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REVIEW

# Factors driving cereal response to fertilizer microdosing in sub-Saharan Africa: A meta-analysis

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**Abstract**

Fertilizer microdosing (FM) is being promoted in sub-Saharan Africa (SSA) to boost crop productivity on smallholder farms. However, yield response variability is a barrier to adoption. We conducted a meta-analysis to analyze the variability in cereal crop yield response to FM and to determine the main factors associated with this variability. Thirty publications pertaining to millet [*Pennisetum glaucum* (L.) R. Br.], sorghum (*Sorghum bicolor* L. Moench) or maize (*Zea mays* L.) were assessed. Factors analyzed were crop type, rainfall, soil texture, type and rate of fertilizer, and complementary practices. On average, FM improved millet, sorghum and maize crop yields by 68%. Yield response tended to increase with increasing rainfall and the largest yield gains were observed in medium-textured soils (81%), as compared to light (61%) and heavy-textured soils (30%). The combined application of N and P performed better than either element alone. Crop response tended to increase with increasing rates of N. In the case of P, this was true only on light textured-soils. On medium-textured soils, the response appeared independent of the rate of P. There was a synergetic effect of water conservation measures on the performance of FM, while combining FM with organic matter (OM) amendments decreased its performance. Results highlighted major trends in cereal crop response to FM that could be used to prioritize target areas. However, these may require additional, site-specific field experiments, especially for factors for which little data is currently available.

## 1 | INTRODUCTION

In sub-Saharan Africa (SSA), cereals are mostly grown under rainfed conditions by smallholder farmers with limited resources. Crop yields are low due to low inherent soil fertility, limited availability of organic amendments and high cost of mineral fertilizers (Yanggen, Kelly, Reardon, & Naseem, 1998; Van der Velde et al., 2013). In particular, fertilizer application rates remain below the recommended rates (Haigis et al., 1999; Ibrahim, Abaidoo, Fatondji, & Opoku, 2015a; Thigpen, 2006). The concept of microdose fertilization (FM) was developed in the late 1990s to tackle this low fertilizer use. This technique consists in applying small amounts of mineral fertilizer (2 to 6 g) in the planting holes at planting or next to the seedlings after emergence (Buerket, Bationo, & Piepho, 2001; Muehlig-versen, Buerket, Bationo, & Roemheld, 2003; Twomlow et al., 2006). Common fertilizer formulations are DAP (18–46–00), NPK (15–15–15 or 14–23–14) and urea (46–00–00). FM rates in West Africa

**Abbreviations:** AGRA, Alliance for a Green Revolution in Africa; CORAF/WECARD, West and Central African Council for Agricultural Research and Development; FM, Fertilizer Microdosing; OM, Organic Matter; SSA, Sub-Saharan Africa.

generally aim at providing between 0.2 to 0.4 g P hill$^{-1}$ (AGRA, 2014; Bagayoko et al., 2011; Tabo et al., 2007). Depending on fertilizer type (NPK, DAP, with or without additional urea), crop type and seeding density, FM provides 6–46 kg N ha$^{-1}$, 2–12 kg P ha$^{-1}$, and 0–14 kg K ha$^{-1}$. Because it is more financially accessible to smallholder farmers, this approach has been widely promoted in production in SSA, mainly for millet, sorghum and maize (AGRA, 2014; Camara, Camara, Berthe, & Oswald, 2013; CORAF/WECARD, 2011; Twomlow et al., 2010). Average yield improvements of 50% have been reported for sorghum following FM application (Tonitto & Ricker-Gilbert, 2016), but increases greater than 100% have been reported in some studies (Aune, Doumbia, & Berthe, 2007; Bagayoko et al., 2011; Buerket et al., 2001; Hayashi, Abdoulaye, Gerard, & Bationo, 2008).

**Core Ideas**

- Fertilizer microdosing increases maize, sorghum and millet yields by 68, 70 and 63%.
- Crop response to fertilizer microdosing tends to increase with rainfall amount.
- Fertilizer microdosing performs best on medium-textured soils.
- Water conservation techniques show a synergistic effect with fertilizer microdosing.
- Combining fertilizer microdosing with organic amendments decreases its performance.

Despite the many advantages of FM, the challenge that is increasingly emerging from its scaling up is the high variability in crop response often observed from one field to another (Camara et al., 2013; Twomlow et al., 2010). An analysis of millet response to FM conducted by Bielders and Gérard (2015) in Niger on 276 farmers' fields indicated that, due to high variability, FM was not profitable in 34% of farms.

High crop yield variability is not specific to microdose fertilization. It has been observed for various fertility management practices in sub-Saharan countries such as fertilizers, conservation agriculture, or cereal-legume intercropping (Falconnier, Descheemaeker, Mourik, & Giller, 2016; Fermont, van Asten, Tittonell, van Wijk, & Giller, 2009; Giller et al., 2011; Ronner et al., 2015; Sommer et al., 2013). This variability in crop response is most often attributed to the spatial heterogeneity of soil fertility. For instance, in SSA, many authors have reported on the occurrence of a fertility gradient around homesteads or villages (Prudencio, 1993; Samaké, Smaling, Kropff, Stomph, & Kodio, 2005; Zingore, Murwira, Delve, & Giller, 2007), nearby plots being in general more fertile than distant plots (Achard & Banoin, 2003; Schlecht, Hiernaux., & Turner, 2001; Tittonell, Vanlauwe, Leffelaar, Shepherd, & Giller, 2005). Various studies have shown that the response of cereal crops to fertilizer inputs is often better on the less fertile, distant plots (Vanlauwe, Tittonell, & Mukalama, 2006; Zingore et al., 2007). Thus, poor responses to fertilizer inputs may result from a good soil fertility status, especially when the quantity of applied nutrients is low as with FM (Bielders & Gerard, 2015; Tovihoudji, Akponikpè, Agbossou, & Bielders, 2019).

Poor response to fertilizer inputs may also result from deficiencies in nutrients other than those provided by the fertilizers (Njoroge, Otinga, Okalebo, Pepela, & Merckx, 2017a). Although it is well established that nitrogen and phosphorus are the most limiting nutrients in the majority of agricultural soils in SSA (Bationo, Lompo, & Koala, 1998; Kurwakumire et al., 2014; Masvaya et al., 2010), some soils have multiple deficiencies and only respond when multiple nutrient restoration strategies are implemented (Kihara et al., 2016; Zingore, Delve, Nyamangara, & Giller, 2008). In addition to nutritional deficiencies, non-response or differences in soil response to fertilizer inputs may also result from constraints related to physical (compaction, depth, etc.) or chemical (acidity, toxicity) characteristics that require prior lifting (Kihara et al., 2016; Serme, Ouattara, Bandaogo, & Wortmann, 2018; Voortman, Brouwer, & Albersen, 2004).

In addition to soil factors, rainfall is a fundamental factor governing the response to fertilizers under rainfed conditions. Kravchenko, Robertson, Thelen, and Harwood (2005) observed that the coefficient of variation of crop yields reaches 45% in years of low rainfall, but only 14% in years of above-average rainfall. This phenomenon is potentially more important in semi-arid and arid sub-Saharan areas characterized by high spatial and temporal rainfall variability (Akponikpè, Minet, Gérard, Defourny, & Bielders, 2011; Traore et al., 2015). For example, following FM application, Camara et al. (2013) observed millet yield increases in only 2 out of 4 years in areas with lower rainfall while for areas with higher rainfall, yield increases were observed each year. In addition to the biophysical factors mentioned above, farm-management practices can also play a decisive role in the response to fertilization. Indeed, farmers sometimes give priority to plots perceived as more fertile (Tittonell et al., 2005) or, on the contrary, to the least fertile areas within a plot (Lamers & Feil, 1995). In addition, late planting or poor weed management can lead to poor fertilizer responses (Kamanga, Waddington, Whitbread, Almekinders, & Giller, 2014; Tovihoudji et al., 2019). Finally, deep placement of fertilizers (around 10 cm) tends to give better responses compared to more superficial applications (Ibrahim, Pasternak, & Fatondji, 2014; Nkebiwe, Weinmann, Bar-Tal, & Müller, 2016).

Variability in crop yield response to fertilizers is a major challenge for the promotion of fertilization in the sub-Saharan context (Njoroge et al., 2017b). The work of Vanlauwe, COE,

**TABLE 1** Criteria used for inclusion of studies in the meta-analysis

| Inclusion criteria | Comments |
|---|---|
| Study conducted after 1990 | Period of conceptualization of fertilizer microdosing (FM) in sub-Saharan Africa |
| Mineral fertilizer applied to millet, sorghum and maize according to the FM concept as defined. | FM has occasionally been tested on other crops, but the number of such studies is too limited to be included in a meta-analysis. |
| Study indicating the yields of treatment without fertilizer and at least one FM treatment | The objective is to assess the magnitude of the response associated with FM in a given context. Thus, when FM has been tested in combination with another practice (organic manure for example), the control must be the practice without fertilizer (in this example, organic manure alone). |
| Study conducted in stations or on-farm areas | The objective is to analyze variations in response in real environments. Thus, pot, greenhouse and survey studies were excluded. |

and Giller (2016) clearly shows that the risk of not gaining the expected yields is high when causal factors of variability are not taken into account by extension services. Taking this into consideration is imperative for FM since this technology targets risk-averse smallholder farmers for whom FM offers a real opportunity for transition to more productive systems (Aune & Bationo, 2008). To this end, it seems useful to perform a meta-analysis of crop response to FM as a function of the biophysical environment in which the technique is being implemented. Recently, Okebalama et al. (2017) and Demisie (2018) conducted narrative literature reviews that report on the performance and challenges associated with the FM technology. However, these reviews did not explicitly address questions related to crop response variability. Tonitto and Ricker-Gilbert (2016) included FM in their meta-analysis of sorghum yield responses to nutrient management practices in Africa. However, their work was limited to sorghum and covered only 18 pairs of data related to FM, which seems insufficient to assess specifically the factors that influence FM yields. The purpose of this work was therefore to conduct a meta-analysis of scientific published data on FM in SSA in order to assess crop yield variability in response to FM and determine the main factors potentially associated with this variability. Such an analysis seems timely given that it is about 20 years since the first studies on FM in SSA were published, and a reasonable number of studies are now available for the main cereal crops millet, sorghum and maize.

## 2 | MATERIALS AND METHODS

### 2.1 | Selection of studies

The present meta-analysis focusses on the practice of localized fertilizer application as applied in SSA to cereal crops. It is commonly referred to as "fertilizer microdosing". The literature research was conducted by querying the Scopus and ScienceDirect databases, the Google Scholar search engine and the ResearchGate network to collect scientific journal articles, conference proceedings, theses and grey literature documents regarding the FM technique. Search was limited to the period from 1991 to 30 Mar. 2019. The keywords used were in English: fertilizer micro(-)dosing, fertilizer (hill) placement, microfertilization, reduced mineral fertilizer, minute application of fertilizer, strategic fertilizer application; and in French: *fertilisation microdose, microdose d'engrais, microfertilisation.*

Based on titles and summaries, 78 documents dealing with at least one FM study conducted in SSA were selected. The documents were read in detail to select those studies that met the criteria listed in Table 1. A 'study' is defined here as an experiment conducted at a given location (e.g. locality, region or country), in a given growing season or year. Each document could therefore possibly include several studies and a study could include several pairs of data (yield of an unfertilized control compared to the yield of an FM treatment) for at least one of the three cereal crops. Data from the same study but reported in several documents were included only once. In that case, the document with the most complete data was used. In situations where only the average of several studies conducted over several seasons or years was provided, this was taken into account, provided that the pooled studies compare the same treatments for the same crop. In the end, 30 documents were selected (27 articles, 1 thesis, and 2 reports from the grey literature; Table 2), comprising 121 studies and 488 data pairs, spread across 11 countries.

### 2.2 | Data extraction and analysis

For each study, yields were extracted from tables and graphs. When the data were presented in graphical form, they were digitized using the Graph Grabber V2.0 software. In addition to yields, statistical measures (standard deviation, standard error, standard error of the difference, least significant difference, coefficient of variation, P-value, etc.) were also encoded and the following variables were extracted when available: geographical coordinates of the site, type of crop

**TABLE 2** List of documents used in the meta-analysis and their main characteristics

| Reference | Country | Experimental years | Crop | Type of experiment | Number of data pair |
|---|---|---|---|---|---|
| Tovihoudji et al., 2019 | Benin | 2014–2015 | Maize | On-farm | 4 |
| Tovihoudji, Akponikpè, Agbossou, Bertin, & Bielders, 2017 | Benin | 2014–2015 | Maize | On-station | 20 |
| Saba et al., 2017 | Burkina Faso | 2010–2011 | Millet, Sorghum | On-farm | 12 |
| Ibrahim, Abaidoo, Fatondji, & Opoku, 2016 | Niger | 2013–2014 | Millet | On-station | 16 |
| Okebalama, Safo, Yeboah, Abaidoo, & Logah, 2016 | Ghana | 2012–2013 | Maize | Researcher-managed on-farm | 18 |
| Abdalla et al., 2015 | Sudan | 2009–2013 | Sorghum | Researcher-managed on-farm | 8 |
| Kisinyo et al., 2015 | Kenya | 2008 | Maize | On-station | 18 |
| Bielders et al., 2015 | Niger | 2000–2002 | Millet | On-farm | 8 |
| Ibrahim et al., 2015b | Niger | 2013–2014 | Millet | On-station | 16 |
| Ibrahim, Abaidoo, Fatondji, & Opoku, 2015c | Niger | 2013, 2014 | Millet | On-station | 4 |
| Ibrahim et al., 2014 | Niger | 2008–2009 | Millet | On-station | 8 |
| Sime et al., 2014 | Ethiopia | 2011–2012 | Maize | Researcher-managed on-farm | 9 |
| Kamanga et al., 2014 | Malawi | 2003 | Maize | On-farm | 20 |
| Camara et al., 2013 | Mali | 2010–2011 | Millet, Sorghum | On-farm | 20 |
| Mashingaidze et al., 2013 | Zimbabwe | 2006–2008 | Maize | On-farm | 12 |
| Aune et al., 2012 | Mali | 2007–2008 | Millet, Sorghum | On-farm | 12 |
| Jamil et al., 2012 | Mali | 2010–2011 | Millet | On-station | 4 |
| Bagayoko et al., 2011 | Burkina Faso, Mali, Niger | 2001–2006 | Millet | On-farm, On-station | 45 |
| Aune et al., 2011 | Sudan | 2007 | Millet, Sorghum | On-farm, On-station | 38 |
| CORAF/WECARD, 2011 | Burkina Faso, Mali, Niger, Senegal | 2005–2007 | Millet, Sorghum | On-farm, On-station | 20 |
| Twomlow et al., 2010 | Zimbabwe | 2004–2006 | Maize, Millet, Sorghum | On-farm | 33 |
| Pale et al., 2009 | Burkina Faso | 2003–2005 | Sorghum | On-station | 16 |
| Hayashi et al., 2008 | Niger | 1999–2002 | Millet | On-farm, On-station | 17 |
| Aune et al., 2007 | Mali | 2001 | Millet, Sorghum | On-farm | 8 |
| Opala et al., 2007 | Kenya | 1998 | Maize | Researcher-managed on-farm | 3 |
| Ncube et al., 2007 | Zimbabwe | 2002–2004 | Maize | On-farm | 10 |
| Tabo et al., 2007 | Burkina Faso, Mali, Niger, | 2002–2003 | Millet, Sorghum | On-farm | 14 |
| Manyame, 2006 | Niger | 2003–2004 | Millet | Researcher-managed on-farm | 60 |
| Muehlig-versen et al., 2003 | Niger | 1995-1996 | Millet | On-station | 12 |
| Buerket et al., 2001 | Niger | 1998-1999 | Millet | On-farm | 3 |

and variety, number of replicates, sowing density, seasonal and/or annual rainfall during experimentation, average annual rainfall of the area, type and texture of the soil, soil pH and nutrient contents (N, P, and K), type of fertilizer and rate applied per hill or per hectare, timing of fertilizer application, and type of trial (on-station, on-farm, researcher-managed on-farm). When the site coordinates or average annual rainfall were not provided, they were filled-in using information available on Google Earth and WorldClim Global Climate Data (http://worldclim.org/version2), respectively.

The variables for which there were sufficient observations were used to analyze their impact on crop response to FM. Classes were created for these variables. Three classes were specified for the type of crop (sorghum, millet, maize) as well as for observed rainfall (≤ 600 mm, 600–800 mm, 1000–1200 mm). For the latter, the 800–1000 mm class was not considered because of lack of data. Because observed rainfall was not always reported, average annual rainfall of the area was also used, with three classes (≤ 600 mm, 600–1000 mm, > 1000 mm). The choice of class boundaries was in part driven by the need to ensure a certain balance in terms of number of studies among classes. Soils were characterized by their texture in three classes, with reference to the USDA triangle (Tonitto & Ricker-Gilbert, 2016): light-textured soil (sandy, loamy sand, sandy loam, sandy clay loam), medium-textured soil (loam, silt loam, sandy clay), and heavy-textured soil (silty clay, clay). Too few documents provided information on nutrient levels and soil pH in the experimental plots to allow for these factors to be taken into account.

Four classes were established for the type of nutrients provided (N, P, N+P, N+P+K). Considering the common FM rates targeted in West Africa, three classes of P (≤ 6, 6–12, > 12 kg P $ha^{-1}$) and four classes of N (≤ 10, 10–20, 20–30, > 30 kg N $ha^{-1}$) were established. The practices most commonly combined with FM such as organic amendments (OM), water conservation techniques and seed priming (soaking the seeds in water for about eight hours prior sowing) were used as classes.

Crop response to FM (effect size) for each data pair was expressed as the ratio of the yield of the FM treatment to the yield of the unfertilized control treatment. The natural logarithm of this ratio (equation 1) was used for the meta-analysis to reduce the risk of non-normally distributed data (Chivenge, Vanlauwe, & Six, 2011; Johnson & Curtis, 2001; Tonitto & Ricker-Gilbert, 2016).

$$ln\left(\frac{\bar{X}_t}{\bar{X}_c}\right) \tag{1}$$

where $X_t$ = the average yield of the FM treatment, and $X_c$ = the average yield of the control treatment.

For studies in which several FM treatments (e.g., different FM rates) were compared to the same control, the responses of each treatment were considered independent. Gurevitch et Hedges (1999) indicate, however, that in such situations the occurrence of non-independence may lead to an underestimation of the standard error of the mean response and thus an underestimation of its confidence interval.

Very few studies provided statistical measures that would have allowed determining the standard deviations of treatment averages. Therefore, to compute the overall mean response and the mean response of the classes of variables of interest, the response of each pair was weighted according to equation (2), and the confidence intervals were derived by non-parametric bootstrap at 95% confidence intervals with 1000 iterations (Adams, Gurevitch, & Rosenberg, 1997; Lajeunesse, 2013).

$$W_i = \left(\frac{n_t \times n_c}{n_t + n_c}\right) \tag{2}$$

where $n_t$ = sample size of the FM treatment, and $n_c$ = sample size of the control treatment.

## 2.3 | Explanation and data quality assessment

The OpenMEE software (Wallace et al., 2017) was used for the meta-analysis. Data quality was assessed by analyzing publication bias and sensitivity (Philibert, Loyce, & Makowski, 2012). A funnel plot was generated with the effect size (response) on the horizontal axis and the inverse of the square root of the sample size on the vertical axis, and an asymmetry test was performed by regression testing (Metafor package of R). The asymmetry test of the funnel plot was not significant ($t = -0.4975$, $df = 474$, $p = 0.6190$; Supplemental Figure S1), suggesting the absence of publication bias. The sensitivity of the group or category effect means to individual observations was examined by leave-one-out meta-analysis (Wallace et al., 2017). There were few or no influential observations and the group averages calculated after removing these observations remained well within the limits of the group's confidence interval calculated with these observations included.

The responses observed by group were considered significant (different from zero) when their confidence intervals did not contain the zero value, and significantly different from each other when their confidence intervals did not overlap (Chivenge et al., 2011; Tonitto & Ricker-Gilbert, 2016; Wortman, Holmes, Miernicki, Knoche, & Pittelkow, 2017). To facilitate the interpretation of the responses (effect sizes), the results are presented as the percentage variation in yield of FM compared to the control. In addition, for some groups, the FM response was also presented in terms of absolute yield variation (difference in yield between FM and

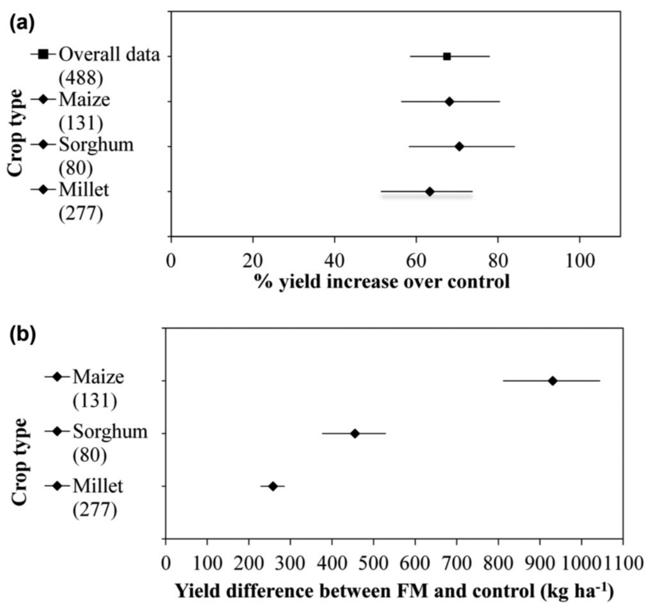


**FIGURE 1** Yield increase following microdose fertilization (FM) relative to the control by crop type, expressed as a percentage (a) and absolute value (b). The numbers in brackets represent the number of data pairs that contributed to the calculation of the averages. The error bars represent the 95% confidence intervals obtained by bootstrap

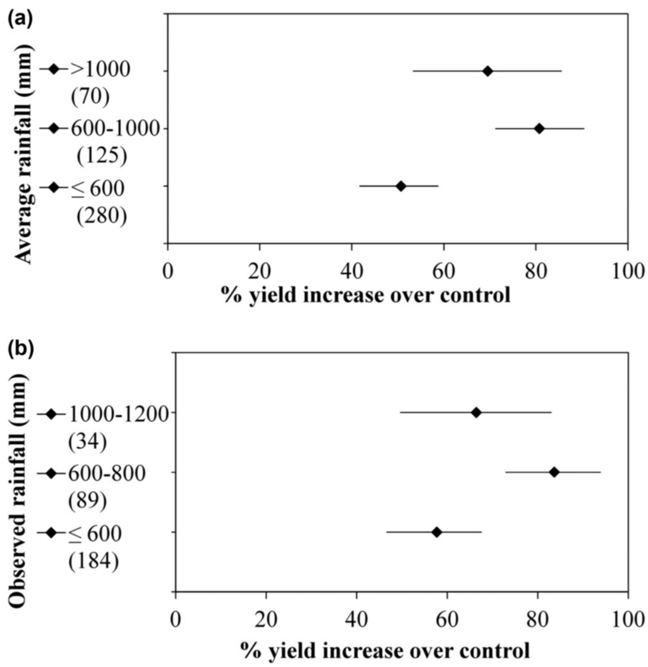


**FIGURE 2** Yield increase following microdose fertilization (FM) relative to the control expressed as a percentage, per climatic zone (a) and as a function of the observed rainfall (b). The numbers in brackets represent the number of data pairs that contributed to the calculation of the averages. The error bars represent the 95% confidence intervals obtained by bootstrap

control) in units of kilogram per hectare (kg ha$^{-1}$) to show the expected real yield gain under such conditions.

## 3 | RESULTS AND DISCUSSION

### 3.1 | Microdose fertilization response by crop type

Average yields of unfertilized millet, sorghum and maize are 577 ± 349, 591 ± 234 and 1491 ± 1125 kg ha$^{-1}$, respectively. On average for all studies, the application of FM leads to a 68% increase in yield compared to the control (Figure 1a). There was no significant difference between the three crops when the increase was expressed as a percentage. In terms of absolute yield, however, yield gains are significantly different, with an average yield gain ranging from 260 kg ha$^{-1}$ for millet to 930 kg ha$^{-1}$ for maize (Figure 1b). This reflects the yield potential of these crops as well as the climatic and soil conditions in which they are grown, millet being dominant in the most unfavorable areas while maize dominates in the more favorable areas of SSA.

The yield increases confirm the overall relevance of FM as a means to boost cereal crop productivity levels in SSA with input levels that remain accessible to smallholder farmers (Aune & Bationo, 2008; Twomlow et al., 2010; Okebalama et al., 2017; Van der Velde et al., 2013). The average performance reported here is significantly better than that previously reported by Tonitto and Rickert-Gilbert (2016) for FM applied to sorghum. Their meta-analysis showed an average increase of about 50%, but this was calculated for a significantly smaller number of data pairs (n = 18) than the present meta-analysis.

### 3.2 | Microdose fertilization response by climatic zone and observed rainfall

Figure 2a shows a statistically significant increase in the percentage yield gain from 51% in climatic zones with rainfall ≤600 mm to 80% in zones with rainfall 600–1000 mm. The percentage yield gain in the rainfall zone > 1000 mm is slightly lower than the 600–1000 mm rainfall zone, but not significantly different. The same trends and orders of magnitude are observed with respect to the actual rainfall (Figure 2b).

Although millet is preferentially grown in drier areas and maize in wetter areas, the relative yield increases observed in Figure 2 do not result from differences in crop type. Indeed, when analyzing the increase in yield by crop type and rainfall class, the percentage increase in FM yield generally increases with the amount of rain received for each crop considered separately (Figure 3). For sorghum, the increases

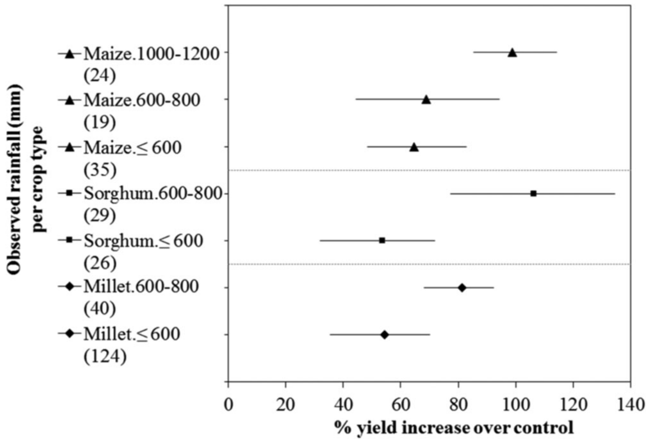


**FIGURE 3** Yield increase following microdose fertilization (FM) relative to the control, per crop type and observed rainfall class. The numbers in brackets represent the number of data pairs that contributed to the calculation of the averages. The error bars represent the 95% confidence intervals obtained by bootstrap. The number of studies on sorghum and millet in rainfall areas >1000 mm were insufficient for analysis

are significantly different, with an increase of 53% for the < 600 mm rainfall class and 106% for the 600–800 mm rainfall class. For millet, the average gains increase from 65% to 100% for the same two rainfall classes, respectively, but they are not statistically significant. For maize, the average gains increase significantly from 54% (< 600 mm) to 81% (1000–1200 mm), respectively. The increasing trend is therefore most likely the result of better agronomic fertilizer use efficiency, as demonstrated in the West African savannah zone with increasing rainfall (Amouzou, Naab, Lamers, & Becker, 2018). It is worth noting that the recommended FM application rate (g hill$^{-1}$) for a given crop is independent of the rainfall class, that is, the observed trends are not the result of adjustments in the FM application rate with rainfall.

In their meta-analysis of sorghum yield response to nutrient inputs (mineral and organic), Tonitto and Rickert-Gilbert (2016) also found an increasing response as a function of rainfall, with a yield increase of 36% in the 420–620 mm rainfall zone, 69% in the 730–890 mm zone and 105% in the 900–1150 mm zone. On the contrary, Chivenge et al. (2011) observed a better relative response of maize to fertilizer application in the < 600 mm zone compared to the 600–1000 mm zone, while noting that the absolute yield response remained better in the higher rainfall zone. Ichami, Shepherd, Hoffland, Sila, and Stoorvogel (2019) did not observe a significant effect of rainfall on the relative increase in maize yield following the application of fertilizer. For this latter publication, however, the number of observations taken into account was low (6 in wetlands and 18 in sub-humid areas). It is difficult to conclude at this stage whether the different trends observed across studies result from true differences in crop response depending on type and mode of application of fertilizers, or from the fact that the meta-analyses rest on different sets of publications.

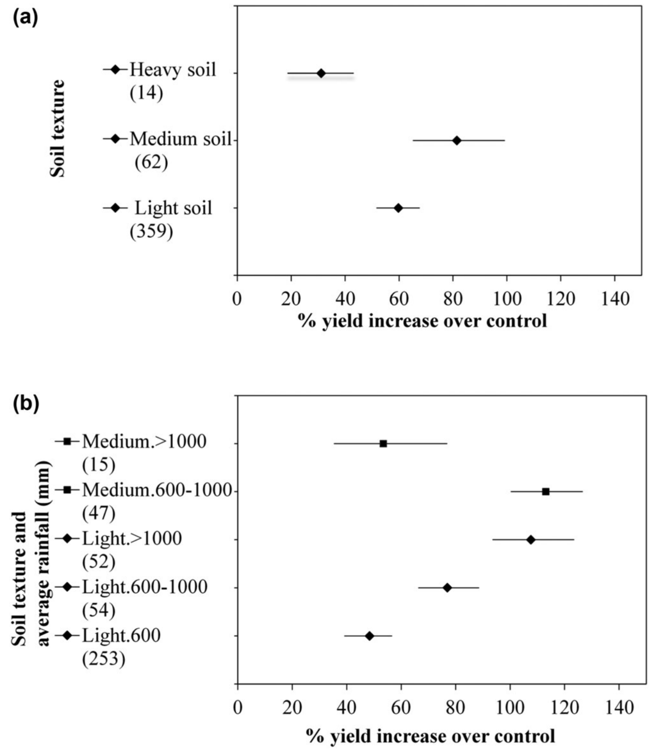


**FIGURE 4** Yield increase following microdose fertilization (FM) relative to the control, as a function of soil texture, for all data (a) and by climate zone (b). The numbers in brackets represent the number of data pairs that contributed to the calculation of the averages. The error bars represent the 95% confidence intervals obtained by bootstrap

## 3.3 | Microdose fertilization response by soil texture

As shown in Figure 4, the relative mean yield increase is 60% for light-textured soils and increases to 81% for medium-textured soils (Figure 4a). For heavy-textured soils, the level of increase decreases to 30% and is significantly lower than that of light and medium-textured soils. In terms of absolute yield gains, the same trends are also observed (data not shown).

So far, FM has been promoted in the semi-arid tropics. Higher yield increases on medium-textured soils compared to light-textured soils could therefore result from the fact that these soils have better water retention capacity and consequently a lower risk of water stress. On these medium-textured soils, all other factors being equal, water is therefore expected to limit crop response to fertilizer inputs less often than on light-textured soils.

This reasoning should in theory also apply to heavy-textured soils, yet the relative yield increases on heavy-textured soils are smaller than those observed on light textured-soils (Figure 4a). The meta-analysis of maize response to fertilizer inputs conducted by Ichami et al. (2019) also revealed lower responses on heavy-textured soils, although it was not statistically different. Soils with heavy texture are often located at the bottom of slopes or in depressions. They are inherently more fertile and, because of their topographical position, may benefit from organic matter and nutrients eroded upstream (Kissou, Gnankambary, Nacro, & Sedogo, 2018; Phiri, Kanyama-Phiri, & Snapp, 1999). In general, on relatively more fertile plots, when water stress is no longer limiting, yields in control plots tend to become higher (Amouzou et al., 2018), and the relative increase in yield following FM could thereby decrease. Indeed, Bielders and Gérard (2015) also observed a decreasing response as a function of the productivity level of the control plot in microdose trials. This observation was also made by Ichami et al. (2019) with respect to fertilization in general. Thus, for FM, heavy-textured soils could be considered as ‘rich, less-responsive soils’ as defined by Vanlauwe et al. (2011). The low responsiveness on clay soils is likely to be further exacerbated by the fact that 40% of the data for heavy-textured soils were derived from studies testing minute amounts of fertilizers (0.3 to 0.9 g hill$^{-1}$), 7- to 20-fold less than in conventional FM.

For medium-textured soils, the yield gain is 113% in the 600–1000 mm rainfall class but drops significantly to 53% in the > 1000 mm rainfall class (Figure 4b). This drop in response between 600–1000 and > 1000 mm could again be due to the fact that the yields of the control plots are better in the > 1000 mm area than in the 600–1000 mm area. For light-textured soils, no decrease in relative response is observed in the high rainfall zones. On the contrary, there is an increasing response to FM as a function of rainfall (Figure 4b). These sandy soils (45–100% sand) are generally not very fertile, with a low water retention capacity (Kissou et al., 2018; Manu, Bationo, & Geiger, 1991; Wortman et al., 2017). Thus, the addition of small amounts of fertilizer combined with good rainfall, can result in high crop response. The above hypotheses could have been analyzed if soil chemical data had reported. However, few studies provide this information. Therefore, further research are needed to address these questions.

Our result are not consistent with Tonitto and Ricker-Gilbert (2016) and Sileshi et al. (2019) who reported that the response to nutrient application was best on light-textured soils. In addition, Chivenge et al. (2011) reported the worst responses for medium-textured soils, followed by light- and heavy-textured soils that were not significantly different. It is difficult to identify the origin of these discrepancies, since the studies differ in terms of data sets used but also in terms of type of fertilizers and fertilization methods studied.

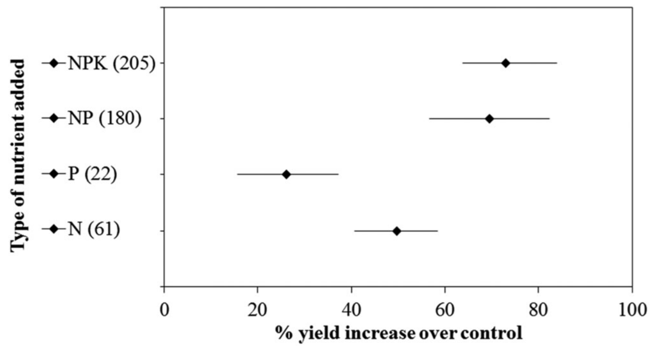


**FIGURE 5** Yield increase following microdose fertilization (FM) relative to the control as a function of the type of nutrients supplied. The numbers in brackets represent the number of data pairs that contributed to the calculation of the averages. The error bars represent the 95% confidence intervals obtained by bootstrap

## 3.4 | Microdose fertilization response according to the dose and type of nutrient provided

Figure 5 shows that NP or NPK fertilizer applications lead to similar levels of response (∼70%), that are significantly higher than applications of P or N alone. The fact that the best responses are observed when P and N are provided together is consistent with the fact that these are the most limiting for crop production in SSA (Bationo et al., 1998; Kurwakumire et al., 2014; Masvaya et al., 2010). Nevertheless, data corresponding to N applications alone come from studies conducted in East and South Africa, mainly in the semi-arid zone of Zimbabwe (Kamanga et al., 2014; Mashingaidze, Belder, Twomlow, Hove, & Moyo, 2013; Ncube, Dimes, Twomlow, Mupangwa, & Giller, 2007; Twomlow et al., 2010). In this area, the scaling-up of FM focused on nitrogen inputs because field and crop simulation tests showed the possibility to increase cereal yields using small amounts of N only (∼10 kg of N ha$^{-1}$).

Multi-site tests conducted by Njoroge et al. (2017a) and Kihara et al. (2016) support this view. They reported that N appears to be the most limiting element in this area due to continuous cropping without legumes and very limited application of fertilizer N or manure. However, in Mali for example, Kihara et al. (2016) reported that P was the most limiting. This is consistent with research reported by Buerket, Piepho, and Bationo (2002) for West Africa. Therefore, the scaling-up of FM in West Africa has so far focused on phosphorus, while also providing nitrogen (Bagayoko et al., 2011; Bielders & Gérard, 2015; Buerket et al., 2001; Camara et al., 2013). Chikowo et al. (2010) showed that the uptake efficiencies of N and P tend to improve when they are applied simultaneously.

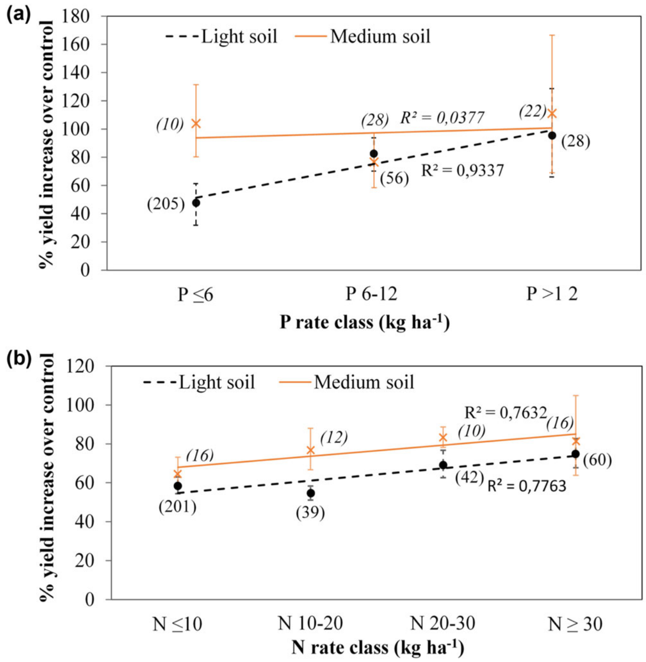


**FIGURE 6** Yield increase following microdose fertilization (FM) relative to the control as a function of the P (a) and N (b) application rates, per soil texture type. The numbers in brackets represent the number of data pairs that contributed to the calculation of the averages. The error bars represent the 95% confidence intervals obtained by bootstrap

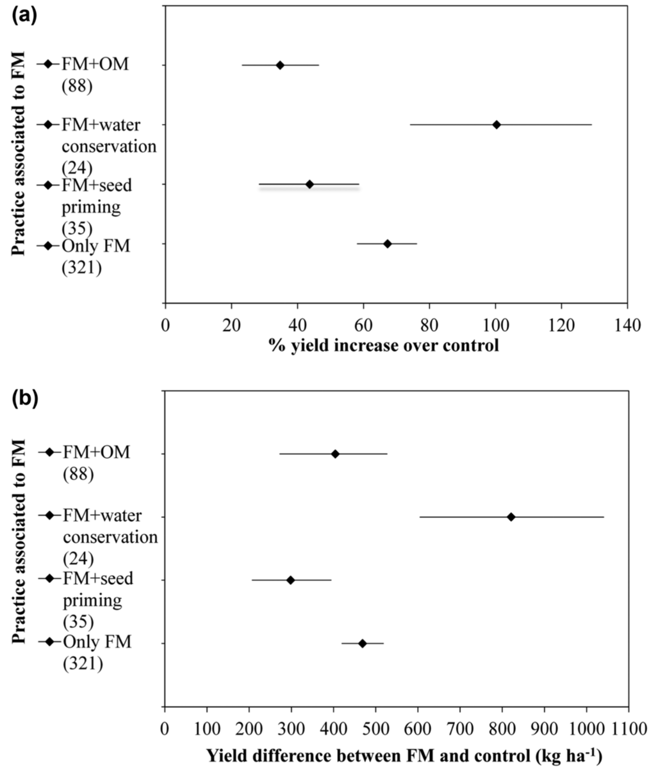


**FIGURE 7** Yield increase following microdose fertilization (FM) relative to the control as a function of the associated practice, expressed as a percentage (a) and in absolute value (b). The numbers in brackets represent the number of data pairs that contributed to the calculation of the averages. The error bars represent the 95% confidence intervals obtained by bootstrap. OM refers to organic matter amendment

Figure 6 shows crop response as a function of rates of N and P. It should be noted that in most studies, these elements were combined (Figure 5). There is a clear trend towards increasing yield gains with increasing P doses on light-textured soils (Figure 6a). On medium-textured soils, however, the response appears independent of the dose of P. Following the addition of N, the response trends are positive and similar for both textural classes, the response levels being higher on average on medium-textured soils than on light-textured soils (Figure 6b).

The lack of response to increasing doses of P could result in part from the fact that the inherent availability of P may be better on medium-textured soils, especially under high rainfall conditions, thereby partly masking the response within the range of fertilizer rates used in FM. Indeed, in the humid savannah area of West Africa, Nwoke et al. (2003) found a strong positive correlation between the amount of P in the soil solution and the clay content. In addition, Vanlauwe et al. (2006) reported that, although the responses to P inputs were a function of soil P contents, the wide variability in P content between plots masked a clear response to P. Alternatively, the small amounts of P provided in FM could be poorly available to crops due to its binding with amorphous and crystalline forms of aluminum and iron which are common in strongly-weathered tropical soils (Chikowo et al., 2010).

## 3.5 | Microdose fertilization response by type of associated practice

Thirty-one of the studies analyzed have tested FM in combination with other practices such as organic amendments, water conservation techniques and seed priming. Figure 7 illustrates the amplitude of crop response to FM when combined with these practices. As a reminder, the response is the excess yield attributable to FM compared to the practice alone. The results indicate that in relative (Figure 7a) and absolute terms (Figure 7b), the highest gains are observed when FM is combined with water conservation techniques such as the Zaï or planting basins, tied ridges, and mulching (Ibrahim, Abaidoo, Fatondji, & Opoku, 2015b; Mashingaidze et al., 2013; Pale, Mason, & Taonda, 2009). As a matter of fact, water conservation measures appear to induce a synergistic effect, i.e., the response to FM is substantially larger when combined with water conservation measures than in the absence of these measures. Although these combinations were mostly tested in environments where water shortage is expected, the results nevertheless clearly demonstrate the importance of improving soil water availability in order to increase the efficiency of fertilizer use in areas with low rainfall (Fatondji et al., 2006; Zougmoré, Jalloh, & Tioro, 2014; Farooq and Nawaz, 2016).

The lowest yield responses to FM are observed when combined with organic amendments (OM) and seed priming (pre-wetting of seeds). The latter likely results from the fact that only minute amounts of fertilizer (0.3 to 0.9 g hill$^{-1}$) were combined with the seed priming (Abdalla et al., 2015; Aune et Ousman, 2011; Aune, Traoré, & Mamadou, 2012). While some previous studies reported an additive effect when combining FM with OM (Ibrahim et al., 2015a; Manyame, 2006; Somda et al., 2017, Tovihoudji et al., 2019), it appears here that the yield increase attributable to FM on plots amended with OM is lower than on unamended plots (FM only). Chivenge et al. (2011) also reported that negative interactions between organic amendments and fertilizers are most frequently observed. The benefits of OM therefore appears to come primarily from the nutrients provided. This would be true under conditions that favor rapid decomposition of the OM. Under such conditions, the agronomic efficiencies of N and P (yield gain per unit of nutrient applied) are not significantly different whether the recommended amount of fertilizer is entirely provided by mineral fertilization or when part of the nutrient requirements are substituted by organic amendment inputs (Sileshi et al., 2019). Wortman et al. (2017) pointed out that on sandy soils with low biological activity and/or in arid conditions, soil moisture and hence mineralization of organic matter may be limited. Consequently, the effect of organic matter in improving soil moisture can become more important than the nutrients released. Under these conditions, an increase in the amplitude of FM response with organic matter may be observed.

### 3.6 | Research needs

A meta-analysis was used to analyze the factors that determine the variability of crop yield response to FM. Major trends were highlighted: (i) relative yield increase is independent of the type of cereal crop (maize, sorghum, millet); (ii) yield response to FM is better on medium-textured soils than on light- and heavy-textured soils; (iii) yield response to FM increases with rainfall level, with a limit on finer-textured soils in the highest rainfall areas (> 1000 mm); (iv) water conservation techniques have a synergistic effect on yield response in low rainfall areas; (v) yield response to FM decreases when combined with OM inputs.

While these conclusions can usefully be integrated into FM extension efforts, several questions remain unaddressed. First, it was not possible to determine whether chemical fertility or water-related issues best determine the tendency towards reduced response on heavy-textured soils or on medium-textured soils under high rainfall conditions (Figure 4; Figure 6). More generally, this meta-analysis revealed similarities and divergences with others studies (Chivenge et al., 2011; Tonitto & Ricker-Gilbert, 2016), noticeably with regard to the effects of soil type on crop response to fertilization. Thus, future FM studies should focus more on the effect of soil type, and in particular on heavy and medium-textured soils. Second, Gemenet et al. (2015), Gemenet et al. (2016), and Leiser, Rattunde, Weltzien, and Haussmann (2014) have shown that millet and sorghum yields increase with phosphorus uptake (amount of P uptake per hectare), and that this capacity depends among others on varieties. However, the effect of crop variety could not be analyzed due to the great diversity of varieties reported across studies.

Furthermore, it emerged that the effect of FM is reduced when combined with OM (Figure 7). However, studies have shown that the response to organic fertilizer inputs is a function of the quality (nitrogen, polyphenol and lignin content), quantity and type of organic fertilizer (Chivenge et al., 2011; Wortman et al., 2017). Future research should aim at finding combinations of doses and types of organic amendments leading to synergistic effects when combined with FM, as a function of soil types and agro-climatic conditions. Finally, it would be useful to have studies in which the different ways of applying fertilizers are compared. Such studies exist, but not in sufficient numbers to allow for a reliable meta-analysis at this stage.

## 4 | CONCLUSIONS

The meta-analysis of millet, sorghum and maize response to FM in SSA indicates that, on average, this technique improves yields by almost 70%. This confirms the relevance of the FM technology in boosting productivity on smallholder farms with more affordable levels of investments than classically recommended fertilization rates. Yet the analysis also reveals that soil and climatic conditions strongly impact the mean response to FM. Such effects must be better integrated into extension schemes to provide farmers with the best possible information and to target FM technology to sites where the highest gains can be obtained. Based on the analysis, the following recommendations can be issued regarding FM: (i) overall, apply N+P fertilizer rather than either one alone, although cost of fertilizer may have to be taken into consideration as well; (ii) give priority to medium-textured soils, then to light-textured soils; (iii) do not give priority to inherently fertile soils (low responsive soils); (iv) combine FM with water conservation techniques in drought-sensitive areas; (v) if the availability of OM is limiting, it may be more effective not to combine FM and OM on the same plots. Nevertheless, there appear to be complex interactions between several factors, in particular between soil and climate, yet the information provided in most studies is insufficient to properly unravel the processes that underlie these interactions. In order to improve on the above guidelines, it will thus be necessary to further test the hypotheses underlying them through site-specific field experiments that cover a range of well-documented factors that could not be analyzed in this study.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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