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Drivers of sorghum response to fertilizer microdosing on smallholder farms across Burkina Faso

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ABSTRACT

Fertilizer microdosing (FM) is being disseminated to resource-limited smallholder farmers within the framework of sustainable intensification in order to boost crop productivity. However, scaling up of this technology revealed that yield response variability may be a barrier to its adoption. A total of 351 on-farm trials across three agro-climatic zones (Sissili: 800–1000 mm, Oubritenga: 600–800 mm and Zandoma: $\leq$ 600 mm mean annual rainfall) over two years in Burkina Faso were therefore conducted in order to identify the factors driving sorghum (*Sorghum bicolor (L.) Moench*) yield response to FM (2 g/hill of N-P-K 14–23–14 and 1 g/hill of urea). The trials were stratified to consider soil types (indigenous classification) as well as the distance between homesteads and fields as a criterion of fertility. Additional variables included previous crop management practices and weed pressure. On average, FM application increased yields by 385, 571 and 388 kg/ha in Sissili, Oubritenga and Zandoma, respectively. The proportion of fields with a value-cost ratio (VCR) $\geq$ 2 was 34% in Sissili, 56% in Oubritenga, and 30% in Zandoma. In the three zones, yield response to FM tended to increase with increasing soil depth and plot duration of cultivation, as well as with the proper timing of weeding and fertilizer application. Within Sissili lower responses were observed on stony-gravelly and sandy soils compared to black soils, and also on plots previously amended with high amounts of fertilizer compared to soils with moderate or no previous fertilizer application. For plots with no previous fertilizer application, better responses were observed on plots with legumes as antecedent crop. In Oubritenga, responses were greater on clayey soils compared to other soil types. In Zandoma, yield response was greatest in lower floodplain soils compared to other soils, and increased with increasing delay in sowing. Overall, crop response to FM was affected by (i) soil type and topographic position, (ii) plot history through the duration of cultivation, the antecedent crop and the previous fertilization rate, and (iii) plot management. The relative importance of these factors was site-specific and can be easily communicated to farmers.

1. Introduction

Fertilizer microdosing (FM) consists in placing small amounts of mineral fertilizer in the planting holes at sowing or next to the seedlings after emergence (Muehlig-Versen et al., 2003; Twomlow et al., 2006). The most commonly used rates correspond to applications of 2–6 g/hill of fertilizer depending on the type of fertilizer and crop (Bagayoko et al., 2011; Tabo et al., 2011; Bielders and Gérard, 2015). However, very low application rates (0.3–0.9 g/hill) have also been tested (Aune et al., 2007; Aune and Ousman, 2011). Since its conceptualization by ICRISAT in the 1990′s, it has been demonstrated repeatedly that this technology results in similar or greater yields compared to the recommended rates used for broadcast fertilization while requiring 30–50% less fertilizer (Fatondji et al., 2016; Aune et al., 2017; Okebalama et al., 2017;

Abbreviations: AGRA, Alliance for a Green Revolution in Africa; BUNASOLS, National Soil Office of Burkina Faso; CIMMYT, International Maize and Wheat Improvement Center; DAS, Days After Sowing; FM, Fertilizer microdosing; ICRISAT, International Crops Research Institute for the Semi-Arid Tropics; IGB, Geographical Institute of Burkina Faso; UTM, Universal Transverse Mercator; VCR, Value-Cost Ratio; VIF, Variance Inflation Factor; WGS, World Geodetic System; WRB, World Reference Base.

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Demisie, 2018; Ouedraogo et al., 2020). Therefore, FM facilitates smallholder farmers' access to fertilizers, and it is seen as an opportunity for resource-constrained farmers to move towards more productive and sustainable production systems (Aune and Bationo, 2008).

FM has been widely promoted in sub-Saharan Africa over the last decade (Twomlow et al., 2010; Camara et al., 2013; AGRA, 2014). However, like many other agricultural technologies, FM is being disseminated to farmers without really considering the variability of its performance related to the biophysical heterogeneity of the environment and farming contexts (Zingore et al., 2007; Fermont et al., 2009; Vanlauwe et al., 2015; Falconnier et al., 2016; Kihara et al., 2016). Recommendations are usually provided on the basis of expected average performance at the national or regional level, without paying attention to the sometimes large variations in yield response observed across fields and/or farms (Vanlauwe et al., 2016). Thus, there is a risk that this indiscriminate promotion of FM will stunt the interest of farmers experiencing yield responses below the expected range and lower than expected economic profitability (Bielders and Gérard, 2015). The effectiveness of FM could therefore be improved by site-specific targeting.

The first evidence of variability in crop response to FM was reported in the works of Buerkert et al. (2001), Twomlow et al. (2010), Tabo et al. (2011) and Camara et al. (2013), albeit with no specific focus of these authors on the drivers of variability. The study of Bielders and Gérard (2015) focused specifically on the variability of millet (*Pennisetum glaucum (L.) R. Br.*) response to FM in southwest Niger. These authors reported that 34% of the 276 studied plots fell below the profitability threshold. In a more humid area in northern Benin, Tovihoudji et al. (2019) found a probability of non-profitability ranging from 6% to 86% depending on fertilizer and maize (*Zea mays L.*) prices. Both studies observed that yield response to FM tended to increase as yields in control plots decreased. In a meta-analysis of millet, sorghum (*Sorghum bicolor (L.) Moench*), and maize response to FM from across sub-Saharan Africa, Ouedraogo et al. (2020) reported greater responses to FM with increasing rainfall, on medium-textured soils compared to heavy or light-textured soils, and when combined with water harvesting techniques. However, in order to turn the latter results into operational recommendations, they must be refined and further validated by field experiments that take into consideration, for each agro-climatic zone, the complex interactions that can occur between climate, the diversity of soil types, and cropping practices (Nyamangara et al., 2011; Vanlauwe et al., 2016; Diallo et al., 2019). The objective of this study was therefore to identify the factors driving sorghum response to FM in three agro-climatic zones of Burkina Faso and to draw up recommendations with regard to the biophysical domains and cropping practices for which the best responses are observed.

2. Materials and methods

2.1. Study area

The study was conducted in three provinces of Burkina Faso (Sissili, Oubritenga and Zandoma provinces), corresponding to three agro-climatic zones following the south-north climatic gradient of the country (Table 1; Fig. 1). Rainfall in the three provinces follows a unimodal distribution with a rainy season from May to October. However, the amount of rainfall does not allow to start sowing operations until early June in Sissili and until late June in Oubritenga and Zandoma. In each province, a municipality was chosen based on the availability of farmer organizations that are active in the promotion of FM. These were the municipality of Bieha (11° 03′ 26″N, 1°49′ 20″ W), Nagreongo (12°28′58″ N, 1°11′36″W), and Gourcy (13°13′ 00″ N, 2°21′00″ W) in Sissili, Oubritenga and Zandoma provinces, respectively (Fig. 1). In each municipality, three villages were selected to widen the diversity of environmental contexts.

Table 1
Agro-climatic characteristics of the study zones (provinces).

	Sissili	Oubritenga	Zandoma
Agro-ecological zone	Sudanian	Sudano-Sahelian	Sahelian
Annual rainfall (mm)	800–1000	600–800	500–600
Main crops (by order of importance)	Maize, sorghum, sesame, cotton groundnut	Sorghum, millet, sesame groundnut, cowpea	Sorghum, millet, groundnut, cowpea

Due to the higher rainfall, the Sissili province is a maize and cotton growing area (Table 1). These crops generally benefit from mineral fertilization (100–150 kg ha^{-1} of N-P-K + urea) compared to other crops that are generally grown without fertilizer in this province (MAAH, 2020). In Oubritenga, crops are generally grown without fertilizer. However, with the promotion of FM in this province, some farmers are applying mineral fertilizer to their cereal crops at average rates of about 90 kg N-P-K ha^{-1} (MAAH, 2020). In Zandoma, besides low rainfall, soils are more degraded. Thus, farmers routinely apply small amounts of N-P-K fertilizer to their sorghum plots, which is the staple food of families. The average amount of fertilizer applied is 72 ± 29 kg ha^{-1} for plots receiving only mineral fertilizer and 62 ± 21 kg ha^{-1} for those also receiving organic amendments (data from a survey in the study area).

2.2. Set-up of on-farm trials

2.2.1. Identification of trial plots

To capture response variability, it is necessary that the location of experimental plots reflects the heterogeneity of cropland in the study areas. Taking soil samples from all farmers' fields in each study area and analyzing them prior to plot selection is, however, not realistic in practice (Ronner et al., 2015). Variations in soil properties are often high over short distances and existing soil mapping (1:100 000 scale) would not capture this variability. It was therefore decided to choose farmer's classification of soil types as a soil stratification criterion. This is a pragmatic classification related to the characteristics and behavior of the cultivated soils in terms of topographical position, texture, color, and water retention (Kissou et al., 2014, 2018). Thus, focus groups were organized in the villages to identify the soil types used for sorghum growing, a crop that is grown in all three regions (Table 2).

In addition, the distance of the plot from the farmer's homestead was retained as a stratification criterion, as it is associated with a gradient in soil fertility (Prudencio, 1993). Hence, the plots were categorized into: (i) homestead plots (0–100 m from the homestead), (ii) village plots (100 m - 1 km from the homestead), and (iii) bush plots (> 1 km from the homestead). For each combination of soil type and distance from homestead (soil x distance), plots were proposed by farmers belonging to the farmers' organizations involved in the study in each province. Those plots were subsequently visited to ensure that they indeed met the required criteria. Spatial heterogeneity of plots was also assessed since high heterogeneity (e.g., due to the presence of large termite mounds or tree canopies, local depressions or steep local slopes, localized deposits of previous organic amendment, etc.) could result in biased response levels to FM. Hence plots with large intra-plot spatial variability were excluded. The choice was made to focus on the combination of these two stratification factors (soil type and distance) in order to have a sufficient number of plots each year (between 6 and 10 plots) for each combination of factors. Note that not all Soil type x Distance combinations existed in each study area. It was further assumed that plot selection based on these two criteria would also encompass a diversity of plots in terms of cropping history (number of years of cultivation, crop rotation and fertility management).

The experiments were conducted in 2018 and 2019. Each year, around 75 plots were set up in each province, trying as much as possible to balance the different soil x distance combinations. In total, the trial was set up on 445 plots over the two years. In the three provinces, plots

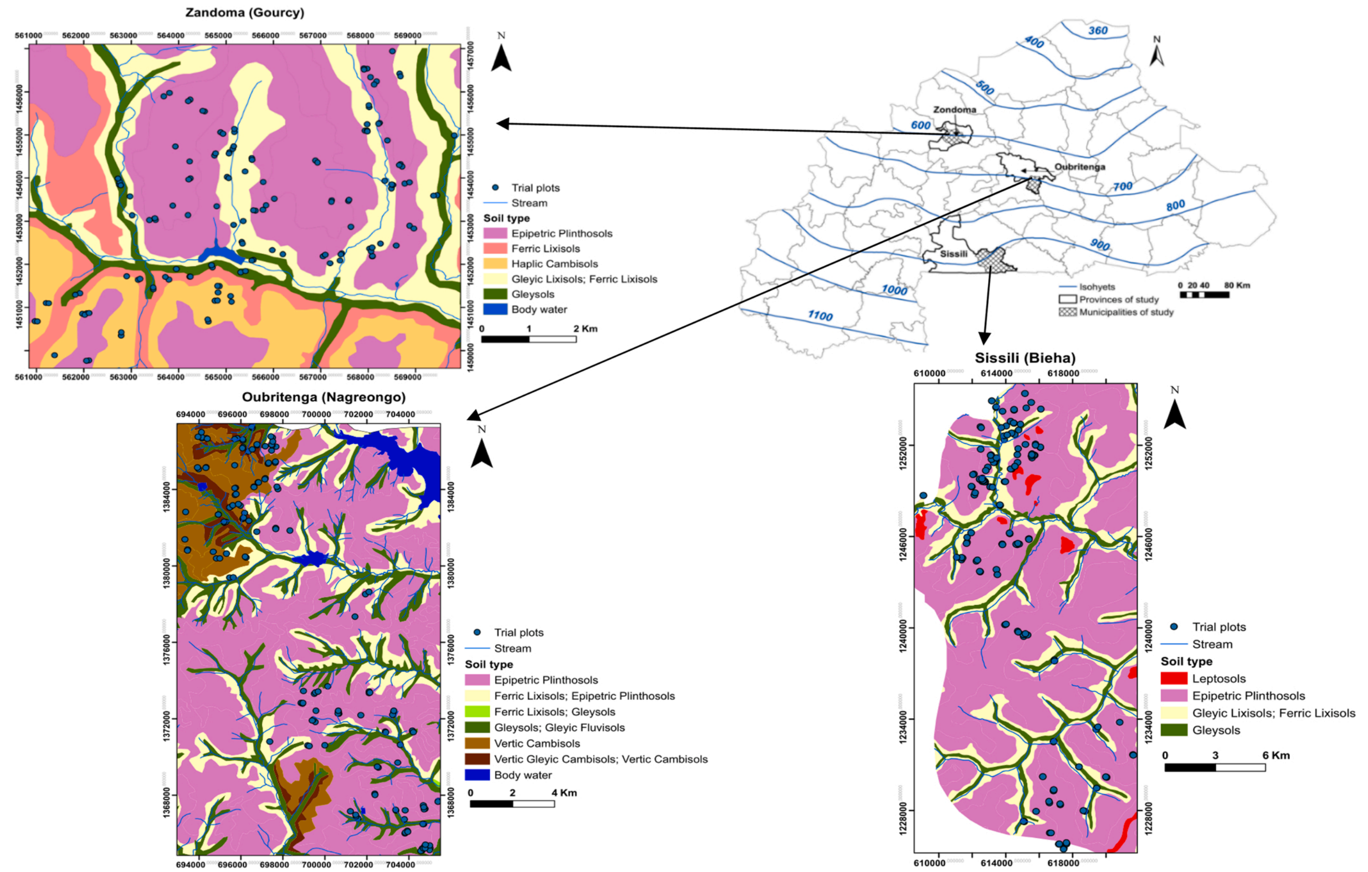

Fig. 1. Location of study zones and trial plots, and (co-)dominant soils in the three study zones. Sources: - Morpho-pedological mapping (1/100 000) from National Soil Office of Burkina Faso (BUNASOLS) - Hydrography (1/200 000) from Geographical Institute of Burkina Faso (IGB). Projection: UTM Zone 30 N Datum: WGS 1984 Coordinates: meters.

Table 2
Soil types in the 3 provinces according to endogenous classification and their likely equivalent in World Reference Base (WRB) classification, and their characteristics, qualities and drawbacks according to farmers.

Soil type in endogenous classification	Characteristics and Landscape position	Soil qualities	Soil drawbacks	Soil name in English	Possible equivalent in WRB classification
Zandoma and Oubritenga (in *mooré* language)					
Zinka	Gravelly, shallow soil Up - and mid-slope positions	Low weed pressure	Sensitive to drought	Gravelly soil	Epipetric Plinthosol
Bisga	Sandy, deep soil, Mid - and down-slope positions	Easy to till, Rapid seed germination	Dries out quickly, Week seedlings	Sandy soil	Gleyic Lixisol (ferric)
Zi-naaré[a] (in Zandoma only)	Clayey tendency, deep soil, Flat areas and down-slope position	Retains soil moisture	Requires early sowing	Upper floodplain	Endogleyic Lixisol (ferric), Fluvisols
Bolle (in Oubritenga only)	Clayey, deep soil, Flat areas and mid-slope position	Retains soil moisture	Risk of waterlogging	Clay soil	Vertisol, Vertic Cambisol
Baongo/Kossogo	Clayey tendency, deep soil, Stream bank position	Remains wet during drought periods	Risk of flooding, High weed pressure	Lower floodplain soil	Eutric Gleysol, Fluvisols
Sissili (in *nuni* language)					
Kapatotia	Presence of stone outcrop, Stony and gravelly, shallow soil, Up-slope and mid-slope positions	Low weed pressure	Difficult to plow and weed, Sensitive to drought	Stony-gravelly soil	Epipetric Plinthosol
Kafnoutia	Gravelly, shallow soil, Up-slope and mid-slope positions	Low weed pressure	Sensitive to drought	Gravelly soil	Epipetric Plinthosol
Kassouloutia	Sandy, deep soil Down-slope position or flat areas	Easy to till, Quick seed germination	Dries out quickly	Sandy soil	Gleyic Lixisol (ferric)
Tizounoutia	Black soil, Clayey tendency, deep soil, Up -, mid -, or down-slope positions	Fertile soil, Retains soil moisture, Quick seed germination	More rapid yield decline compared to gravelly soil	Black soil	Eutric Gleysol, Vertic Cambisol, Vertisols

[a] Following the toposequence from bottom to top, the *Zi-naaré* soil corresponds to the soils located in the upper part of the stream bank, with a lower occurrence of flooding. We called this location 'upper floodplain'

categorized as "homestead plots" often corresponded to very small areas (< 0.05 ha on average), something that was also described by Prudencio (1993). Many of these plots were thus too small to accommodate the experimental design (0.06 ha without the alleys between treatments). In addition, given that homestead plots are considered more fertile than more remote plots due to high inputs in organic amendments, they are usually used for growing maize and/or vegetables. Consequently, farmers were reluctant to let these plots be used for trials because of their important function in supplying vegetables. As a result, homestead plots were less represented in the trials than other combinations (9% in Sissili, 12% in Oubritenga, and 6% in Zandoma).

2.2.2. Trials

The trials were conducted with sorghum (*Sorghum bicolor (L.) Moench*; variety Kapelga, 90–100 days), a crop cultivated both in the northern and southern parts of Burkina Faso. The experimental design consisted of two 300-m^2 plots with no replicate: a control treatment without fertilizer and an FM treatment. The FM treatment consisted in applying N-P-K (14−23−14) fertilizer at a rate of 2 g/hill (62.5 kg ha^{-1}; sowing density of 31250 hills/ha) around the 15th day after sowing (DAS) and urea (46%) at a rate of 1 g/hill (31.25 kg ha^{-1}) around the 45th DAS. These rates correspond to what is commonly promoted to famers as FM in Burkina Faso and represent fertilizer applications (N-P-K and urea) reduced by 38% compared to the recommended rates for sorghum in broadcast fertilization (100 kg/ha of N-P-K 14–23–14 and 50 kg/ha of urea) (Taonda et al., 2015; Somda et al., 2017; Saba et al., 2018). A minimum set of management guidelines was agreed upon with the farmers to minimize the risk of treatment failure and to reduce the variability that may result from too much difference in trial management between farmers. These included: (i) animal-drawn plowing with no organic amendment applied to the plots, (ii) sowing by means of a hoe at a spacing of 80 cm x 40 cm, (iii) weeding by means of a hoe, coupled with thinning to two plants per hill just prior N-P-K fertilizer application, and (iv) hoe weeding just prior to urea application.

2.3. Data collection

The trial plots and farmers' homesteads were georeferenced and the distances from plots to homesteads were calculated with ArcGIS 10.4. Besides, the coordinates of the plots were projected onto morpho-pedological mapping shapefiles (scale 1/100,000) of each province provided by the National Soil Bureau of Burkina Faso (BUNASOLS) to determine the topographic positions of the plots. The history of the plots (duration of plot cultivation from 0 to ≤ 30 years, crop rotation over the last 4 years, previous fertilizer and organic amendment application rates, etc.) was recorded through a survey with the farmers. It was difficult for farmers to quantify the organic amendments previously applied. This variable was therefore collected by considering the modalities "yes" and "no", respectively if organic amendments were applied or not. One-kilogram composite soil samples (0–20 cm) from 5 points on the diagonals were collected between the rows of each treatment around 30 DAS. Samples were dried and sieved to 2 mm to determine the proportions of coarse elements. During the wettest month (August), soil depth was assessed by means of an auger at two locations on the diagonals of each treatment to a maximum depth of 1 m or to the depth at which a rocky or indurated layer was encountered.

Rain gauges were positioned in each village ensuring a maximum distance of 2 km between any given plot and the nearest gauge. Data from the nearest rain gauge were assigned to each plot. Rainfall amounts at different stages of the sorghum development cycle (Gerik et al., 2014) were calculated for each plot: 0–14 DAS (initial growth stage), 15–39 DAS (crop development stage), 40–80 DAS (boot stage to hard-dough stage), 81–100 DAS (hard-dough to physiological maturity).

The dates of the cropping operations conducted on the plots (from ploughing to harvest) were recorded on forms by technicians supported by local facilitators. Weed cover on the plots was assessed by visual observation of the percentage cover (Chicouène, 1999) using weed cover charts (1%, 2%, 5%, 10%, 20%, 30%, 40%, 50% and over 50% cover). Weed cover was assessed at 40 and 75 DAS. It was combined with an assessment of the severity of striga infestation (*striga sp.*) on a scale 1–4 (1 = no striga infestation, 2 = low infestation, 3 = moderate infestation, 4 = high infestation). Evidence of crop damage by pests and diseases was also recorded. Grain yields and plant densities were assessed at physiological maturity for 5 subplots of 25 m^2 (5 m × 5 m) located on the diagonals of each treatment. Areas not representative of plot conditions (partial shading by tree crowns, presence of small termite mounds, damage areas, etc.) were avoided. Harvested grain was air-dried and weighed to obtain yields in kg ha^{-1}.

2.4. Data analysis

Prior to any analysis, the database was checked to remove data from plots that had not complied with the experimental design, not been weeded, or been destroyed by animals, pests, erosion or flooding. In total, 351 plots were retained (106, 138 and 107 plots in the Sissili, Oubritenga and Zandoma provinces, respectively). In Sissili, 36% of the plots were black soils, 28% were gravelly soils, 25% were sandy soils and 10% were stony-gravelly soils. In Oubritenga, clay and gravelly soils represented 28% each, sandy soils 24%, and lower floodplain soils 20%. In Zandoma, 43% of plots were gravelly soils, 30% lower floodplain soils, 17% sandy soils and 10% upper floodplain soils. All analyses were performed separately for each zone after pooling data from 2018 and 2019. Analyses were done with R 4.0.4.

Descriptive analyses were first performed using box plots and cumulative probability plots to assess the distribution of the collected variables. Scatter plots were then used to assess the relationships between yield response and independent variables. Sorghum yield response (Δyield) is defined as:

$$\Delta\text{yield} = \text{Yield FM} - \text{Yield Control} \quad (1)$$

where Yield FM is the yield of the FM plot (kg ha^{-1}) and Yield Control is the yield in the unfertilized control plot (kg ha^{-1}).

To analyze the risk faced by farmers when applying FM, the level of response needed to obtain a value-cost ratio (VCR) of 2 was calculated for each province.

$$VCR = \frac{(\Delta yield) \text{ x } (Unit \text{ price of grain})}{Cost \text{ of } fertilizer} \quad (2)$$

where Unit price of grain = unit market price of sorghum grain (local currency, XOF kg^{-1}), and Cost of fertilizer = cost of applied N-P-K and urea in XOF.

VCR was calculated considering the average of the lowest market prices of sorghum in each province over the last five years, i.e., 129, 125 and 135 XOF kg^{-1} for Sissili, Oubritenga and Zandoma provinces, respectively (data from National Food Security Stock Management Company of Burkina Faso) and the average price of FM fertilizer in the provinces in 2020 (33750 XOF, survey from farmers). It should be noted that the price of fertilizer between provinces does not differ much. The cost of labor for fertilizer application was not considered. According to CIMMYT (1988), a VCR ≥ 2 is needed to ensure adoption by small-holder farmers in developing countries.

To identify the factors driving variability of FM response, a multiple linear regression was performed with yield response (Δyield; Eq. (1)) as the dependent variable. The independent variables were year, distance from homestead, rainfall amounts at the different stages of the crop development cycle, biophysical factors (i.e., soil type, soil depth and gravel content, topographic position, etc.) and plot management factors (timing of cropping operations, weed cover, previous fertilizer amount, duration of plot cultivation, etc.). Interactions between variables that emerged from the exploratory analysis were included in the multiple regression. Multicollinearity was addressed by removing variables with variance inflation factors (VIF) > 10, while considering the relevance of the variables for the model (package "car"). The "stepAIC" command of the "MASS" package was used for the selection of the best model with the selection direction "both". The contributions of the variables to the percentage variance explained by the model were determined with the "relaimpo" package. The variables not retained in the multiple linear regression were used in a generalized additive model to investigate the variables with possible non-linear relationships with yield response (package "gam"). Finally, only variables retained by stepwise selection in the regressions (linear and non-linear) were reported.

In addition to these regressions, boundary lines of the response were investigated as a function of the collected variables (Shatar and Mcbratney, 2004; Fermont et al., 2009). The boundary lines allow to highlight the yield response potential (highest achievable yield response) as a function of exploratory variables (e.g., soil depth, weed cover) in the study context. For large datasets, based on the scatter plot of the data (over the range of values of an exploratory variable), it is assumed that an upper limit (boundary line) can be drawn considering the maximum values of the response if there is a cause-effect relationship between the response and the exploratory variable, and if the limits of response in the context are reached (Webb, 1972). The boundary lines were fitted using nonparametric boundary regression using the "npbr" package (Daouia et al., 2017). Only variables that showed a clear trend along the boundary line were retained.

3. Results

3.1. Year and trial characteristics

The annual rainfall received in 2018 and 2019 in the Sissili (1008 and 996 mm) and Oubritenga (860 and 853 mm) provinces were similar or slightly higher than the average rainfall for the past five years in these areas, which was 945 ± 203 mm in Sissili and 788 ± 66 in Oubritenga (data from National Meteorological Agency and rain gauges placed on the plots). The amount of rainfall in 2019 in the Zandoma (744 mm) province was also within the range received over the last 5 years (733 ± 100 mm), while 2018 (926 mm) was a wetter than average year.

Compared to Oubritenga and Zandoma, the heterogeneity of cropping system factors was more important in Sissili. In the latter province, a wider range of duration of plot cultivation was observed due to the presence of large areas not yet deforested or the occurrence of very long fallows (Table 3). Half of the experimental plots in this province had a duration of cultivation or recultivation ≤ 12 years versus 24 years in Oubritenga and 21 years in Zandoma. Sissili is also a maize and cotton growing area (Table 1; both crops are generally fertilized, see Section 2.1), thus, the previous fertilizer inputs were on average higher on plots in Sissili than in the two other provinces (Table 3). Although the amount of fertilizer applied in Sissili was higher on average, the proportion of plots having benefitted from a previous fertilizer application was higher in Zandoma (70% of plots) compared to Sissili (41%) and Oubritenga (23%). Finally, the plot history survey revealed that whereas legume haulms are systematically harvested and stored for livestock in Zandoma and Oubritenga, the early-groundnut haulms are generally left on the ground or buried in the soil in Sissili, which can lead to potential residual effects. Observance of experimental plot management instructions was generally better in Oubritenga than in the other two provinces (Table 3). The first weeding was conducted on average around 17 DAS and N-P-K fertilizer application around 14 DAS. In addition, weed control was better overall in Oubritenga than in the other two provinces (Table 3).

3.2. Sorghum grain yield and yield response variability to FM

Sorghum grain yields increased with increasing mean annual rainfall in the agro-climatic zones (Fig. 2). In Sissili, control yields ranged from 117 to 3520 kg ha^{-1} and FM yields from 200 to 4000 kg ha^{-1}. Intermediate yield levels were observed in Oubritenga, with yields ranging from 160 to 2480 kg ha^{-1} for the control and 280–3440 kg ha^{-1} for the FM. Yields were lowest in Zandoma and ranged from 0 to 800 kg ha^{-1} for the control and from 120 to 1720 kg ha^{-1} for the FM.

The best sorghum yield responses to FM (Eq. (1)) were observed in Oubritenga with an average response of 571 kg ha^{-1}, compared to

Table 3
General and management characteristics of experimental plots in each of the three provinces.

	Sissili				Oubritenga				Zandoma			
	Mean±SD	Min	Median	Max	Mean±SD	Min	Median	Max	Mean ±SD	Min	Median	Max
Plots characteristics												
Soil depth (cm)	57 ± 22	15	51	> 100	67 ± 21	24	71	> 100	73 ± 27	23	80	> 100
Distance between plot and farmer's home (m)	1599 ± 1399	48	1285	5456	1181 ± 1187	34	628	4869	977 ± 748	55	814	3548
Duration of plot cultivation or re-cultivation (year)[a]	16 ± 12	0	12	30	20 ± 11	0	24	30	18 ± 13	0	21	30
Duration of fallow before plot cultivation (year)[b]	28 ± 6	2	30	30	17 ± 12	1	20	30	12 ± 10	2	8	30
Previous fertilizer amount(kg ha^{-1})[c]	93 ± 121	0	0	360	25 ± 51	0	0	300	48 ± 44	0	50	200
Plot Management												
Number of days between start of rainy season and sowing date[d]	25 ± 6	10	26	38	13 ± 6	1	12	27	19 ± 4	9	19	29
Number of days between sowing and first weeding	20 ± 11	7	17	49	17 ± 6	5	15	35	26 ± 8	6	25	45
Number of days between sowing and N-P-K fertilizer application	19 ± 6	8	18	43	14 ± 5	6	14	29	18 ± 6	8	17	41
Number of days between sowing and urea application	45 ± 6	30	46	57	49 ± 6	25	48	63	44 ± 6	30	44	66
Weed cover at 75 DAS (%)	29 ± 19	1	30	70	14 ± 15	1	10	70	19 ± 20	1	10	70

DAS = Days after sowing

[a] It was difficult for farmers to provide information that went back many decades into the past. Thus, information collected on the duration of cultivation and fallowing of plots were limited to 30 years.

[b] Only plots under cultivation for less than 10 years have been considered for this variable. It corresponds to 50%, 25% and 36% of the studied plots in Sissili, Oubritenga and Zandoma, respectively.

[c] Average calculated across all plots, including unfertilized plots.

[d] The actual start of the rainy season was considered to be June 15 in Sissili and July 1 in Oubritenga and Zandoma.

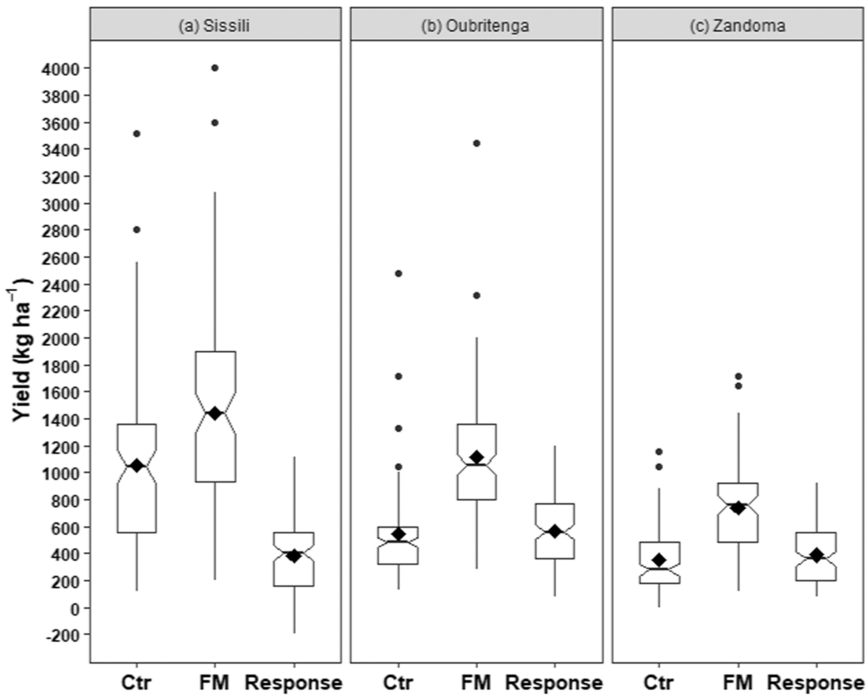

Fig. 2. Sorghum grain yield distribution for the control (Ctr) and fertilizer microdosing (FM) treatments, and yield response to FM (Response = yield FM – yield Control; Eq. (1)) for the three provinces. The diamond shape in the center of the box indicates the means.

385 kg ha^{-1} in Sissili and 388 kg ha^{-1} in Zandoma (Fig. 2). Yield response variability (coefficient of variation) was greater in Sissili (CV=73%) than in Oubritenga (CV=49%) and Zandoma (CV=56%). With the exception of a few sites in Sissili, yield gains (Δyield > 0) were consistently observed in FM (Fig. 3). In Zandoma, the response to FM was not directly related to plot productivity as reflected in the yield of the control (Fig. 3c). In contrast, in Sissili and Oubritenga, response to FM increased with increasing yield in the control plot up to a control yield of 600 (Oubritenga; Fig. 3b) or 800 kg ha^{-1} (Sissili; Fig. 3a). Above this optimum value, there is a slight decrease in response for these two provinces. Above 900 kg ha^{-1} (Zandoma and Oubritenga) and 2000 kg ha^{-1} (Sissili), the number of observations is insufficient to support a significant trend.

Given fertilizer and sorghum market prices, the level of grain yield response to FM that achieves a value-cost ratio (VCR; Eq. (2)) of 2 was 522, 538, and 501 kg ha^{-1} in Sissili, Oubritenga, and Zandoma,

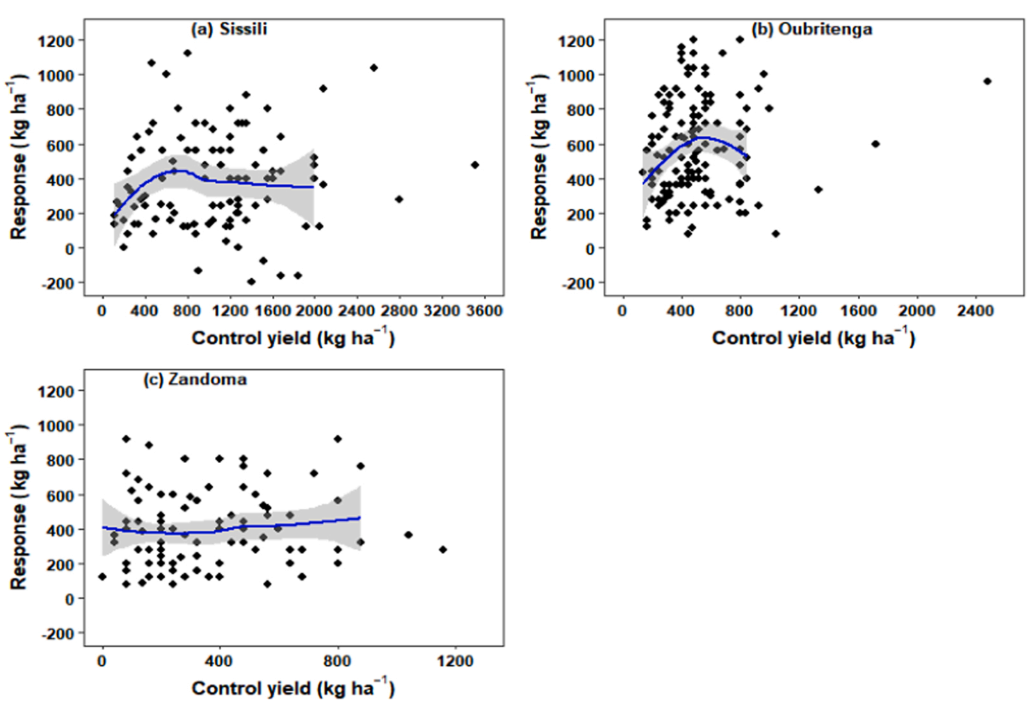

Fig. 3. Sorghum grain yield response (Δyield; Eq. (1)) to fertilizer microdosing (FM) as a function of yield in control plots in the three provinces. The blue curve corresponds to the local regression estimate.

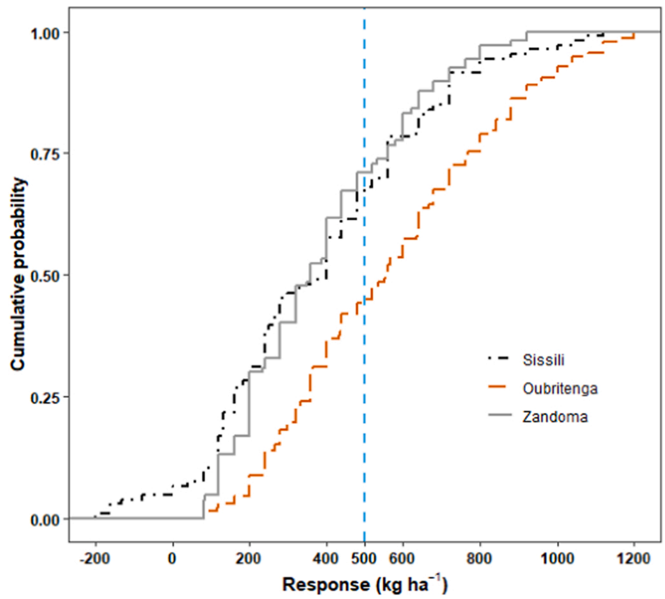

Fig. 4. Cumulative probability of sorghum grain yield response (Δyield; Eq. (1)) to fertilizer microdosing (FM) for the three study provinces. The vertical dashed line corresponds to a yield response of 500 kg ha^{-1}, which in this study corresponds to the response at which the value-cost ratio is ≥ 2.

respectively. Given the small range of variation between provinces, a threshold value of 500 kg ha^{-1} was used to facilitate comparison. Thus, the proportion of plots achieving a VCR ≥ 2 was 56% in Oubritenga versus 34% in Sissili and 30% in Zandoma (Fig. 3). The proportion of plots for which FM was not profitable (VCR < 1) was 37%, 15%, and 33% in Sissili, Oubritenga, and Zandoma, respectively.

3.3. Factors explaining variability in sorghum grain yield response to FM

The model selected by the linear regression for the Sissili province explained 29% of the total variance (Table 4). Plots' history (the combination of previous crop type and previous fertilizer amount) contributed to 29% of this explained variance. Trial management characteristics contributed to 40%, of which 25% related to plot weed cover, and 11% and 4% to timing of fertilizer application and weeding, respectively. Soil type and topographical position contributed 18% and 17%, respectively.

On average, the responses observed on stony-gravelly soils and to a lesser extent on sandy soils were significantly lower than on black soils. No significant differences were observed between the response of black soils and gravelly soils (Table 4). In terms of topography, the best responses were observed on plots located at mid- and up-slope positions compared to plots at valley bottom position. Significantly lower responses were observed on plots previously amended with high amounts of fertilizers (301–400 kg ha^{-1}) compared to plots with no previous fertilizer application (Table 4). Also, better responses were observed on plots with legumes as a previous crop compared to plots with no legumes and no previous fertilizer application. High weed pressure as well as delayed urea application resulted in significantly lower responses.

In Oubritenga, the model also explained 29% of the total variance (Table 5). Two thirds of this explained variance (66%) resulted from the contribution of the soil type. Topographic position contributed to 15%. The interaction between soil type and the amount of fertilizer applied the previous year contributed 8% and soil depth contributed to 7%. The variables 'amount of rainfall received at 81–100 DAS' and 'amount of previous fertilizer' shared the remaining 4%.

Table 5 shows that the average response on clay soils was very significantly higher than on lower floodplain soil. In terms of topographical position, the best responses were also observed on plots

Table 4
Optimal multiple linear regression model to explain sorghum grain yield response (Δyield; Eq. (1)) to fertilizer microdosing (FM) in the Sissili province.

Δ (yield) = SoilType + Landscape + Fert.Prev.Crop + IntSowWeed + IntSowUrea + Weed.cover

Parameter	Estimate	Std. Error	t value	Pr (>|t|)
(Intercept)	1173.7	229.5	5.115	1.73e-06 * **
Gravelly soil	-48.6	69.4	-0.701	0.485
Sandy soil	-122.8	69.7	-1.763	0.081.
Stony-Gravelly soil	-313.5	81.6	-3.843	0.000 * **
Down-slope	51.9	106.6	0.488	0.627
Mid-slope	196.6	100.1	1.964	0.053.
Up-slope	203.9	105.3	1.937	0.056.
Cuirassed plateau	-55.2	134.2	-0.412	0.682
0. Fert.legume	150.2	72.2	2.079	0.040 *
100–200. Fert.Cot.Maize	34.8	68.5	0.509	0.612
201–300. Fert.Cot.Maize	77.9	66.1	1.179	0.241
301–400. Fert.Cot.Maize	-381.3	119.8	-3.183	0.002 * *
IntSowWeed1	-4.1	2.6	-1.614	0.110
IntSowUrea	-13.7	4.2	-3.233	0.002 * *
Weed.cover	-5.8	128.9	-4.491	2.07e-05 * **

Significance codes: * ** $p < 0.001$, * * $p < 0.01$, * $p < 0.5$, "." $p < 0.1$
Adjusted R-squared: 0.285
F-statistic: 3.996 on 14 and 91 DF, P-value: 2.478e-05
SoilType = soil type; Landscape = topographic position; Fert.Prev.Crop = previous crop and fertilizer amount; IntSowWeed1 = Interval between sowing and 1st weeding (days); IntSowUrea = Interval between sowing and application of urea (days); Weed.cover = weed cover (%).
0. Fert.legume = Legume as previous crops, without fertilizer application;
100–200. Fert.Cot.Maize = Cotton or maize as previous crops, with 100–200 fertilizer amount (kg ha^{-1});
201–300. Fert.Cot.Maize = Cotton or maize as previous crops, with 201–300 fertilizer amount (kg ha^{-1});
301–400. Fert.Cot.Maize = Cotton or maize as previous crops, with 301–400 fertilizer amount (kg ha^{-1}).
" Black soil ", " Valley Bottom", and " No legume as previous crops, without fertilizer application" were used as reference levels in the model for the "soil type", "topographic position" and "previous crop and fertilizer amount" variables, respectively.

Table 5
Optimal multiple linear regression model to explain sorghum grain yield response (Δyield; Eq. (1)) to fertilizer microdosing (FM) in the Oubritenga province.

Δ (yield)= SoilType + Landscape + Soil.depth + Prev.Fert.Amount + Rain.81-100. DAS + SoilType: Prev.Fert.Amount

Parameter	Estimate	Std. Error	t value	Pr (>|t|)
(Intercept)	43.1	189.9	0.227	0.820
Sandy soil	17.7	81.3	0.218	0.828
Gravelly soil	99.9	107.5	0.930	0.354
Clayey soil	354.7	80.3	4.417	2.14e-05 * **
Valley bottom	54.4	107.5	0.506	0.614
Mid-slope	135.2	72.7	1.859	0.065.
Up-slope	200.8	73.0	2.750	0.007 * *
Soil depth	3.2	1.8	1.734	0.085.
Prev.Fert.Amount	2.1	1.4	1.486	0.140
Rain.81–100. DAS	0.8	0.5	1.516	0.132
Sandy soil:Prev.Fert.Amount	-1.1	1.7	-0.665	0.507
Gravelly soil:Prev.Fert. Amount	-2.0	1.6	-1.291	0.199
Clayey soil:Prev.Fert.Amount	-3.3	1.6	-2.088	0.039 *

Significance codes: * ** $p < 0.001$, * * $p < 0.01$, * $p < 0.5$, "." $p < 0.1$
Adjusted R-squared: 0.294
F-statistic: 5.744 on 12 and 125 DF; P-value: 7.917e-8
SoilType = Soil type; Landscape = topographic position; Prev.Fert.Amount = Previous crop fertilizer amount (kg ha^{-1}); Rain.81-100; DAS = cumulative amount of rainfall between 81 and 100 days after sowing (mm). " Lower floodplain soil " and " Down-slope position " were used as reference levels in the model for the " soil type " and " topographic position " variables, respectively.

located at mid- and up-slope positions. Soil depth was found to have a positive effect on response. Finally, the improvement in response due to the effect of previous year's fertilizer application was significantly lower on clay soils than on lower floodplain soil.

The linear model selected in Zandoma province explained only 12% of the total variance (Table 6). Soil type contributed to 29% of this explained variance, and the duration of cultivation or recultivation of plots contributed 20%. Management variables contributed 41%, including 13% for the timing of urea application, 12% for weed pressure, 9% for the timing of the first weeding, and 7% for the sowing period. Rainfall amounts at 0–14 and 81–100 DAS contributed to the remaining 10%.

In Zandoma, the best responses were observed on average on lower floodplain soils and, to a lesser extent, on upper floodplain soils (Table 6). Besides, the response tended to increase with the duration of plot cultivation. In terms of management factors, delayed weed control and increased weed pressure were found to decrease the response of FM. However, unexpectedly, there was a trend of increasing response with delay in urea application (Table 6). An increase in response was also observed with delayed seeding.

Generalized Additive Model regression analyses did not highlight non-linear relationships between the response and the collected variables. Potential response curves (upper boundary lines) were therefore sought as a function of the variables. In Sissili, boundary lines of yield response were identified as a function of soil characteristics and plot management factors (Fig. 5). An increase in yield response potential was observed with increasing soil depth and duration of plot cultivation (Fig. 5a and c). The lowest response potentials were obtained for soils with depths less than 30 cm. These plots correspond to stony-gravelly and gravelly soils (Fig. 5a). Beyond 30 cm, the effect of depth on the increase in response is less pronounced, and the maximum response was found on mid-slope black soils. A strong decrease in response potential is observed when the duration of plot cultivation is less than 5 years (Fig. 5c). From Fig. 5b and d, it appears that the increase in coarse element content in the soil and the delay in weeding lead to a decrease of the yield response potential. The expected response potential starts dropping when stone content exceeds approx. 30%. It drops strongly after 30 days without weeding (Fig. 5d). Finally, the period of N-P-K application that maximizes yield response potential is at about 15 DAS (Fig. 5e). Beyond this period, the response potential decreases.

Table 6
Optimal multiple linear regression model to explain sorghum grain yield response (Δyield; Eq. (1)) to fertilizer microdosing (FM) in the Zandoma province.

Δ (yield)= SoilType + Dur.Cult + IntStartSeasonSow + Rain.0-14. DAS + Rain.81-100. DAS + IntSowWeed1 + IntSowUrea + Weed.cover

Parameter	Estimate	Std. Error	t value	Pr (>|t|)
(Intercept)	-542.8	337.7	-1.607	0.111
Upper floodplain soil	145.8	79.3	1.838	0.069.
Gravelly soil	61.9	54.0	1.146	0.254
Lower floodplain soil	183.2	62.1	2.950	0.004 * *
Dur.Cult	3.4	1.7	2.083	0.040 *
IntStartSeasonSow	17.7	8.5	2.081	0.040 *
Rain.0–14. DAS	1.4	0.8	1.832	0.070.
Rain.81–100. DAS	2.2	1.4	1.578	0.117
IntSowWeed1	-4.7	2.8	-1.700	0.092.
IntSowUrea	9.4	3.9	2.395	0.018 *
Weed.cover	-2.3	1.1	-2.060	0.042 *

Significance codes: * ** $p < 0.001$, * * $p < 0.01$, * $p < 0.5$, "." $p < 0.1$
Adjusted R-squared: 0.118
F-statistic: 2.417 on 10 and 96 DF; P-value: 0.013
SoilType = Soil type; Landscape = topographic position; Dur.Cult = number of years of cultivation (years); Rain.0-14. DAS = cumulative amount of rainfall between 0 and 14 days after sowing (mm);
Rain.81-100. DAS = cumulative amount of rainfall between 81 and 100 days after sowing (mm);
IntSowWeed1 = interval between sowing and 1st weeding (days);
IntSowUrea = interval between sowing and application of urea (days);
IntSowUrea = interval between sowing and application of urea (days);
IntStartSeasonSow = interval between onset of season and sowing date (days);
Weed cover = weed cover (%). "Sandy soil" was used as reference level in the model for the "soil type" variable.

In Oubritenga, the best responses to FM were largely determined by soil type and were observed mostly on clay soils (Table 5 and Fig. 6). The boundary lines were therefore adjusted first with all data, then after excluding clay soils, to separate the effect of other factors from the influence of these clay soils.

When clay soils are included, a strong positive relationship between soil depth and the potential response was observed over the entire depth range (Fig. 6a). Without clay soils, the positive relationship was only found for soil depths < 30 cm on gravelly soils. Beyond this depth, the positive relationship is almost non-existent (Fig. 6a). Fig. 6b also shows that the observed negative relationship between yield response and proportion of coarse elements disappears when clay soils are not included. Finally, when clay soils are included, there is no clear relationship between the level of response potential and the duration of the plot cultivation due to the important effect of clay soils on the response (Fig. 6c). In contrast, after excluding clay soils, the lowest response potentials were observed for plots with a cultivation duration < 5 years (Fig. 6c).

As in Sissili and Oubritenga, positive relationships of response potential with soil depth and duration of the plot's cultivation were found in Zandoma (Fig. 7a and b). The lowest response potentials were again observed for shallow soils (depth < 30 cm) and newly cultivated or recultivated plots (< 5 years of cultivation). Also, N-P-K application around 15 DAS again appeared to maximize yield response potential (Fig. 7d). This maximization of yield response was also observed on plots with moderate fertilizer applications (around 75 kg ha^{-1}) in the previous year (Fig. 7c). In addition, an almost linear decrease in response potential was observed with an increase in weed pressure (Fig. 7e).

4. Discussion

4.1. Factors driving variability in sorghum response to FM

Yields in the control and FM treatments tended to increase with the mean annual rainfall across the three study areas (Fig. 2). This likely results from better nutrient use as water availability increases (Buerkert et al., 2002; Tabo et al., 2011; Tonitto and Ricker-Gilbert, 2016), but also from differences in overall soil quality between the provinces. Indeed, Sissili and Oubritenga benefit from the presence of more fertile soils, i.e., black and clay soils, respectively (Table 2). In addition, the mean duration of plot cultivation is lower overall in Sissili (Table 3).

The higher yields observed in the FM plots compared to the controls resulted from better plant survival in the FM plots and also from the formation of bigger panicles in these plots (Supplementary Figs. S1 and S2). FM boosts root development of the plants (Ibrahim et al., 2014). As a result, the plants are more vigorous and better able to withstand potential physiological stresses, which include water deficits or excesses.

Although mean yield responses are comparable in Sissili and Zandoma (Fig. 2), the variability is higher in Sissili (CV=73% in Sissili and 56% in Zandoma). This higher variability in sorghum yield response in the Sissili province reflects the greater heterogeneity in cropping system factors in this province, in particular the greater diversity in the duration of cultivation of the plots and in previous fertilizer application rates. In Sissili and Oubritenga, the response to FM tends to increase, on average, with increasing productivity of the control plots, up to a certain threshold yield of control plot after which the response to FM begins to decrease (Fig. 3). This general relationship is also observable in the data published by Bielders et al. (2015) and was partly observed by Tovihoudji et al. (2019) who found a trend of decreasing FM responses with increasing yields in control plots. This observation is consistent with what is classically observable in terms of a crop's response to fertilizer

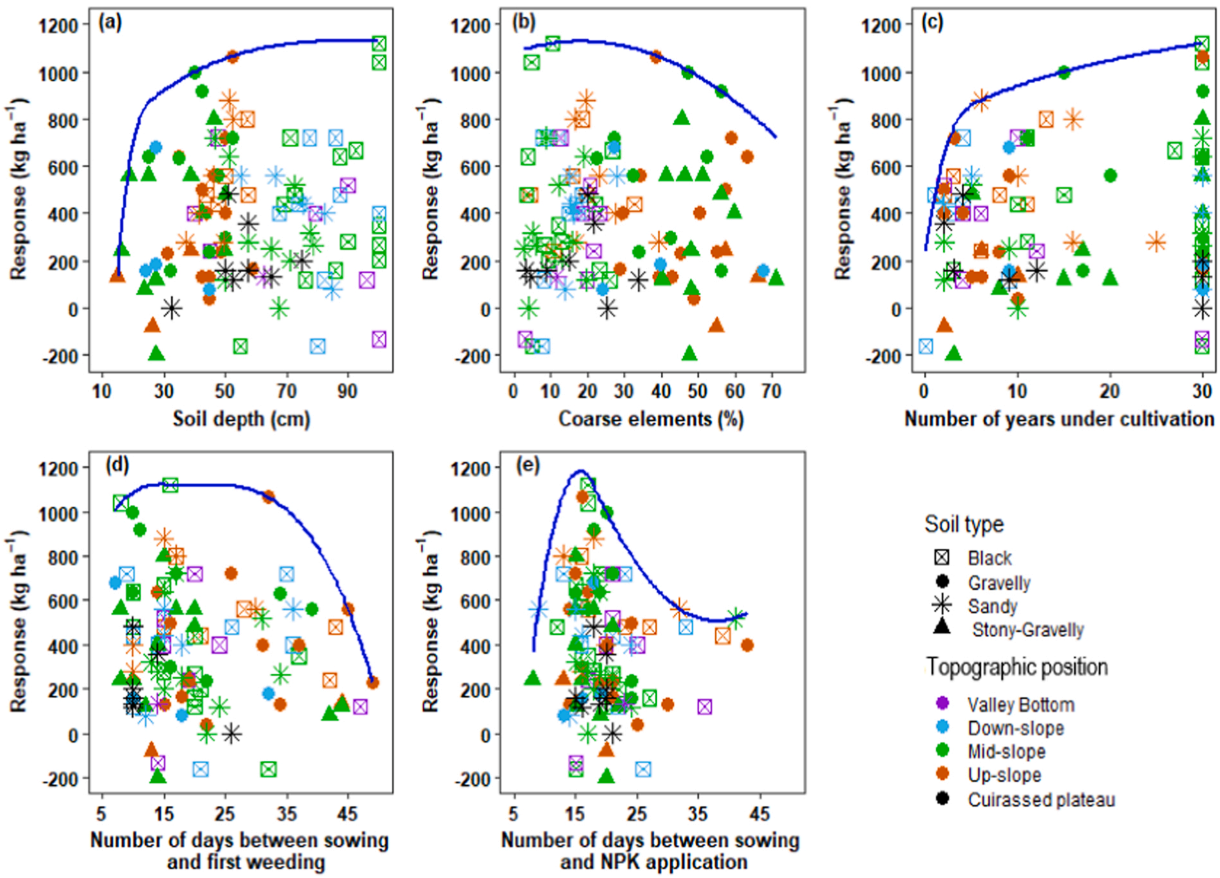

Fig. 5. Boundary lines for sorghum grain yield response (Δyield; Eq. (1)) to fertilizer microdosing (FM) in the Sissili province for (a) soil depth, (b) percentage of soil coarse elements, (c) number of years the plot has been under cultivation, (d) number of days between sowing and first weeding, (e) number of days between sowing and N-P-K application.

application, namely that the yield gains due to the application of a given amount of fertilizer decreases at a certain level of soil fertility (Caldwell et al., 2002; Vanlauwe et al., 2011; Gram et al., 2020; Serme et al., 2020). The high variability in response to FM found across provinces further emphasizes the need to address variability in crop response to agricultural technology as part of scaling up processes in sub-Saharan Africa (Vanlauwe et al., 2016; Falconnier et al., 2016).

As generally stated by Tittonell et al. (2007), the factors that determined variability in response to FM in this study were soil characteristics (soil type, topographical position, depth), plot history (duration of cultivation, previous crops and fertilizer amount), and trial management factors (weed cover, timing of cropping operations). The relative importance of these factors and the processes underlying this variability were, however, quite specific for each agro-climatic zone.

In the Oubritenga province, the best responses are mostly observed on clay soils (Table 5, Fig. 6). These soils likely correspond to Vertisols or vertic Cambisols in the WRB classification (Table 2) and are known as being inherently more fertile (Casenave and Valentin, 1989; Kissou et al., 2018) compared to other cultivated soil types present in the province. Inherent fertility encompasses the chemical, physical and biological fertility resulting from soil parent material, depth, texture, etc., excluding the human-induced changes. In Sissili, the best responses were found on black soils (Table 4, Fig. 5). According to Sissili farmers, black soils are inherently the most fertile in this area (Table 2). In the cotton zone of Mali with similar climatic conditions to Sissili, Falconnier et al. (2016) highlighted that black soils (as defined by farmers) had the best SOC and nutrient contents. Finally, in Zandoma, the best responses were found on lower floodplain soils (Table 6, Fig. 7) compared to other soils. Under the low rainfall conditions of Zandoma, lower floodplain soils are less prone to drought (Table 2) and are appreciated by farmers. Due to their low topographic position, these soils benefit from the water, nutrient and organic matter inflows from upstream (Phiri et al., 1999; Rockström et al., 1999; Kissou et al., 2018). The highest responses to FM in each province were thus observed on soil types that are known to be inherently the most fertile there. This suggests that a certain threshold of inherent soil fertility is required in order to achieve the potential of FM response. Ibrahim et al. (2014) and Tovihoudji et al. (2017) have shown that by stimulating crop development, FM results in greater nutrient uptake by crops than what is provided through FM fertilization. A strong response to FM therefore implies an additional uptake of soil nutrients. By being capable of providing these additional nutrients as well as better moisture conditions, such soils with better inherent fertility levels may thus boost the response to FM.

In terms of topographic position, the best responses were observed on plots at mid- and up-slope positions in Oubritenga and Sissili (Tables 4 and 5). In Oubritenga, this is due to the fact that clay soils, which are the soils with the best responses to FM, are mostly located in the up-slope and mid-slope positions (Fig. 6a). In Sissili, this result is the combined effect of two processes. On the one hand, when we consider stony-gravelly soils and gravelly soils, we observe that the best responses of these types of soils are found in the mid-slope position where these soils are deeper and with lower coarse element content (Fig. 5a and b). On the other hand, unlike those in the mid- and up-slope positions, some black and sandy soils located in the valley bottom or down-slope positions in the Sissili province were affected by waterlogging and tended to have lower responses. Thus, the general trend in Sissili was to have better responses on plots at mid- and up-slope positions. In Zandoma, the landform is less rugged, without "valley bottom" topographical positions

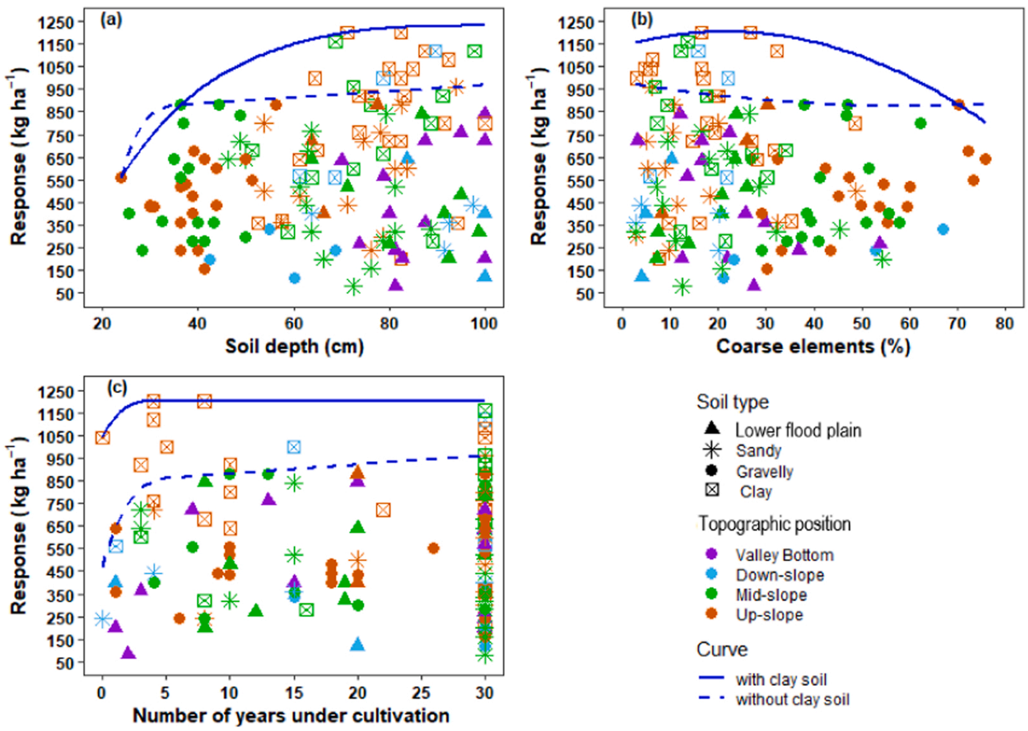

Fig. 6. Boundary lines for sorghum grain yield response (Δyield; Eq. (1)) to fertilizer microdosing (FM) in the Oubritenga province for (a) soil depth, (b) percentage of soil coarse elements, (c) number of years the plot has been under cultivation. Solid lines represent boundary lines for the overall data set, while dashed lines represent boundary lines without the clay soils (see text for explanation).

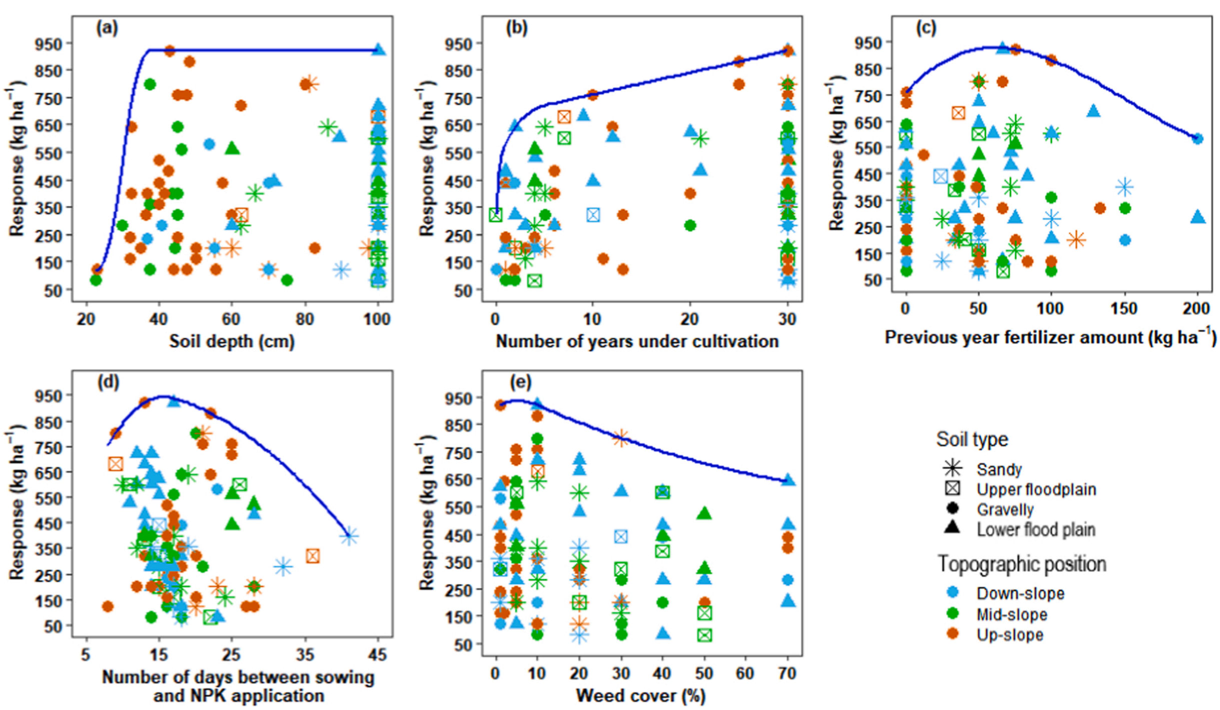

Fig. 7. Boundary lines for sorghum grain yield response (Δyield; Eq. (1)) to fertilizer microdosing (FM) in Zandoma province for (a) soil depth, (b) number of years the plot has been under cultivation, (c) previous crop fertilizer amount, (d) Number of days between sowing and N-P-K application, (d) weed cover.

(Fig. 7) in the study locations, unlike in Sissili and Oubritenga (Figs. 5 and 6). It is also an area with lower rainfall compared to Sissili and Oubritenga (Table 1). As result, the lower floodplain soils in this province were less prone to waterlogging. In summary, it appears that in terms of soil characteristics, the best responses were observed on soil types and topographical positions characterised by good inherent fertility, soil depth and water availability.

In terms of the history of plots, the lowest response potentials were observed in newly cultivated or recultived plots (Table 6, Figs. 5c, 6c and 7b), particularly in the Sissili and Zandoma provinces. In Sissili, newly cultivated plots are plots that were cleared for the first time or after a long period of fallow (Table 3). These plots have a better level of fertility (better organic matter and nutrient content) compared to those that have been under cultivation for a long time (Serpantié and Ouattara, 2001; Samaké et al., 2005). Thus, on average, control yields of plots with duration of cultivation $\leq$ 5 years were high (1267 kg ha^{-1}), and in the same range as FM yields of plots with duration of cultivation $>$ 10 years (Sissili; Supplementary Fig. S3). In such situations where soil productivity levels are already high, the potential of plots to respond to small amounts of fertilizer as those in FM would be low (Vanlauwe et al., 2016; Amouzou et al., 2018; Tovihoudji et al., 2019).

In contrast to Sissili, the low response observed on newly recultivated plots in Zandoma is unlikely to result from a high fertility status. In fact, in this province, land availability is limited, leading to shorter fallow periods (Table 3). Furthermore, based on our data, it was observed that if we consider only plots cultivated for less than 10 years since the last fallow period, the lowest yield levels (control and FM) are observed on plots with fallow durations $<$ 10 years (data not shown). In these low-input systems characterized by almost continuous cropping, the restoration of soil fertility after short-duration fallowing is limited, especially on sandy or gravelly ferruginous soils (Roose, 1993; Serpantié and Ouattara, 2001). In contrast, plots under continuous cropping may benefit from the cumulative residual effects of applied nutrients such as phosphorus (Coulibaly et al., 2012). They may also be less crusted due to repeated tillage (Ambouta et al., 1996). As a result, continuously cropped plots with systematic application of small amounts of fertilizer - as is observed on sorghum plots in Zandoma - may have better responses to FM than plots newly recultivated after a short fallow whose fertility level may be too low (Kurwakumire et al., 2014). To a lesser extent, this may also explain the low yield response potentials of newly recultivated plots in Oubritenga when clay soils are excluded from the dataset (Fig. 6c). This trend is, however, not as apparent in Oubritenga as in Zandoma, probably because fertilizers are not systematically applied to sorghum plots in Oubritenga.

Still in relation to the history of plots, analysis of yield response as a function of residual effects of previous cropping practices in Sissili and Zandoma showed that response was better on plots benefitting from the residual effects of previous-year fertilization or legume crops. Yield response tended to first increase with the amount of fertilizer applied in the previous year, then drop for plots previously amended with the highest amounts of fertilizer (Table 4, Fig. 7c). All else being equal, it is likely that plot fertility and yield response potential to FM increase with the magnitude of the fertilizer and legume residual effects, up to a given level of fertility at which point the potential response to nutrient supply by FM starts decreasing (Vanlauwe et al., 2002; Kihara et al., 2010). This is similar to the situation of newly cleared plots described above for the Sissili province. This relationship is also reflected in the 'soil type' x 'previous fertilizer amount' interaction observed in the Oubritenga province, where it was found that the effect of previous fertilizer amount on yield response increase is lower on soils considered more fertile, such as clays soils (Table 5).

The variable 'distance from homesteads' was not identified as a determinant factor of FM response, contrary to what might have been expected (Vanlauwe et al., 2006; Tittonell et al., 2007). This could be due to a predominant effect of the 'duration of plot cultivation' variable on the 'distance of plots from homesteads' variable. Indeed, particularly in the Sissili province, newly cultivated plots generally corresponded to the plots that were the most remote from homesteads. In addition, it should also be noted that, as the population increases, new households are increasingly settling around existing homesteads, resulting in a trend toward a decrease in the proportion of 'homestead plots'. Thus, from our field observations, we did not find noticeable differences in the physiognomy of crops according to the distance of the plots from the farmers' homesteads. This suggests that the distance-related gradient in plot fertility is no longer as steep in these areas as was reported earlier by Prudencio (1993), or as observed in other regions in sub-Saharan Africa (Vanlauwe et al., 2014).

The sorghum response levels to FM obtained in Sissili and Zandoma provinces were strongly affected by the management of trial plots. The best responses were obtained when the timing of fertilizer application and weed control operations (Tables 4 and 6, and Figs. 5 and 7) was respected. The trend of increasing response with delayed seeding as observed in Zandoma results from the fact that delayed seeding significantly reduces yield in control plots ($t = -2.03$, $P = 0.045$) whereas this reduction is not significant in FM plots ($t = -1.21$, $P = 0.227$), something that was also observed by Bielders et al. (2015) in Niger. Fertilization may have shortened crop duration, thereby avoiding end-of-season drought (Nourou et al., 2020). The importance of plot management on crop response to agricultural technologies has been noted by authors who have analyzed variability (Fermont et al., 2009; Ronner et al., 2015). In Oubritenga, where plot management guidelines were better followed by the farmers (Table 3), plot management was not found to determine crop response. This overall better management of the plots and the occurrence of clay soils with high yield response potential to FM, could explain the fact that more than 50% of the trial plots in this province achieved a VCR $\geq$ 2, compared to only about 30% in Sissili and Zandoma (Fig. 4).

Overall, the dynamics of yield response to FM highlighted in our study refer to the idea of response classes formulated by Vanlauwe et al. (2010), and illustrated by Kihara et al. (2016) for fertilization in general. Thus, the response curve to FM as a function of plot fertility can be seen as a bell-shaped curve that can be divided into three zones: (i) an initial zone of low response to FM due to major constraints that may be, among others, those identified in this study, namely shallow soil and/or high coarse element content, waterlogging problems, high weed pressure, or too low initial fertility (e.g., newly recultivated plots after a short fallow in Zandoma); (ii) a central zone that corresponds to plots with intermediate fertility, where the nutrients provided by FM stimulate plant development and provide a significant yield gain, as observed on average on black (Sissili), clayey (Oubritenga) and lower floodplain (Zandoma) soils but also on plots having benefitted from the residuals effects of legume crops or moderate prior fertilization; (iii) then a zone beyond a given fertility threshold, where the yield gain due to FM is low because yield levels on these plots are already fairly high without FM. This corresponds for instance to the newly cultivated plots in Sissili or to plots having benefitted from large prior fertilization rates.

4.2. Recommendation domains for better sorghum response to FM

Based on the identified factors and on the general pattern of response to FM (bell-shaped curve), the following recommendations can be drawn up for the dissemination of FM to farmers. To benefit from the full response potential of FM, it is necessary to ensure good weed control and to respect the fertilizer application timing (15 DAS for N-P-K and 45 DAS for urea).

In addition to the requirement of good plot management, FM application should be prioritized on plots with intermediate levels of fertility. Empirically, this would correspond to plots where sorghum yields, without fertilization, range from 400 to 1000 kg ha^{-1} in Sissili and from 400 to 700 kg ha^{-1} in Oubritenga (Fig. 3). Although there was no evidence of a relationship between the yield level on control plots and sorghum response to FM in Zandoma, the range of 400–700 kg ha^{-1} could be considered given the similarities in rainfall and cropping system with the Oubritenga province (Table 1). Regarding the variability factors, FM application should be prioritized on soils of good inherent fertility such as black soils in Sissili, clay soils in Oubritenga and lower floodplain soils in Zandoma. In addition, it would be most beneficial on plots that received moderate fertilizer inputs the previous year (50–100 kg ha^{-1} in Zandoma and Oubritenga, and 100–300 kg ha^{-1} in Sissili; Fig. 7c and Table 4) or on plots where legume haulms from a previous crop have been buried (Table 4).

FM should not be applied on plots that already have high levels of productivity with no fertilizer. This is the case for newly cleared plots or plots that have benefited from previous fertilizer applications of more than 300 kg ha^{-1} in Sissili. By extension, this would also be the case for plots that have benefited from previous large inputs of high-quality organic amendments (e.g., compost and manure). A rule of thumb for this recommendation would be to not apply FM on plots whose yield levels in the absence of fertilization reach the 3rd quartile of the FM yield distribution in the agricultural context of interest. In the contexts of our study, this would correspond to plots with yield levels $\geq$ 1900, 1300, and 1000 kg ha^{-1} for Sissili, Oubritenga, and Zandoma provinces respectively (Fig. 2). FM application should also be avoided on shallow soils (depth < 40 cm), on plots with too low initial fertility level, and on plots subject to waterlogging. Shallow soils generally correspond to gravelly and stony-gravelly soils (Figs. 5a, 6a and 7a), and plots with low initial fertility correspond in this study to plots newly recultivated after fallows of less than 5 years in the Zandoma province. The waterlogging constraint could be mitigated by implementing techniques that improve drainage (e.g., cropping on ridges with drainage furrows). Furthermore, combining FM with water harvesting or soil moisture conservation techniques could greatly improve crop response to FM in low rainfall areas such as Zandoma and Oubritenga, especially on gravelly soils (Palé et al., 2009; Ouedraogo et al., 2020).

Recommendations have been made based on FM trials (2 g/hill of N-P-K 14–23–14 and 1 g/hill of urea) conducted over two years with rainfall amounts close to the long-term average for the study areas. Therefore, the recommendation domains may be different under extreme (dry or wet) rainfall conditions, or for different rates and/or types of fertilizer. For example, best responses might also be observed in the lower floodplains in Oubritenga in dry years, or on gravelly soils in high rainfall years, mostly in the Sissili province. Moreover, for very low fertilizer rates such as those tested by Aune and Ousman (2011) (0.3–0.9 g/hill), the best responses may not be observed on soils of good inherent fertility as highlighted in this study. To foster adoption of FM, extension approaches should not only target domains of best response but also support the development of mechanized FM application tools suited to smallholder farmers' conditions in order to reduce labor constraints associated with localized placement of fertilizer (Okebalama et al., 2017; Aune et al., 2019).

4.3. Challenges in better understanding response variability

The proportion of variability in FM response captured by the linear models was 29% for Sissili and Oubritenga province, and 12% for Zandoma. These explained variances remain low, similar to the explained proportions of 14% and 25% reported for FM by Bielders et al. (2015) and Tovihoudji et al. (2019), respectively. Nonlinear model fitting did not improve the proportion of variance explained. In contrast, boundary lines improved the understanding of response variability by highlighting factors not identified by linear regressions. Beyond the limitations of the methods (multiple linear regression and boundary line) that were used (Shatar and Mcbratney, 2004; James et al., 2013), the large proportion of unexplained variance likely results from insufficient characterization of environmental heterogeneity. In particular, plot history was captured through farmer surveys but farm management characteristics are not recorded by farmers. As a result, it has been difficult, for example, to accurately assess the amounts of fertilizer previously applied and the acreage on which these fertilizers were applied. In addition, the dynamics of plot transfer between farmers and the complexity of crop rotations often encountered on small areas do not always allow for accurate determination of the duration of cultivation of plots and/or clear identification of previous cropping practices. Besides, within the same soil type, there may be differences in microtopography or inherent fertility. In Sissili, for example, it can be noted that the "black soil" class is less homogeneous than other indigenous soil types and may correspond to Gleysols, Vertic Cambisols or Vertisols in the WRB classification (Table 2). Thus, the intrinsic fertility levels of the plots may have been only partially captured.

In addition, there are possible complex interactions between factors that cannot be analyzed properly given the size of the dataset. Including physical and chemical parameters from soil analyses might have improved the explained variance (Fermont et al., 2009; Ronner et al., 2015). However, soil testing is still largely out of reach for the small-holder farmers targeted by the FM technology, which would make the resulting recommendations less relevant. The main advantage of this analysis is that the results can easily be understood and disseminated to smallholder farmers. The results have some genericity, however, and could be used to promote FM in other contexts in Burkina Faso or sub-Saharan Africa. Indeed, although the soil types were defined by farmers in their local context, there is some equivalence between the soil types defined by farmers and soil types according to the World Reference Base (WRB) classification (Table 2). Furthermore, endogenous soil classifications (i.e., farmer soil types) for similar agro-climatic zones have similarities in the sense that endogenous classifications are generally based on common criteria such as topographic position, texture, color and soil water retention capacity (Kissou et al., 2014, 2018; Falconnier et al., 2016). Finally, the overall pattern of yield response to FM highlighted in this study (bell-shaped curve) - with the best responses observed in the intermediate fertility range - could be a sensible approach for FM extension. However, depending on the agro-climatic context and the fertilizer types and rates promoted, it would be necessary to determine the fertility thresholds that define the range of best responses (Fig. 3).

5. Conclusions

Field trials were conducted in Burkina Faso in three provinces following the south-north agro-climatic gradient of the country, allowing to highlight biophysical and management domains where better sorghum yield responses to FM are observed. These domains are related to the timeliness of weeding and fertilization on the one hand, and to soil types, duration of plot cultivation and the residual effects of previous cropping practices on the other hand. Because the provinces differ in terms of soil types, cropping systems and land pressure, the latter factors are specific to each province (agro-climatic zone), thereby justifying the need for site-specific studies.

In each province, the highest levels of response were observed on the soil types known as having a good inherent fertility. However, beyond the fertility levels inherent to the soil types, FM response levels dropped in situations where plots were newly cleared, had benefited from large previous fertilizer applications, or were prone to waterlogging problems. Based on the factors determining yield response, recommendations were formulated to reduce the risk of low response incurred by farmers in the application of FM. However, an important part of the variability of response to FM remains unexplained. Thus, the question of how to better explain response variability and refine the recommendation domains remains an issue for further investigation.

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CRediT authorship contribution statement

Yacouba Ouedraogo: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Jean-Baptiste Sibiri Taonda:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Idriss Sermé:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Bernard Tychon:** Conceptualization, Funding acquisition, Writing – review & editing. **Charles L. Bielders:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors do not have permission to share data.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2022.108709.

References

AGRA, 2014. Achieving pro-poor green revolution in dry lands of Africa: Linking fertilizer micro dosing with markets to boost smallholder farmers' livelihoods in Burkina Faso Final report AGRA-microdose project Mai 2014.

Ambouta, J.-M.K., Valentin, C., Laverdière, M.C., 1996. Jachères et croûtes d'érosion au Sahel. Sécheresse 7, 269–275.

Amouzou, K.A., Naab, J.B., Lamers, J.P.A., Becker, M., 2018. Productivity and nutrient use efficiency of maize, sorghum, and cotton in the West African Dry Savanna. J. Plant Nutr. Soil Sci. 181, 261–274. https://doi.org/10.1002/jpln.201700139.

Aune, J.B., Bationo, A., 2008. Agricultural intensification in the Sahel - the ladder approach. Agric. Syst. 98, 119–125. https://doi.org/10.1016/j.agsy.2008.05.002.

Aune, J.B., Ousman, A., 2011. Effect of seed priming and micro-dosing of fertilizer on sorghum and pearl millet in western sudan. Exp. Agric. 47, 419–430. https://doi.org/10.1017/S0014479711000056.

Aune, J.B., Doumbia, M., Berthe, A., 2007. Microfertilizing sorghum and pearl millet in mali: agronomic, economic and social feasibility. Outlook Agric. 36, 199–203. https://doi.org/10.5367/000000007781891504.

Aune, J.B., Coulibaly, A., Giller, K.E., 2017. Precision farming for increased land and labour productivity in semi-arid West Africa. A review. Agron. Sustain. Dev. 37. https://doi.org/10.1007/s13593-017-0424-z.

Aune, J.B., Coulibaly, A., Woumou, K., 2019. Intensification of dryland farming in Mali through mechanisation of sowing, fertiliser application and weeding. Arch. Agron. Soil Sci. 65, 400–410. https://doi.org/10.1080/03650340.2018.1505042.

Bagayoko, M., Maman, N., Palé, S., Sirifi, S., Taonda, S.J.B., Traore, S., Mason, S.C., 2011. Microdose and N and P fertilizer application rates for pearl millet in West. Afr. Afr. J. Agric. Res 6, 1141–1150. https://doi.org/10.5897/AJAR10.711.

Bielders, C.L., Gérard, B., 2015. Millet response to microdose fertilization in south-western Niger: Effect of antecedent fertility management and environmental factors. Field Crop. Res. 171, 165–175. https://doi.org/10.1016/j.fcr.2014.10.008.

Buerkert, A., Bationo, A., Piepho, H.-P., 2001. Efficient phosphorus application strategies for increased crop production in sub-Saharan West Africa. Field Crop. Res. 72, 1–15. https://doi.org/10.1016/S0378-4290(01)00166-6.

Buerkert, A., Piepho, H.-P., Bationo, A., 2002. Multi-site time-trend analysis of soil fertility management effects on crop production in sub-Saharan West Africa. Exp. Agric. 38, 163–183. https://doi.org/10.1017/S0014479702000236.

Caldwell, P.M., Ward, J.M.J., Miles, N., Laing, M.D., 2002. Assessment of the effects of fertilizer applications on gray leaf spot and yield in maize. Plant Dis. 86, 859–866. https://doi.org/10.1094/PDIS.2002.86.8.859.

Camara, B.S., Camara, F., Berthe, A., Oswald, A., 2013. Micro-dosing of fertilizer – a technology for farmers' needs and resources. Int. J. Agric. 3, 387–389.

Casenave, A., Valentin, C., 1989. Les états de surface de la zone Sahélienne: Influence sur l'infiltration. Orstom,.

Chicouène, D., 1999. Evaluation du peuplement de mauvaises herbes en végétation à la parcelle: aperçu des méthodes utilisables. Phytoma. La défense Des. Végétaux 522, 22–24.

CIMMYT, 1988. From Agronomic Data to Farmer Recommendations: An Economics Training Manual. CIMMYT, Mexico, D.F.

Coulibaly, K., Vall, E., Autfray, P., Nacro, H.B., Sedogo, M.P., 2012. Effets de la culture permanente coton-maïs sur l'évolution d'indicateurs de fertilité des sols de l'Ouest du Burkina Faso. Int. J. Biol. Chem. Sci. 6, 1069–1080. https://doi.org/10.4314/ijbcs.v6i3.13.

Daouia, A., Laurent, T., Noh, H., 2017. npbr: a package for nonparametric boundary regression in R. J. Stat. Softw. 79. https://doi.org/10.18637/jss.v079.i09.

Demisie, W., 2018. Fertilizer microdosing technology in sorghum, millet and maize production at small-scale level in africa: a review. Int. J. Adv. Sci. Res. Dev. 5, 39. https://doi.org/10.26836/ijasrd/2018/v5/i4/50407.

Diallo, B.M., Akponikpè, I.B.P., Abasse, T., Fatondji, D., Agbossou, K.E., 2019. Why is the spatial variability of millet yield high at farm level in the Sahel? Implications for research and development. Arid L. Res. Manag. 33, 351–374. https://doi.org/10.1080/15324982.2019.1625984.

Falconnier, G.N., Descheemaeker, K., Mourik, T.A.V., Giller, K.E., 2016. Unravelling the causes of variability in crop yields and treatment responses for better tailoring of options for sustainable intensification in southern Mali. Field Crop. Res. 187, 113–126. https://doi.org/10.1016/j.fcr.2015.12.015.

Fatondji, D., Taonda, S.J.B., Sogodo, D., Mamane, S., Zida, Z., 2016. Taking fertilizer microdosing to scale in sahel. In: Tiff Harris, T.C.L. (Ed.), Going Beyond Demos to Transform African Agriculture: The Journey of AGRA's Soil Health Program, 39. Alliance for a Green Revolution in Africa, Nairobi, Kenya, p. 53 (Kenya).

Fermont, A.M., van Asten, P.J.A., Tittonell, P., van Wijk, M.T., Giller, K.E., 2009. Closing the cassava yield gap: an analysis from smallholder farms in East Africa. F. Crop. Res. 112, 24–36. https://doi.org/10.1016/j.fcr.2009.01.009.

Gerik, T., Bean, B., Vanderlip, R., 2014. Sorghum Growth and Development. https://doi.org/10.1016/j.fcr.2009.01.009.

Gram, G., Roobroeck, D., Pypers, P., Six, J., Merckx, R., Vanlauwe, B., 2020. Combining organic and mineral fertilizers as a climate-smart integrated soil fertility management practice in sub-Saharan Africa: A meta-analysis. PLoS One 15, 1–30. https://doi.org/10.1371/journal.pone.0239552.

Ibrahim, A., Pasternak, D., Fatondji, D., 2014. Impact of depth of placement of mineral fertilizer micro-dosing on growth, yield and partial nutrient balance in pearl millet cropping system in the Sahel. J. Agric. Sci. 1–10. https://doi.org/10.1017/S0021859614001075.

James, G., Witten, D., Hastie, T., Tibshirani, R., 2013. An Introduction to Statistical Learning, with application in R. Springer, New York. https://doi.org/10.1007/978-1-4614-7138-7.

Kihara, J., Vanlauwe, B., Waswa, B., Kimetu, J.M., Chianu, J., Bationo, A., 2010. Strategic phosphorus application in legume-cereal rotations increases land productivity and profitability in western Kenya. Exp. Agric. 46, 35–52. https://doi.org/10.1017/S0014479709990810.

Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., Njoroge, S., Palm, C., Huising, J., 2016. Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. "Agric., Ecosyst. Environ. 229, 1–12. https://doi.org/10.1016/j.agee.2016.05.012.

Kissou, R., Traoré, E., Gnankambary, Z., Nacro, H.B., Sédogo, M.P., 2014. Connaissance endogène de la classification et de la fertilité des sols en zone Sud-Soudanienne du Burkina Faso. VertigO Rev. Électronique En. Sci. l'environnement 14, 1–17 https://doi.org/DOI: 10.4000/vertigo.14616.

Kissou, R., Gnankambary, Z., Nacro, H.B., Sedogo, M.P., 2018. Classification locale et utilisation des sols en zone sahélienne au Burkina Faso. Int. J. Biol. Chem. Sci. 12, 610. https://doi.org/10.4314/ijbcs.v12i1.46.

Kurwakumire, N., Chikowo, R., Mtambanengwe, F., Mapfumo, P., Snapp, S., Johnston, A., Zingore, S., 2014. Maize productivity and nutrient and water use efficiencies across soil fertility domains on smallholder farms in Zimbabwe. Field Crop. Res. 164, 136–147. https://doi.org/10.1016/j.fcr.2014.05.013.

MAAH, 2020. Annuaire Des Statistiques Agricoles. Direction Générale Des Études et Des Statistiques Sectoriels. Ouagadougou (Bukina Faso).

Muehlig-Versen, B., Buerkert, A., Bationo, A., Roemheld, V., 2003. Phosphorus placement on acid arenosols of the West African Sahel. Exp. Agric. 39, 307–325. https://doi.org/10.1017/S0014479703001261.

Nourou, A.I.M., Saidou, A.K., Arifa, W., Abdoulaye, A.O., Aune, J.B., 2020. Intensification of pearl millet production in Niger through mechanized sowing and weeding, seed priming, seed treatment, and microdosing. Agronomy 10, 1–12. https://doi.org/10.3390/agronomy10050629.

Nyamangara, J., Makarimayi, E., Masvaya, E.N., Zingore, S., Delve, R.J., 2011. Effect of soil fertility management strategies and resource-endowment on spatial soil fertility gradients, plant nutrient uptake and maize growth at two smallholder areas, north-western Zimbabwe. South Afr. J. Plant Soil 28, 1–10. https://doi.org/10.1080/02571862.2011.10640006.

Okebalama, C.B., Ibrahim, A., Safo, E.Y., Yeboah, E., Abaidoo, R.C., Logah, V., Uzoh, I. M., 2017. Fertilizer micro-dosing in West African low-input cereals cropping: Benefits, challenges and improvement strategies. Afr. J. Agric. Res 12, 1169–1176. https://doi.org/10.5897/ajar2016.11559.

Ouedraogo, Y., Taonda, J.-B.S., Sermé, I., Tychon, B., Bielders, C.L., 2020. Factors driving cereal response to fertilizer microdosing in sub-saharan Africa: a meta-analysis. Agron. J. 2418–2431. https://doi.org/10.1002/agj2.20229.

Palé, S., Mason, S.C., Taonda, S.J.-B., 2009. Water and fertilizer influence on yield of grain sorghum varieties produced in Burkina Faso. South Afr. J. Plant Soil 26, 91–97. https://doi.org/10.1080/02571862.2009.10639939.

Phiri, A.D.K., Kanyama-Phiri, G.Y., Snapp, S., 1999. Maize and sesbania production in relay cropping at three landscape positions in Malawi. Agrofor. Syst. 47, 153–162.

Prudencio, C.Y., 1993. Ring management of soils and crops in the west African semi-arid tropics: the case of the mossi farming system in Burkina Faso. Agric. Ecosyst. Environ. 47, 237–264. https://doi.org/10.1016/0167-8809(93)90125-9.

Rockström, J., Barron, J., Brouwer, J., Galle, S., De Rouw, A., 1999. On-farm spatial and temporal variability of soil and water in pearl millet cultivation. Soil Sci. Soc. Am. J. 63, 1308–1319. https://doi.org/10.2136/sssaj1999.6351308x.

Ronner, E., Franke, A.C., Vanlauwe, B., Dianda, M., Edeh, E., Ukem, B., Bala, A., van Heerwaarden, J., Giller, K.E., 2015. Understanding variability in soybean yield and response to P-fertilizer and rhizobium inoculants on farmers' fields in northern Nigeria. F. Crop. Res 1–13. https://doi.org/10.1016/j.fcr.2015.10.023.

Roose, E., 1993. Capacité des jachères à restaurer la fertilité des sols pauvres en zone soudano-sahélienne d'Afrique occidentale. In: La Jachère En Afrique de l'Ouest. Collection Colloques et Séminaires. ORSTOM, Paris.

Samaké, O., Smaling, E.M.A., Kropff, M.J., Stomph, T.J., Kodio, A., 2005. Effects of cultivation practices on spatial variation of soil fertility and millet yields in the Sahel of Mali. Agric. Ecosyst. Environ. 109, 335–345. https://doi.org/10.1016/j.agee.2005.02.024.

Serme, I., Tarfa, B., Ouattara, K., Wortmann, C., 2020. Maize response to applied nutrients for West African savannas. Agron. J. 112, 2230–2239. https://doi.org/10.1002/agj2.20152.

Serpantié, G., Ouattara, B., 2001. Fertilité et jachères en Afrique de l ' Ouest. In: FLoret, C., Pontanier, R. (Eds.), La Jachère En Afrique Tropicale: Rôles, Aménagement, Alternatives: 2. De La Jachère Naturelle à La Jachère Améliorée: Le Point Des Connaissances. IRD; J. Libbey, Paris (FRA), Montrouge, pp. 21–83.

Shatar, T.M., Mcbratney, A.B., 2004. Boundary-line analysis of field-scale yield response to soil properties. J. Agric. Sci. 142, 553–560. https://doi.org/10.1017/S0021859604004642.

Tabo, R., Bationo, A., Amadou, B., Marchal, D., Lompo, F., Gandah, M., Hassane, O., Diallo, M.K., Ndjeunga, J., Fatondji, D., Gerard, B., Sogodogo, D., Taonda, S.J.-B., Sako, K., Boubacar, S., Abdou, A., Koala, S., 2011. Fertilizer microdosing and "warrantage" or inventory credit system to improve food security and farmers' income in West Africa. In: Bationo, A., Waswa, B., Okeyo, J., Maina, F., Kihara, J. (Eds.), Innovations as Key to the Green Revolution in Africa. Springer, Dordrecht, pp. 113–121. https://doi.org/10.1007/978-90-481-2543-2_10.

Taonda, Jean-Baptiste S., Emmanuel Compaoré, and Nongma Zongo. 2015. Guide de Formation En Technique de Microdose." ⟨https://docplayer.fr/82936334-Guide-de-formation-en-technique-de-microdose.html⟩.

Tittonell, P., Vanlauwe, B., de Ridder, N., Giller, K.E., 2007. Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: soil fertility gradients or management intensity gradients. Agric. Syst. 94, 376–390. https://doi.org/10.1016/j.agsy.2006.10.012.

Tonitto, C., Ricker-Gilbert, J.E., 2016. Nutrient management in African sorghum cropping systems: applying meta-analysis to assess yield and profitability. Agron. Sustain. Dev. 36, 1–19. https://doi.org/10.1007/s13593-015-0336-8.

Tovihoudji, P.G., Akponikpè, P.B.I., Agbossou, E.K., Bertin, P., Bielders, C.L., 2017. Fertilizer microdosing enhances maize yields but may exacerbate nutrient mining in maize cropping systems in northern Benin. F. Crop. Res. 213, 130–142. https://doi.org/10.1016/j.fcr.2017.08.003.

Tovihoudji, P.G., Akponikpè, P.B.I., Agbossou, E., Bielders, C.L., 2019. Variability in maize yield and profitability following hill-placement of reduced mineral fertilizer and manure rates under smallholder farm conditions in northern Benin. F. Crop. Res. 230, 139–150. https://doi.org/10.1016/j.fcr.2018.10.018.

Twomlow, S., Rohrbach, D., Rusike, J., Mupangwa, W., Dimes, J., Ncube, B., 2006. Spreading the word on fertilizer in Zimbabwe. Global theme on agroecosystems, report no. 24. PO Box 776, Bulawayo, Zimbabwe, International Crops Research Institute for the Semi-Arid Tropics,16 pp.

Twomlow, S., Rohrbach, D., Dimes, J., Rusike, J., Mupangwa, W., Ncube, B., Hove, L., Moyo, M., Mashingaidze, N., Mahposa, P., 2010. Micro-dosing as a pathway to Africa's Green revolution: evidence from broad-scale on-farm trials. Nutr. Cycl. Agroecosyst. 88, 3–15. https://doi.org/10.1007/s10705-008-9200-4.

Vanlauwe, B., Diels, J., Lyasse, O., Aihou, K., Iwuafor, E.N.O., Sanginga, N., Merckx, R., Deckers, J., 2002. Fertility status of soils of the derived savanna and Northern Guinea savanna and response to major plant nutrients, as influenced by soil type and land use management. Nutr. Cycl. Agroecosyst. 62, 139–150. https://doi.org/10.1023/A:1015531123854.

Vanlauwe, B., Tittonell, P., Mukalama, J., 2006. Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. Nutr. Cycl. Agroecosyst. 76, 171–182. https://doi.org/10.1007/s10705-005-8314-1.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K.D., Smaling, E.M.A., Woomer, P.L., Sanginga, N., 2010. Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. Outlook Agric. 39, 17–24. https://doi.org/10.5367/000000010791169998.

Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., Six, J., 2011. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. Plant Soil 339, 35–50. https://doi.org/10.1007/s11104-010-0462-7.

Vanlauwe, B., Wendt, J., Giller, K.E., Corbeels, M., Gerard, B., Nolte, C., 2014. A fourth principle is required to define Conservation Agriculture in sub-Saharan Africa: The appropriate use of fertilizer to enhance crop productivity. F. Crop. Res. 155, 10–13. https://doi.org/10.1016/j.fcr.2013.10.002.

Vanlauwe, B., Descheemaeker, K., Giller, K.E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., 2015. Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation 491–508. https://doi.org/10.5194/soil-1–491-2015.

Vanlauwe, B., Coe, R., Giller, K.E., 2016. Beyond averages: New approaches to understand heterogeneity and risk of technology success or failure in smallholder farming. Exp. Agric. 55, 84–106. https://doi.org/10.1017/S0014479716000193.

Webb, R.A., 1972. Use of the Boundary Line in the analysis of biological data. J. Hortic. Sci. 43. https://doi.org/10.1080/00221589.1972.11514472.

Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 2007. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agric. Ecosyst. Environ. 119, 112–126. https://doi.org/10.1016/j.agee.2006.06.019.