, one combined model was computed for each of these variables, and the one with the lowest AIC was retained.

A similar combined regression analysis was performed to better understand which explanatory variables best explain maize yields in microdose fertilization treatments using yield response (rather than absolute yields) as independent variable. For this, a separate analysis for each treatment was first performed and the models retained the same significant explanatory variables for both microdose rates. Since the difference between the average yield of the two microdose treatments was not significant, the average yield of the treatments was used in the final model to analyze the yield response. This is expected to increase the robustness of the outcome since averaging yields over a larger surface reduces the impact of small scale, intra-site yield variability.

The performance of the models was evaluated based on the significance level of the estimated coefficients, the coefficient of determination (R^2), the root mean square error (RMSE), the plots of predicted vs. observed values, and the AIC value. High values of R^2 and low values of RMSE and AIC indicate a better performance of the model. All analyses were performed using GenStat Release 12.1 statistical software (GENSTAT, 2009).

3. Results

3.1. Farmer field site characteristics

Soil texture was predominantly loamy-sand, with sand content above 70% in most fields. Most soil chemical characteristics varied widely across farm sites (Supplementary Table S2). Soil pH (H_2O) ranged from acidic (4.8) to near neutral (6.8). Soil total N and P Bray 1 contents at most sites were very low to moderate (range of 0.39–1.40 g kg^{-1} and 1.60–22.43 mg kg^{-1}, respectively) compared to optimal values of 2.5 g kg^{-1} and 17 mg kg^{-1}, respectively (Hazelton and Murphy, 2007). In general, soil samples at most sites showed moderate to low limitations with respect to exchangeable bases (Ca, Mg, K and Na). Soil organic carbon was within the low to moderate range (3.40–15.40 g kg^{-1}). Experimental farms were located between 0.1 and 6 km away from the nearest village (Supplementary Table S2).

There were significant correlations among a number of soil parameters. Total C and N were strongly correlated ($r = 0.92$; $p < 0.001$), and inversely correlated with distance from the village ($r = -0.63$ and -0.55 respectively; $p < 0.001$). Except between Ca and Na, there were positive and significant correlations ($p < 0.05$) among all exchangeable cations with bivariate correlation coefficients ranging between 0.24 and 0.75. Soil pH, exch-K, -Ca and -Mg, and clay content were also positively correlated ($p < 0.001$).

Total rainfall (from May to October) varied between sites and years, ranging from 819 to 1183 mm in 2014, and from 918 to 1103 mm in 2015. This range corresponds to the low to medium range of rainfall conditions observed in the region (long-term average = 1148 mm). Rains in 2014 started early with rainfall more evenly distributed than in 2015 despite a greater number of short dry spells. Rainfall in 2015 was poorly distributed, with more heavy rainfall events but also longer dry spells than in 2014. This caused delay in sowing, partial crop failure and major differences in crop establishment. Sowing occurred on average around mid-June, but ranged anywhere between mid-May (DOY 138) and mid-July (DOY 220) in 2014. In 2015, sowing occurred on average 20 days later than in 2014 (DOY 183). As for the total rainfall, the cumulative rainfall between sowing and plant physiological maturity also varied widely across sites and cropping years (Supplementary Table S2) and showed a high degree of correlation with the sowing date ($r = 0.49$; $p < 0.001$).

About 18% of the experimental plots had less than 25% weed cover, while 26% had a cover greater than 75% when averaged over the two observation dates. The antecedent crops were mostly maize (51%), cotton (37%) and soybean (12%). Most sites (64%) had received fertilizers at least once during the last 3 years. As is common in the study area, mostly cotton and rarely maize received mineral fertilizer, on average for both crops about 150 ± 50 kg NPK15-15-15 ha^{-1} and 100 ± 50 kg urea ha^{-1}, before the first and second weeding, respectively.

3.2. Maize grain yields and response to treatments

The LMM analysis of maize grain yield revealed significant treatment effects within the two years ($p < 0.001$; Table 2). The average grain yield was slightly higher in the relatively wetter 2014 year (2432 kg ha^{-1}) than in the drier 2015 year (2301 kg ha^{-1}; $p = 0.013$). Across years, all fertilizer treatment yield means were significantly higher than those of the control ($p < 0.001$; Table 2). We observed a strong positive response at all sites to both MD1 and MD2 which significantly increased maize grain yields by 1090 and 1201 kg ha^{-1}, respectively, compared to the unfertilized control (1096 kg ha^{-1}). Overall, there was no significant difference in yields between MD1, MD2 and RR in both years (Table 2). On average, the addition of manure in microdose plots significantly increased grain yields by 848 kg ha^{-1} compared to microdose fertilization alone ($p < 0.001$; Table 2). There was no significant difference between the two manured treatments (MD1 + FYM and MD2 + FYM).

The range of environmental and management conditions encountered across the sites resulted in a high variability of yields within a given treatment (Fig. 2; Table 2). Yields in the control plots ranged from 420 kg ha^{-1} to 1687 kg ha^{-1} across sites and years. About 30% of the control plots yielded less than 1000 kg ha^{-1} in 2014 while in 2015 this was almost 42%. Across all fertilized treatments, maize yields varied from 1602 to 3707 kg ha^{-1} in 2014 and 1419 to 4475 kg ha^{-1} in 2015. Yield distributions differed among fertilizer treatments and years.

Table 2
Effect of treatments on maize grain yield statistics across the two years of the trials. The statistical analysis was performed on square root transformed yield data.

Year	Treatment	Mean	SD	Min	Max	Median	$P_{90} - P_{10}$*	Mean response
kg ha^{-1}								
2014	Control	1089a	264	617	1429	1127	734	–
	MD1	2240b	332	1602	2796	2246	768	1152
	MD2	2330b	343	1653	2791	2412	896	1241
	MD1 + FYM	3072c	431	2443	3707	3159	1121	1983
	MD2 + FYM	3268c	206	2802	3596	3261	485	2179
	RR	2590b	490	1767	3290	2633	1263	1502
	p-value	*< 0.0001*						
2015	Control	1103a	364	420	1687	1170	981	–
	MD1	2127b	419	1419	2960	2010	1226	1027
	MD2	2262b	506	1432	3418	2115	1237	1161
	MD1 + FYM	2931c	579	1834	4236	2819	1483	1831
	MD2 + FYM	3079c	717	1846	4475	3041	1780	1978
	RR	2305b	573	1423	3815	2296	1411	1203
	p-value	*< 0.0001*						

MD1 = microdose option 1, MD2 = microdose option 2, RR = recommended rate, FYM = farmyard manure at 3 t ha^{-1}. Means followed by the same letter in the same year are not significantly different at p = 0.05.
* Interpercentile range; SD = standard deviation.

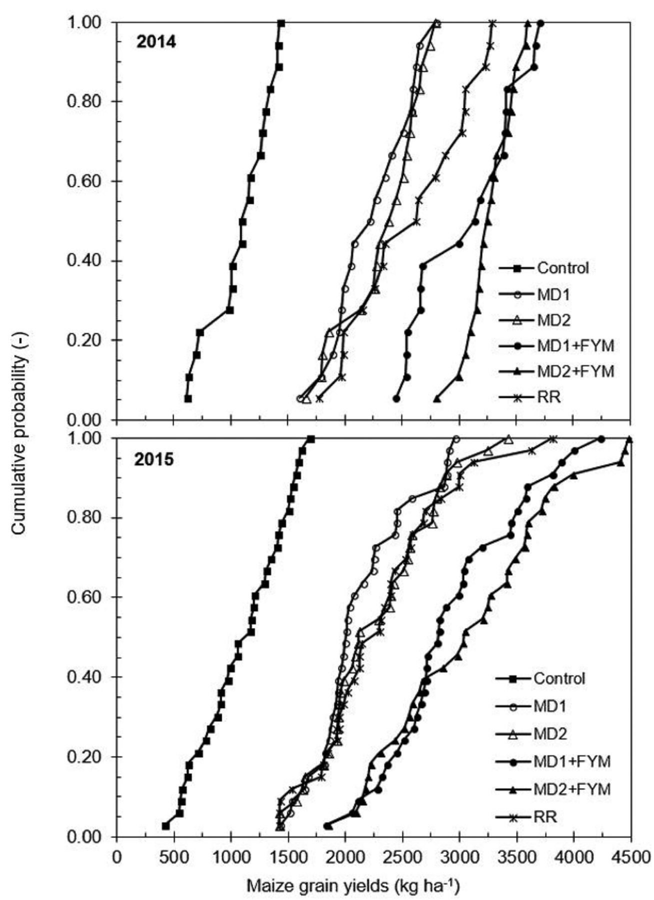

Fig. 2. Cumulative probability density function of maize grain yields (kg ha^{-1}) for the different treatments across the two years of the trials. MD1 = microdose option 1, MD2 = microdose option 2, RR = recommended rate, FYM = farmyard manure at 3 t ha^{-1}.

The Levene's test for heteroscedasticity (homogeneity of variances) revealed that the yield variances of the six treatments are equal ($p > 0.05$; not shown). However, on average across both years, the control treatment had the lowest yield variability based on the interpercentile range (Table 2). With the noticeable exception of MD2 + FYM in 2014 for which the interpercentile range was low, the interpercentile ranges in the combined MD + FYM treatments were higher than in the sole microdose treatments. The variability in the RR treatment was also higher than in the sole microdose treatments based on the interpercentile range (Table 2).

Yield stability was highest for the control treatment (Supplementary Fig. S1). The treatments without manure (MD1, MD2 and RR) had intermediate responses in all environments whereas the combined treatments (MD + FYM) were the most responsive to improvement in environmental conditions.

As for the absolute yields, yield responses to microdose fertilization also varied widely from +157 to +2863 kg ha^{-1} and +739 to +3428 kg ha^{-1} for sole microdose and combined MD + FYM treatments, respectively. Yield response to microdose fertilization tended to decrease with increasing yields in the control plots, especially when microdosing was applied alone (Fig. 3).

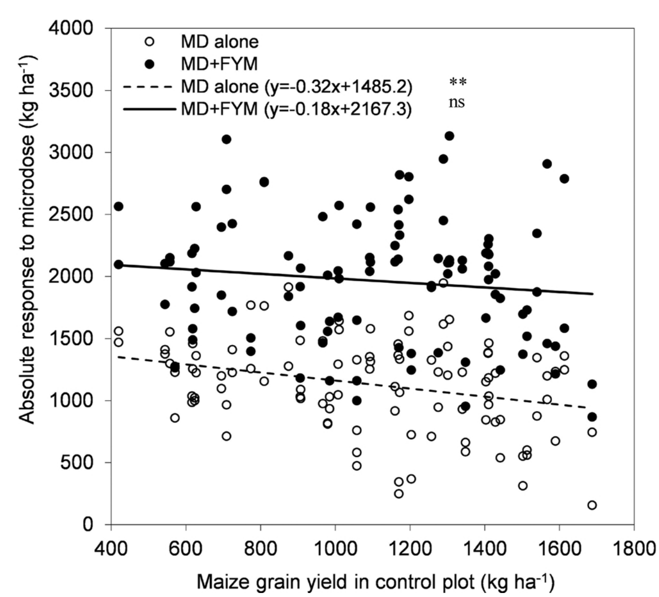

Fig. 3. Absolute response to microdose fertilization as a function of yield in control plots (2014–2015). Since yields for the two microdose rates were not significantly different, the average yield of these two treatments was used with a distinction between microdose (MD) alone and microdose + farmyard manure at 3 t ha^{-1} (MD + FYM). The slope of the equation is not significant (ns) or significantly different from zero at p = 0.01 (**) (linear regression analysis).

Table 3
Partial budget analysis (US\$ ha^{-1}) for the different treatments over the two years of trial (2014–2015). Partial gross margin (PGM) and value cost ratio (VCR) calculations were based on the average prices for inputs and outputs (Scenario S0; see Table 2B).

Treatment	GM (US\$ ha^{-1})*				VCR (-)			
	Mean	SD	Min	Max	Mean	SD	Min	Max
MD1	574.3a	117.7	191.5	932.4	4.3a	1.4	1.3	6.9
MD2	565.0a	134.7	243.3	1065.4	3.0b	1.2	0.4	5.1
MD1 + FYM	735.3b	158.6	306.1	1166.1	3.6ab	0.9	1.9	6.0
MD2 + FYM	742.8b	177.4	355.4	1223.6	3.1b	0.8	1.3	4.6
RR	533.1c	166.4	240.9	963.3	2.1c	0.9	0.4	4.1
p-value	*< 0.0001*				*< 0.0001*			

MD1 = microdose option 1, MD2 = microdose option 2, RR = recommended rate, FYM = farmyard manure at 3 t ha^{-1}. Means followed by the same letter are not significantly different at p = 0.05 (REML analysis); SD = standard deviation.

* the local currency in Benin is XOF or FCFA, 1 US\$ = 500 F CFA.

3.3. Economic profitability and risk analysis

The economic analysis based on average costs of inputs and outputs (scenario S0; see Table 1B) revealed a larger benefit for microdose fertilization (alone or combined with manure) compared to the recommended fertilizer rate (Table 3). Overall, the partial gross margin of microdose fertilization and RR treatments were statistically similar, despite the higher additional labor costs for microdose fertilization (Table 3). Indeed, for each fertilizer type (NPK or Urea), the total labor needed to apply fertilizer microdosing (MD1 and MD2) is nearly 2.6 times greater (55.7 h ha^{-1} equivalent to 7 man-days ha^{-1}) than the RR treatment (21.2 h ha^{-1} equivalent to 3 man-days ha^{-1}) (not shown). Combining hill-placed manure with microdose fertilization significantly increased the partial gross margin by 170 US\$ ha^{-1} on average, compared to sole microdose fertilization ($p < 0.001$; Table 3).

Based on average costs, the VCR of the MD1 treatment was 1.3 and 2.2 times greater than the MD2 and RR treatments, respectively ($p < 0.001$; Table 3). Like grain yields, there was no significant difference between the two manured treatments (MD + FYM; Table 3). Despite the fairly high cost associated with microdose fertilization in scenario S0, applying MD1 or MD2 allowed 94–100% of farmers to break even (VCR ≥ 1). Most farmers (80–94%) applying microdose fertilization surpassed a VCR of 2, compared to only 47% for the RR treatment (Fig. 4; Table 4). Combining microdose fertilization with manure was also highly profitable (VCR ≥ 2) for 88–98% of the farmers (Fig. 4; Table 4).

VCR values depended greatly on fluctuations in input (fertilizer and additional labor costs) and output prices (Fig. 4; Table 4). For the worst-case scenario S2 (low prices of grain and high fertilizer and labor costs), 41%–86% of the farmers had a VCR < 2 using microdose fertilization (alone or in combination with manure), while for the RR treatment 96% of farmers had VCR < 2 (Fig. 4; Table 4). In contrast, following a reduction of fertilizer and labor costs and an increase in prices of grain (scenario S3), only 0–10% had a VCR < 2 when applying the microdose fertilization (alone and with manure) whereas 18% of the farmers had a VCR < 2 for the RR treatment (Fig. 4; Table 4). For all treatments, S1 and S4 tended to yield similar VCR distributions to the S0 scenario, indicating that costs and income tended to compensate each other in these scenarios.

3.4. Effects of other management practices and environmental factors

3.4.1. Effect of individual factors on grain yield

On average over all treatments, late sowing resulted in a significant decrease in grain yield ($p < 0.001$; Supplementary Table S3). Besides late sowing, high total rainfall was negatively correlated with grain yields (p = 0.008; Supplementary Table S2). Among the management factors, weed pressure and previous crop significantly affected maize yield ($p < 0.001$). Demonstration sites with higher weed pressure scores (> 50%) had a lower mean yield (on average 2180 kg ha^{-1}) while those with lower pressure (< 25%) had a higher mean yield (2650 kg ha^{-1}). Cotton and soybean as previous crop increased maize grain yield on average by 379 and 296 kg ha^{-1}, respectively, compared to maize as previous crop (2171 kg ha^{-1}) (Supplementary Fig. S2). Differences in soil and land characteristics between sites (distance from village, soil clay + silt content, total carbon and nitrogen contents) were significantly associated with yield (Supplementary Table S3). Yields tended to decrease with increasing distance from the village ($p < 0.001$), while it increased with increasing soil clay + silt (p = 0.010), total carbon ($p < 0.001$) and nitrogen content (p = 0.002; Supplementary Table S3). There was no significant interaction between the explanatory variables and microdose and/or manure treatments regarding grain yield, except for total carbon where significant interaction was found with some treatments.

3.4.2. Combined analyses

Table 5 shows the best regression model for maize grain yield which contains all significant variables. Interactions are not included in the final model to facilitate interpretation, but significant interactions were found between total carbon or clay content and some treatments. In addition to the treatment effects ($p < 0.001$), all variables that were significant in the separate analyses (e.g., sowing date, weed pressure, previous crop, soil clay + silt and total carbon contents) were systematically retained by the final regression model (Table 5). The final model also retained soil P-Bray1 ($p < 0.001$), exch-Mg (p = 0.023) and pH ($p < 0.001$) despite not being significant in the separate analyses. This final model explained overall 80% of the yield variability. Treatments effects explain the largest part of the variability (61%), while management and environmental factors explain 19% of the total variability of which 9%, 7% and 3% for rainfall and related variables (sowing date), management and edaphic factors, respectively. The plot of predicted vs. observed yields indicates good overall performance with a root mean square error (RMSE) of 416 kg ha^{-1} (not shown). Based on the RMSE calculated for individual treatments, the model performance tended to be better (lower RMSE) for the control and worse (higher RMSE) for the high nutrient input treatments (not shown). However, the relative RMSE (RRMSE) was reasonably similar for all treatments (14–20%).

To better understand which explanatory variables best explain maize yield response to microdose and recommended fertilization, a LMM analysis was performed using yield response (rather than absolute yields) as independent variable. Furthermore, since the LMM analysis revealed no significant difference between the two microdose rates (MD1 and MD2; MD1 + FYM and MD2 + FYM; Table 2), the average yield of the treatments was used to analyze the yield response. Overall, the regression analysis revealed three parameters of influence: soil texture (clay and silt), total carbon content, and pH (Table 6). The response to microdose fertilization was negatively related total carbon and pH and positively related to soil clay content. In addition, soil silt content had a negative impact on yield response to microdose fertilization when applied without manure, whereas soil exch-Mg had a negative significant relationship with the response to MD + FYM (Table 6). Weed pressure had a negative impact on yield response but this effect was significant only for the MD + FYM treatment and high weed pressure. For the RR treatment, the response was negatively related to soil clay + silt content, pH and sowing date, and positively related to soil exch-Mg and P-Bray1 (Table 6).

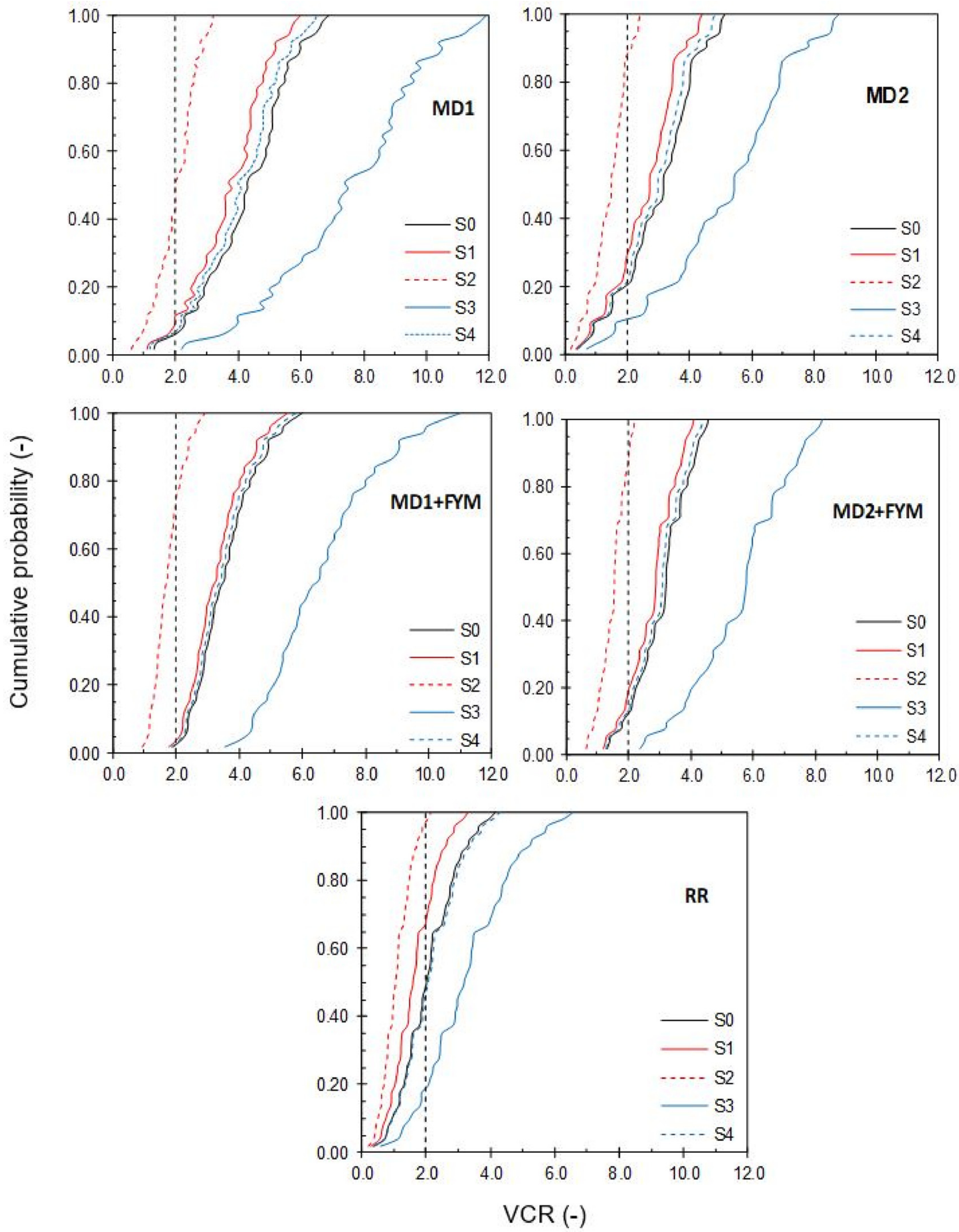

Fig. 4. Cumulative probability distributions of value-cost ratios (VCR) following different treatments and scenarios of input and output prices over the two years of the trials (2014–2015). Vertical dashed lines represent a VCR of 2. MD1 = microdose option 1, MD2 = microdose option 2, RR = recommended rate, FYM = farmyard manure at 3 t ha^{-1}. See Table 2B for an explanation of the different scenarios.

4. Discussion

4.1. Effect of combined application of microdose fertilizer and manure on grain yield and economic profitability

Irrespective of environmental and management conditions, all fertilized treatments increased yields compared to the unfertilized control in both years (Table 2). The observed average yield response to microdose fertilization (alone or combined with manure) in farmer fields confirm the overall good performance of this technology as reported earlier on the basis of on-station experiments in northern Benin for the same treatments at the same rates (Tovihoudji et al., 2017a). The average yield increases are substantially higher than what has been reported previously from on-farm demonstrations with maize in Zimbabwe and Malawi (e.g, Twomlow et al., 2010; Kamanga et al., 2013; Mashingaidze et al., 2013). For instance, results of Twomlow et al. (2010) showed that fertilizer microdosing (17 kg N ha^{-1}) consistently increased maize grain yields by 19–51% compared to the control plots (894-1546 kg ha^{-1}), across a broad spectrum of soil, farmer management and seasonal climate conditions. Mashingaidze et al. (2013) reported that microdose application (28 kg N ha^{-1}) significantly increased maize grain yield on average by +50 to +2000 kg grain ha^{-1}

Table 4
Proportion of fields (%) with value-cost ratios (VCR) < 1 or < 2 depending on the treatments and for different scenarios of input and output prices over the two years of the trials (2014–2015). See Table 2B for an explanation of the different scenarios.

Value-cost ratio	Treatment	Scenarios				
		S0	S1	S2	S3	S4
%fields with VCR < 1	MD1	0	0	6	0	0
	MD2	6	10	20	2	10
	MD1 + FYM	0	2	2	0	0
	MD2 + FYM	0	0	12	0	0
	RR	10	18	37	2	10
%fields with VCR < 2	MD1	6	8	41	0	6
	MD2	20	27	86	10	20
	MD1 + FYM	2	2	71	0	2
	MD2 + FYM	12	16	84	0	12
	RR	47	65	96	18	45

MD1 = microdose option 1, MD2 = microdose option 2, RR = recommended rate, FYM = farmyard manure at 3 t ha^{-1}.

Table 5
Results of the multivariate linear mixed model analysis to explain the variability in maize grain yields (square root transformed) over the two years of farmer field trial (2014–2015).

	Estimate	Std. Error	Pr (> |t|)
(Intercept)	58.640	6.540	< 0.001
Treatment			
Control vs. MD1	13.570	0.876	< 0.001
Control vs. MD2	14.697	0.876	< 0.001
Control vs. MD1 + FYM	21.101	0.876	< 0.001
Control vs. MD2 + FYM	22.304	0.876	< 0.001
Control vs. RR	15.359	0.876	< 0.001
Previous crop			
Maize vs. Cotton	3.522	0.634	< 0.001
Maize vs. Soybean	1.580	1.020	0.036
Weed pressure*			
1 vs. 2	0.150	0.871	0.864
1 vs. 3	−3.165	0.910	< 0.001
1 vs. 4	−4.190	1.120	< 0.001
Sowing date	−0.077	0.017	< 0.001
Clay + silt content	0.131	0.089	0.034
Soil total carbon	0.532	0.097	< 0.001
P_Bray1	0.235	0.059	< 0.001
pH_H2O	−2.904	0.810	< 0.001
Exch. Mg	−4.400	1.930	0.023
Adjusted R-squared: 0.80			
F-value = 63.11 on 16 and 239 DF; p-value: < 0.001			

Weed pressure: 1 (< 25%) to 4 (> 75% of the plot surface covered with weeds). MD1 = microdose option 1, MD2 = microdose option 2, RR = recommended rate, FYM = farmyard manure at 3 t ha^{-1}.

irrespective of N formulation compared to the control plots (591–2429 kg ha^{-1}), across three seasons in farmers' fields. Even though the application method of manure and fertilizer differed from what was done in the present study, Ncube et al. (2007) reported that maize grain yield was increased by 550 to 1810 kg ha^{-1} compared to the control plots (1260 kg ha^{-1}) when small doses of manure and nitrogen (3 t manure + 12–19 kg N ha^{-1}) were applied in combination on farmers' fields in Zimbabwe.

From an economic point of view, all treatments led to mean VCR values > 2 (Table 3), which is generally considered as the lower threshold for adoption in smallholder, risk-averse farming systems. Hence all tested technologies may appear suitable for the conditions of northern Benin. Nevertheless, mean VCR values were notably higher for treatments involving the lower microdose rate compared to the higher microdose rate. This is a direct consequence of the fact that yields were similar for MD1 and MD2 at a given rate of FYM, yet the cost of fertilizer is 1.7 times higher for MD2 compared to MD1. Similarly, although average yields in MD1 and RR were similar, microdose application was economically more profitable, with an average VCR two times larger for MD1 compared to RR (Table 3). In the microdose technology, the lower cost of fertilizer more than compensates for the higher labor cost, resulting in a technology that is much better suited to smallholder farmers than RR. By combining MD1 with manure the average economic return still remained interesting, even though this technology demands even more labor than sole microdosing (Table 3). MD1 + FYM may thus be an optimal choice when considering economic but also edaphic (soil improvement) benefits in environments where organic resources are scarce and farmer's capacity to invest is limited.

The importance of taking into account labor costs in calculating VCRs for the fertilizer microdosing technology cannot be overstressed. In the present study, mean VCR values for MD1 and MD1 + FYM were 6.5 and 7.4, respectively, when not considering labor requirements, as opposed to 4.3 and 3.6 when labor is included (Supplementary Table S4). Similarly, on the basis of on-farm demonstrations in Malawi, Kamanga et al. (2013) reported VCRs of 1–2 and 2–10 with and without labor consideration, respectively, across N rates, price scenarios and weeding intensities. Labor is a major bottleneck for the microdosing technology and greater effort should be invested in alleviating the labor requirements of this technology (e.g., mechanization) in order to reduce application time and ensure more precise application rates (Aune et al., 2018).

4.2. Understanding variability in yields and responses

Average crop responses provide only partial insight into the agricultural intensification potential of a given technology. Greater insight can be achieved by considering yield variability (Sileshi et al., 2010; Vanlauwe et al., 2016). In the present study, we observed a high variability of yields or yield responses between farms and within a given treatment (Table 2; Figs. 2 and 3). High variability in crop responses to microdose fertilization has been reported for various crops and environments (Buerkert et al., 2001; Bationo et al., 2005; Tabo et al., 2011; Bielders and Gérard, 2015), but only one study related to maize specifically addressed this issue (Twomlow et al., 2010). The yield response values but also the ranges observed in the present study (Fig. 3) were substantial higher than what have been reported previously for maize by Twomlow et al. (2010) in the relatively dry areas of Zimbabwe (from 0 to about 2000 kg ha^{-1}). As the variability increases, even greater care must be taken before widespread diffusion of a technology because the mean yield increasingly becomes a less relevant indicator of performance for individual farmers.

When considering the standard deviation (SD) or inter-percentile ranges, most treatments increased yield variability compared to the unfertilized control (Table 2). Furthermore, the yield variability in the combined treatments was higher than in microdose fertilization alone, except in 2014 when MD2 + FYM had an unexpected very low variability (Table 2; Fig. 2). Njoroge et al. (2017) also reported an increase of SD values for maize yields from 0.8-1.2 t ha^{-1} in the control to 1.1–2.3 t ha^{-1} in the full NPK plots, across sites and seasons following sequential application of macronutrients (N, P and K) in nutrient omission trials. The present results also confirmed the overall trend reported by Kafesu et al. (2018), who showed that intensification strategies increased consistently maize yields, but also led to higher SD values (unfertilized control < full NPK < full NPK + Manure).

A greater variability does not necessarily imply an increased economic risk of low return on investment for farmers as long as mean yields increases are high enough. What may be more important for smallholder farmers is to achieve an acceptable economic return regardless of yield variability. In the present study, based on average grain and fertilizer prices and labor costs (Table 2), the use of microdose fertilization was economically profitable (VCR ≥ 2) for more than 90% of farmers despite the greater yield variability compared to the control (Table 4). Although it increases the risk on average, combining

Table 6
Linear regression model using absolute yield response (kg ha^{-1}) in microdose (mean of MD1 and MD2) and RR plots as dependent variable over the two years of trial (2014–2015).

	MD alone		MD + FYM		RR	
	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error
(Intercept)	3.39e+03	6.84e+02***	4.77e+03	8.78e+02***	6.19e+03	1.62e+03**
Clay	7.50e+01	1.75e+01***	1.45e+02	2.89e+01***	–	–
Silt	−3.50e+01	1.64e+01*	−3.51e+01	2.00e+01	–	–
Clay + Silt	–	–	–	–	−5.19e+01	2.20e+01*
Total carbon	−3.58e+01	1.29e+01**	−3.64e+01	1.64e+01*	–	–
Exch. Mg	−4.89e+02	3.83e+02	−1.16e+03	3.50e+02***	1.27e+03	4.97e+02*
pH-H2O	−3.43e+02	1.07e+02**	−3.58e+02	1.30e+02**	−4.02e+02	1.98e+02*
P-Bray1	–	–	–	–	3.78e+01	1.37e+01*
Sowing date	–	–	–	–	−8.75e+00	4.27e+00*
Weed pressure						
1 vs. 2	−4.60e+01	1.66e+02	−1.88e+02	1.52e+02	–	–
1 vs. 3	−2.30e+01	1.71e+02	−9.70e+01	1.56e+02	–	–
1 vs. 4	−1.57e+02	1.82e+02	−6.31e+02	1.67e+02***	–	–
	Adj. R^2 = 0.25; F-value = 6.31; p-value: < 0.001		Adj. R^2 = 0.33; F-value = 6.49; p-value: < 0.001		Adj. R^2 = 0.44; F-value = 4.04; p-value = 0.002	

Weed pressure: 1 (< 25%) to 4 (> 75% of the plot surface covered with weeds). Since yields in the two microdose rates were not significantly different, the average yield of these two treatments was used with a distinction between microdose (MD) alone and microdose + farmyard manure at 3 t ha^{-1} (MD + FYM). ***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$.

microdose fertilization with manure still remains an attractive technology since more than 80% of the farmers achieved a VCR ≥ 2; Table 4). These levels of risk are much lower than those reported for millet under the dryer, Sahelian conditions of the Fakara region (Niger) by Bielders and Gérard (2015), especially on high productivity plots (yield > 400 kg ha^{-1}) where as much as 56–58% of the demonstrations sites experienced VCR values < 2 (without consideration of labor costs). More favorable edaphic and climatic conditions in northern Benin but also differences in crop type may explain this discrepancy. As shown in Fig. 4 and Table 4, reducing the cost of inputs and increased prices for outputs (scenario S3) may further boost the attractiveness of the MD technology.

4.3. Explaining variability in yields and responses

Overall, the LMM analysis identified sowing date as well as soil- (pH, clay + silt, total carbon, P_Bray1 and exch.-Mg contents) and management-related variables (previous crops and weed pressure) as the environmental and management variables that best explain yield variability across all input treatments (Table 5). Among other variables, better yields were associated with larger clay + silt and total carbon contents, and good weed management (Table 5). In contrast, the yields were negatively related to sowing date and rainfall, these two variables being correlated. Late sowing may reduce the length of the growing period and increase the risk of end-of-season drought-stress. Higher rainfall may have cause temporary waterlogging or increased losses of nutrients by leaching. The negative relationship between yield and Exch-Mg and between yield and pH (Table 5) is counterintuitive, and may have been the result of confounding with other variables or nutrient imbalances.

Based on our dataset, 80% of the variability in maize grain yields could be explained. In itself this adjusted R^2 value is very good, but it is inflated by the contribution of the 'treatment' factor. When applying the model to estimate yields at the level of a given treatment, the model performance tended to be highest (low RMSE) for the control and lowest (high RMSE) for the high nutrient input treatments. The part of variability attributed to environmental and management factors (19%) is comparable to the results of Bielders and Gérard (2015) who found that management and environmental factors explained 20% of the variation in millet yield in Niger following microdose fertilization. Despite this overall good performance of the model, a non-negligible fraction of unexplained variation remains (20% in the present study). This could be related to biotic factors affecting maize yield (such as pests and diseases), climate factors (such as temperature, drought stress, etc) that are poorly considered by simple rainfall-related indices, edaphic factors (such as micronutrient deficiencies, soil structure or slope) but also management factors which were not well characterized here (land preparation, weeding quality, etc…).

As previously reported by Sileshi et al. (2010), Bielders and Gerard (2015) and Kihara et al. (2017), a significant negative relationship was observed between yield response to mineral fertilization and yield in the control plots (Fig. 3). Whereas yields increased by approx. 1300 kg ha^{-1} following microdosing on low yielding control plots, on high yielding control plots this increase was limited to 1000 kg ha^{-1}. This appears consistent with the variable responsiveness concept put forward by Kihara et al. (2016), which states that plots will be increasingly less responsive to additions of macronutrients as their initial fertility increases – especially if these additions are small. This negative relationship between yield response and yield in the control plot was less marked when fertilizer microdosing was combined with hill-placed manure (Fig. 3). This may be because the addition of manure lifted some deficiencies not related to N and P (e.g., micronutrients), thereby allowing a stronger response to macronutrients. A regression analysis was performed to further explain the relationship between response and environmental or management variables. With the variables included in the model, we could explain 25–33% of the yield response variability (Table 6) with three parameters of influence (soil clay and total carbon content, and pH). This is comparable to the results of Ronner et al. (2016) who found that environmental and management factors explained 45% of variability in soybean response to phosphorus fertilizer in farmers' fields in northern Nigeria. Nevertheless, the explanatory power of the regression remains limited. In future trials, plant rather than soil analyses may help clarify the limiting nutrients and the resulting plant response to crop intensification practices. The fact that rainfall was not retained as an explanatory variable (Table 6) was somewhat unexpected but could reflect the fact that soil fertility- and management-related factors are more strongly limiting plant production than water during the 2 years of experimentation. In addition, the rainfall data were collected across a limited area and hence the range of rainfall values also remains limited.

4.4. Opportunities and implications for scaling out

In northern Benin, maize production plays an important role in the rural economy and livelihoods. However, the low inherent soil fertility, high intra-seasonal climate variability, and poor management of agricultural land result in low yields. With the fertilizer microdosing technology, there is a potential opportunity for smallholder farmers who are constrained in their capacity to invest in external inputs to increase maize productivity and resource use efficiency. Indeed, with this technology, the average yields were always close to or even outperform the targeted yield of 3 t ha^{-1} for achieving the African Green Revolution (Sanchez, 2010).

The present study also contributes to the increasing recognition that average crop responses or economic indicators are insufficient to fully assess the performance of a technology, and that measures of variability (e.g. the frequency distributions) are also needed to assess the risks (e.g., Sileshi et al., 2010; Vanlauwe et al., 2016). While there are concerns regarding the extra labor required for hill-placement of manure or fertilizers, the present study established that fertilizer microdosing alone (preferably the MD1 option) or combined with hill-placed manure generally resulted in economic returns that are much higher than the recommended fertilization practice even in low productive fields. In addition, since manure or fertilizer application is done after sowing and before weeding at a period of greater labor availability, it does not interfere with crop sowing and weeding, which are critical labor bottlenecks in the study area. Moreover, the benefits reported here appear to be so economically attractive that they should draw farmers' interest towards fertilizer microdosing. Nevertheless, adequate institutional support and training will be required particularly to develop labor-reducing equipment, to make mineral fertilizer more affordable and accessible and to support the internal maize market, which may allow fertilizer microdosing to remain highly profitable and further motivate farmers to use this technology. These two latter actions would be all the more important in a context of unstable input and output markets leading to a reduction in prices of grain and an increase in fertilizer and labor costs and thereby to an increased economic risk (Fig. 4; Table 4).

The present on-farm experiment allowed testing microdosing technology across a range of climatic, soil and crop management conditions, but challenges remain as to how to improve the relevance of the recommendations regarding microdose fertilization. Although it is clear that maize response to microdosing may be linked to multiple factors, the plot's productivity level can be used as a first approximation to make targeted recommendations. Based on Fig. 4, microdose fertilization should be targeted preferentially to low productive plots. This is particularly true for MD alone since for MD + FYM this effect is much less pronounced. In addition, fertilizer microdosing will perform the best under favorable climatic condition, appropriate sowing dates and good weed management particularly because of the small amount of nutrients applied (Supplementary Fig. S1). Thus, it should be promoted as part of a basket of good agricultural practices.

5. Conclusion

Although microdose fertilization rates correspond to 31–44% of the rates recommended by research and extension for maize in northern Benin, similar average yields and lower financial risks were achieved. MD1 must be favored over MD2 because MD1 is associated with lower economic risk yet yields are similar to MD2. In addition, hill-placed manure application made the application of microdose fertilization more attractive and economically viable for a large proportion of farmers. The range of environmental and management conditions encountered across the sites resulted in a high variability of yields between farms. Sole microdose fertilization should be targeted preferentially to low productive plots, while yield response to MD + FYM treatments seem less affected by management and climatic conditions. However, further studies are needed across a broader range of locations in Benin and over several production seasons in order to better understand crop response to microdose fertilization. Such an endeavor would also be facilitated by the development of dedicated decision support tools.

Acknowledgements

This study was facilitated through a doctoral grant from the West Africa Agricultural Productivity Program (WAAPP-Benin) and a fellowship from the Université catholique de Louvain (UCL). We are also grateful to the staff of the National Agricultural Research Centre of Northern Benin (CRA-Nord) for their technical help.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fcr.2018.10.018.

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