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Article

Maize Response to Fertilizer Dosing at Three Sites in the Central Rift Valley of Ethiopia

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Abstract: This study examines the agronomic response, efficiency and profitability of fertilizer microdosing in maize. An experiment with the following treatments was conducted: control without fertilizer, microdosing treatments, with the rate of 27 + 27, 53 + 53 and 80 + 80 kg ha^{-1}, and banding of fertilizer with 100 + 100 kg ha^{-1} of di ammonium phosphate (DAP) + urea, applied at planting and jointing, respectively. The treatments were arranged in a randomized complete block design with four replications. The experiment was conducted during the 2011/2012 and 2012/2013 cropping seasons at Ziway, Melkassa and Hawassa in the semiarid central rift valley region of Ethiopia. Compared to the control, the fertilizer treatments had higher yield and fertilizer use efficiency (FUE) profitably. The 27 + 27 kg ha^{-1} fertilizer rate increased the grain yield by 19, 45 and 46% at Hawassa, Ziway and Melkassa, respectively, and it was equivalent to the higher rates. The value cost ratio (VCR) was highest with the lowest fertilizer rate, varying between seven and 11 in the treatment with 27 + 27 kg ha^{-1}, but two and three in the banding treatment. Similarly, FUE was highest with the lowest fertilizer rate, varying between 23 and 34 kg kg^{-1} but 7 and 8 kg kg^{-1} in the banding treatment. The improved yield, FUE, VCR and gross margin in maize with microdosing at the 27 + 27 kg ha^{-1} of DAP + urea rate makes it low cost, low risk, high yielding and profitable. Therefore, application of this particular rate in maize may be an option for the marginal farmers in the region with similar socioeconomic and agroecological conditions.

Keywords: fertilizer dose; fertilizer application method; maize yield; semiarid Ethiopia; value cost ratio

1. Introduction

Land degradation in the form of soil erosion and soil nutrient depletion are critical challenges to agricultural production and economic growth in Ethiopia. On farm lands, in particular, there is a continuous decline in soil quality resulting from reduced fallows and the sub-optimal use of input [1]. At the national level, fertilizer is applied to only 45% of the total crop area [2,3]. Factors that limit the use of chemical fertilizer by smallholder farmers are the high cost, lack of access to credit, price risk of fertilizers and lack of technology [4].

The central rift valley of Ethiopia, where this study was undertaken, is characterized by a general decline in fallow periods and the increasing use of marginal land, with consequent land degradation [5–7]. As a result of the increasing land degradation, agricultural productivity has decreased, thus exacerbating food insecurity and poverty [7]. The Ethiopian rift valley, which covers a huge proportion of the vast semi-arid areas in Ethiopia, covers 301,500 km^2 (27% of the country) and represents the crop production zone suffering from serious moisture stress [8]. This study was undertaken in three sites with different land use and management systems and, therefore, possibly having spatial variability in soil quality and, thus, maize yield responses to fertilizers. In this respect, it was reported that different land management systems were found to affect soil quality and agricultural production differently in Ethiopia [1]. There can be a spatial variability in soil nutrients even within farms, due to different soil management [9], and such variability affects nutrient use efficiency and crop productivity [10]. In this respect, there is a need for considering soil fertility gradients and nutrient management to improve resource use efficiency and crop production on smallholder farms [9,10]. Apart from that, the existence of high temporal and spatial variability in rain and high variability in the length of growing season (late onset and early termination) between years was reported to affect crop production in the central rift valley [11,12]. A spatial and temporal variation in crop responses to climate variability has also been reported in East Africa [13]. Several other previous studies have also reported that although the agricultural extension program in Ethiopia has promoted fertilizer use over the last few decades, its success in increasing agricultural productivity has been constrained principally by unpredictable rainfall patterns [14,15]. Therefore, spatial variability in soil quality and rainfall could be among other factors influencing maize yield responses to fertilizer application in the three study sites in the central rift valley.

The important nutrients limiting crop production in the dry land areas of Ethiopia, including the central rift valley, are nitrogen (N) and phosphorus (P) [16]. The cation exchange capacity (CEC) of the soils ranges from a medium to a high level (20.00–39.00 meq/100 gram of soil). The high exchangeable potassium (K) level (2.05–4.03 meq/100 gram of soil) indicates that a response to K fertilizer is unlikely for cereals [17]. Hence, for increased grain/biomass yield, yearly application of N and P fertilizer is required. The easiest way to increase soil N and P is the addition of inorganic nutrients, such as urea and di-ammonium phosphate (DAP). With the available fertilizer application methods that use high fertilizer rates, however, this may be difficult for smallholder farmers in the study sites, due to the high fertilizer cost, lack of credit and insufficient training in the use of fertilizers.

The microdose method of applying fertilizers is an alternative to the banding method that has been recommended through the national extension system. Microdosing consists of the application of small quantities of fertilizer in the planting station at planting, or as a top dressing three to four weeks after emergence. Microdosing fertilizer enhances fertilizer use efficiency and improves yields, while minimizing input cost (requiring low financial risk and low cash outlay) and improving return on investment [18–20]. This is an efficient way to apply fertilizer, because the fertilizer is applied adjacent to the seeds, thereby ensuring a high uptake. Microdosing of fertilizers was found to increase yields by 44% to 120% and farmers' income by 52% to 134% compared to traditional application methods [18]. It is an effective fertilizer application method for sorghum and pearl millet production in Mali and Sudan [19] and in Sudan [21].

There is no documentation on the use of fertilizer microdosing in Ethiopia. The most common fertilizer application methods in Ethiopia are broadcasting, top dressing or banding. National research institutes primarily recommend the banding method, while farmers use the broadcasting method for broadcasted crops and banding for row-planted crops. Maize, which is staple crop in the study sites and the test crop in this study, is an ideal crop for row planting. Presently, the Ethiopian government is promoting the row planting and banding methods of fertilizer application for the major cereal crops to improve crop productivity, food security and farmer income. However, due to the high fertilizer rates with the banding method of fertilizer application, an alternative fertilizer application method, such as the microdose method, is therefore imperative.

Farmers do not generally follow the national fertilizer recommendation rates (for instance, the application of 100 DAP + 100 urea kg ha^{-1} at planting and jointing, respectively, for maize), due to high fertilizer cost, fertilizer supply shortages and insufficient training in fertilizer use [2,4,22]. Due to the high price of fertilizer, the use of urea is limited [22]. Moreover, the effect of fertilizers is marginal, due to applications being below the recommended rates [22,23] and the failure to use DAP and urea in proper combinations [22]. These effects are further exacerbated, because fertilizer recommendations from the early 1990s [24] are largely out-of-date and not tailored to the agro-ecology, soil type and climate [4,24]. Such low technical efficiency leads to non-optimal fertilization [4] and marginal effects on crop production [22]. This study therefore examines the agronomic response, fertilizer use efficiency and fertilizer profitability of variable rates of DAP and urea applied through microdosing and banding methods in maize production in the central rift valley. Specifically, the variable fertilizers rates to be investigated for their agronomic and economic responses in maize were 27 + 27, 53 + 53 and 80 + 80 kg ha^{-1} of DAP + urea under the microdosing method and 100 + 100 kg ha^{-1} DAP + urea under the banding method.

2. Materials and Methods

2.1. Characteristics of Study Sites

The research sites, Ziway, Melkassa and Hawassa, are situated at 7°9′ N and 38°43′ E, 8°4′ N and 39°31′ E, and 7°4′ N and 38°31′ E latitude and longitude, respectively, at 1642, 1550 and 1675 m.a.s.l. in the central rift valley of Ethiopia. Ziway and Melkassa are characterized as semi-arid agro-ecological zones; whereas Hawassa is a moist mid-highland zone. Ziway has a well-drained clay loam soil (40% sand, 32% silt and 28% clay), with pH = 8.40, 3.21% organic carbon (OC), 0.25% total nitrogen (TN) and 18.20 mg kg^{-1} available P. The average total annual rainfall in Ziway over the past 12 years ranges from 518 to 1002 mm (average 815 mm), with an average maximum and the minimum air temperature of 28 °C and 13 °C, respectively. Melkassa has a loam soil (37% sand, 40% silt and 23% clay), with pH = 7.42, 1.7% OC, 0.14% TN and 19.20 mg kg^{-1} available P. The average total annual rainfall for Melkassa over the past 12 years ranges from 549 mm to 1093 mm (average 877 mm), with an average maximum and minimum air temperature of 29 °C and 14 °C, respectively. Hawassa has a well-drained loam (46% sand, 28% silt and 26% clay), with pH = 7.1, 2.3% OC, 0.19% TN and 46.40 mg kg^{-1} available P. The average total annual rainfall for Hawassa over the past 12 years ranges from 776 mm to 1145 mm (average 988.1 mm), with an average maximum and minimum air temperature of 26.6 °C and 13.7 °C, respectively.

2.2. Farm Characteristics

Farmers in the study sites practice mixed farming; characterized by a strong integration between crop and livestock production. Livestock provides draft and threshing power, manure to improve soil fertility and materials for fuel. Crop residues are used as fodder, particularly during dry seasons, as well as providing a source of domestic fuel. Mono-cropping of cereals, mainly maize (*Zea mays* L.); and teff (*Eragrostis tef* (Zucc.) Trotter), and pulses, such as haricot bean (*Phaseolus vulgaris* L.), is a common practice in the region. Maize is the predominant cereal crop and staple food. Increasing food demand in the region, driven by considerable population growth, has increased pressure on the fragile land system [6,7,25].

There are two overlapping seasons for crop production in the study sites. The first season usually extends from April to September, while the second season, which is the main rainy season, extends from June to October. July and August are the wettest months. Mid-maturing maize is the main crop for the first (and longer) season; while haricot bean, wheat and teff are the main crops for the second season. Early-maturing maize is cultivated during both seasons. When the rain starts late, farmers cultivate early-maturing maize varieties during the second season, usually in early June. In recent times, at Ziway and Melkassa, due to the shifting seasons, farmers have started to use the second season for most of the crops. Early-maturing maize is usually cultivated to fill the severe food shortage during pre-harvest. The government also encourages farmers to cultivate early and plant drought-tolerant varieties of maize in these areas. Fertilizer and improved seeds are supplied to farmers through the farmers' cooperative union and agricultural departments; however, delays in supply are frequent. Farmers sell their agricultural produce at local markets. There is broad fluctuation in the input and output market prices.

2.3. Treatments, Experimental Design and Procedures

An experiment was conducted at Ziway, Melkassa and Hawassa during the 2011/2012 and 2012/2013 cropping seasons using the following treatments:

1. Control without fertilizer;
2. Microdosing 26.6 kg DAP at planting and 26.6 kg urea ha^{-1} at maize jointing. This corresponds to applying 0.5 g DAP and urea per planting hill;
3. Microdosing with 53 kg DAP ha^{-1} at planting and 53 kg ha^{-1} urea at maize jointing. This corresponds to applying 1 g DAP and urea per planting hill;
4. Microdosing with 80 kg DAP ha^{-1} at planting and 80 kg ha urea at maize jointing. This corresponds to applying 1.5 g DAP and urea per planting hill;
5. Banding with 100 kg DAP ha^{-1} at planting and 100 kg urea at maize jointing (national recommendation rate).

The microdose rates represent a reduction in the fertilizer rate compared to the recommended rates of 73, 47 and 20% of DAP or urea. In microdosing, the fertilizer is placed adjacent to seeds; whereas, in banding, the fertilizer was dressed in the entire central surface of furrows and covered afterwards with soil at planting. The experiment used di-ammonium phosphate (DAP) ($(NH_4)_2HPO_4$) and urea ($CO(NH_2)_2$); both commonly used fertilizers in Ethiopia. The plot size was 3 m by 4.5 m (13.5 m^2) with six rows. The population was around 53,000 maize plants ha^{-1}. The spacing was 75 cm between rows and 25 cm between plants. The seed rate was 27 kg ha^{-1}. The required microdose rate of DAP was placed together with seeds (two seeds per planting station) in the planting station at planting, while urea was top dressed and covered with the soil immediately to avoid its loss to the air through evaporation in the fifth week when plants were at jointing with approximately a 60-cm plant height. In the microdosing treatment, to save time, a small cap produced from available plastic material was cut into different sizes in order to accurately measure the different fertilizer rates. The treatments were arranged as a randomized complete block design in four replications. The blocks were separated by a 1.5 m-wide open space. Hand weeding was undertaken using a local hand hoe three weeks and six weeks after planting.

2.4. Agronomic Data Collection and Measurement

The major agronomic data collected include pocket seed germination, seedling vigor (rated 1 to 5 where: 1 = poor, 2 = low, 3 = moderate, 4 = vigorous, 5 = very vigorous), lodging count, plant height, grain yield and stover yield. Plants fallen, inclined or with broken stalks were considered as lodging. Plant height was measured from the ground level to the base of the tassel for five randomly selected plants per plot. Stover weight was taken after sun drying for 9 days when almost no change in weight was observed between consecutive measurements. Maize cobs were harvested, shelled, weighed, grain moisture measured and eventually corrected for moisture content at 12.5% by a multi-grain digital moisture meter. Yield was extrapolated and then reported on a hectare basis. To avoid border effects, yield data were collected from the four central rows, with a net plot size of 9 m^2.

2.5. Fertilizer Use Efficiency

The fertilizer use efficiency (FUE) of each treatment was computed as the difference in yield (kg ha^{-1}) between each treatment and the control divided by the amount of fertilizer applied (kg ha^{-1}).

$$FUEt = \frac{Yt - Ct}{Ft} \quad (1)$$

where *FUEt* is the agronomic fertilizer use efficiency of treatment *t*; *Yt* is the grain yield of treatment *t*; *Ct* is the grain yield of the control treatment; and *Ft* is the rate of fertilizer used for treatment *t*.

Standard enterprise budgeting techniques were used to estimate production costs and profitability. Total variable cost (TVC) was estimated from the input costs of labor, fertilizer and seed. Input costs for fertilizers and seeds; and average labor costs for planting, fertilizer application, weeding and harvesting were estimated. Price per kg (averaged over 2011 and 2012) of maize seeds, DAP and urea were 1.14, and 0.82 and 0.63 US$ kg^{-1}, respectively, at the local market at Ziway and Melkassa. Both Ziway and Melkassa are close to fertilizer markets, and the price is therefore the same. The market price for output is also similar. At Hawassa, price per kg (averaged over 2011 and 2012) of maize seeds and DAP and urea fertilizer were 1.19, and 0.84 and 0.64 US$, respectively. The market price of the grain per kilogram was estimated at 0.23 US$ at Ziway and Melkassa and 0.22 US$ at Hawassa. Rental cost was estimated at 10.96 US$ ha^{-1} for one time passage with oxen. Labor cost was estimated at 1.64 US$ $person^{-1}day^{-1}$ across the sites. Gross income (GI) was estimated from grain yield multiplied by grain price. Gross margin (GM) was calculated as the difference between GI and TVC. Monetary values related to cost and income were converted from Ethiopian Birr to US$ at the exchange rate of one US$ to 18.24 Ethiopian Birr.

2.6. Economics of Fertilizer Use

The economic returns of the treatments were calculated based on the GM and value cost ratio (VCR).

For each treatment, the GM was calculated as follows:

$$GMt = GIt - TVCt \quad (2)$$

Where *GMt* denotes gross margin of treatment *t*, *GIt* denotes the gross income from treatment *t* and *TVCt* denotes the total variable cost for treatment *t*.

For each treatment (compared to the control), *VCR* was calculated as follows:

$$VCRt = \frac{(Yt - Yc) \times Gt}{CFt} \quad (3)$$

Where *VCRt* denotes the value cost ratio for treatment *t*, *Yt*−*Yt* denotes the incremental grain yield resulting from fertilizer use in treatment t and control *c*, *PGt* denotes the grain price per kg and *CFt* denotes the cost of fertilizer per hectare in the treatment, *t*.

2.7. Statistical Analyses

For both agronomic and economic data, analyses of variance were carried out using SAS for Windows 9.3 [26]. Wherever there were significant differences, mean separations were carried out using least significant difference (LSD). Significant differences between means of treatments were determined at the 5% significance level ($p < 0.5$). The statistical analyses and presentations for the agronomic and economic data were based on the average of the two seasons' data. The agro-ecologies and socioeconomic conditions at Ziway and Melkassa are assumed to represent most semiarid areas in the rift valley of Ethiopia. Therefore, the findings obtained from this study can be extrapolated to other areas in the rift valley with similar agro-ecological and socioeconomic conditions.

3. Results

3.1. Yield Characteristics and Responses to Fertilizer Microdosing and Banding

Across sites, the highest fertilizer rate (80 + 80 kg ha^{-1} DAP + urea) in microdosing had significantly depressed pocket seed germination. Seedling vigor, however, did not show a considerable response to fertilizer rates. Unfertilized plots had a higher lodging count than fertilized treatments. The plant population at harvest was considerably lower in the treatment with the highest microdosing rate. On average, the fertilizer rate in banding (100 + 100 kg ha^{-1} DAP + urea) was found to have similar effects as the two lower fertilizer rates (27 + 27 and 53 + 53 kg ha^{-1} DAP + urea) in microdosing on seed germination and plant population at harvest (Table 1). Generally, most of the yield characteristics did not vary with fertilization and non-fertilization.

Table 1. Average maize yield characteristics of fertilizer rates in microdosing and banding methods of fertilizer application at Hawassa, Ziway and Melkassa sites over the 2011/2012 and 2012/2013 cropping seasons. DAP, di-ammonium phosphate.

Site	Application Method	Fertilizer rate (DAP + urea) (kg ha^{-1})	Seed Germination (%)	Seedling Vigor	Lodging Count	Plant Height	Stand Count Harvest
Hawassa	Microdose	0	97 a	3.6 a	2.0 a	197 a	46 a
		27 + 27	96 ab	4.1 a	1.0 ab	199 a	47 a
		53 + 53	96 b	3.9 a	1.0 ab	200 a	47 a
		80 + 80	92 c	3.8 a	1.6 ab	202 a	44 b
	Banding	100 + 100	97 ab	4.0 a	1.6 ab	204 a	47 a
		LSD	*1.07*	*0.54*	*1.08*	*28.34*	*1.29*
Ziway	Microdose	0	98 a	2.9 c	2.9 a	203 a	47 a
		27 + 27	98 a	3.5 bc	1.0 b	203 a	48 a
		53 + 53	98 a	4.8 a	1.0 b	212 a	48 a
		80 + 80	97 b	3.4 bc	1.0 b	204 a	46 b
	Banding	100 + 100	98 a	3.9 b	1.0 b	204 a	48 a
		LSD	*1.05*	*0.81*	*1.34*	*11.37*	*0.83*

Table 1. *Cont.*

Site	Application Method	Fertilizer rate (DAP + urea) (kg ha^{-1})	Seed Germination (%)	Seedling Vigor	Lodging Count	Plant Height	Stand Count Harvest
		53 + 53	96 b	3.9 a	1.4 ab	217 a	47 ab
		80 + 80	93 c	3.8 a	1.3 b	219 a	45 c
	Banding	100 + 100	97 ab	4.0 a	1.1 b	215 a	47 a
		LSD	*1.07*	*0.54*	*0.85*	*7.32*	*1.19*

Means in the same column with same letter are not significantly different at p <0.05.

3.2. Maize Yield Responses to Fertilizer Microdosing and Banding

Across the sites, although all of the variable fertilizer rates were able to improve yield significantly over the control, there was no significant difference in yields between the fertilizer treatments. However, maize yield tended to decline with increasing fertilizer doses in microdosing. In microdosing, the maximum yield was recorded in the treatment with the minimum fertilizer rate of 27 + 27 kg ha^{-1} at Hawassa; whereas at Ziway and Melkassa, the maximum yield was found in the treatment with the 53 + 53 kg ha^{-1} fertilizer rate. Across the sites, the microdosing treatment with the 80 + 80 kg ha^{-1} fertilizer gave a consistently lower yield than all other treatments in microdosing and banding. Despite its higher doses, the banding method gave similar yields as the variable doses in microdosing (Table 2).

Table 2. Average maize grain and stover yield in relation to microdosing and banding methods at the Hawassa, Ziway and Melkassa sites over the 2011/2012 and 2012/2013 cropping seasons.

Application	Fertilizer Rate	Grain Yield (kg ha^{-1})			Stover Yield (kg ha^{-1})		
Method	(DAP + urea kg ha^{-1})	Hawassa	Ziway	Melkassa	Hawassa	Ziway	Melkassa
	0	6334 b	4054 b	3649 b	7416 b	6404 b	5610 b
Microdosing	27 + 27	7539 a	5864 a	5320 a	8850 a	8133 a	7375 a
	53 + 53	7222 a	6042 a	5542 a	8391 a	8283 a	7500 a
	80 + 80	7086 a	5743 a	5221 a	8265 a	8042 a	7167 a
Banding	100 + 100	7636 a	5815 a	5226 a	8896 a	7999 a	7375 a
	LSD	*608*	*300*	*339*	*671*	*800*	*406*

Means in the same column with same letter are not significantly different at p-value <0.05.

3.3. Fertilizer Use Efficiency, Value Cost Ratio and Profitability

FUE decreased with increasing fertilizer rates in microdosing across sites. The FUE varied between 23 and 34 for the lowest microdosing rate. Except at Hawassa, the banding method had lower FUE than the microdosing method. Regardless of fertilizer rates and the methods of fertilizer application, Ziway and Melkassa had higher FUE than Hawassa (Table 3). Equally, VCR declined with increasing fertilizer rates in microdosing across sites. The maximum VCR was recorded in microdosing treatments with the lowest fertilizer rate across the sites. Across sites, the banding method generally had a lower VCR compared to the microdosing treatment of 27 + 27 and 53 + 53 kg ha^{-1} fertilizer.

Except at Hawassa with a higher VCR, the banding method had the same VCR as the highest fertilizer rate in microdosing (Table 3).

Table 3. Average fertilizer use efficiency (FUE) and value cost ratio (VCR) of fertilizer rates in microdosing and banding methods at the Hawassa, Ziway and Melkassa sites over two seasons.

Fertilizer application		Hawassa		Ziway		Melkassa	
Method	rate	FUE (kg kg^{-1})	VCR	FUE (kg kg^{-1})	VCR	FUE (kg kg^{-1})	VCR
	0	-	-	-	-	-	-
Micro-dosing	27 + 27	22.6	6.6	33.9	10.6	31.3	9.8
	53 + 53	8.4	2.5	18.8	6.0	17.9	5.7
	80 + 80	4.7	1.4	10.6	3.3	9.8	3.1
Banding	100 + 100	6.5	1.9	8.8	2.8	7.9	2.5

The labor demand (man-day hectare^{-1}) varied with fertilizer application techniques. The microdosing and banding methods required 4.8 and 2.3 man-day hectare^{-1}, respectively. The labor demand for microdosing was therefore twice that of banding.

Corresponding to yields, microdosing of the 27 + 27 kg ha^{-1} fertilizer rate generated the maximum GM at Hawassa, increasing GM by 13% compared to the control; whereas at Ziway and Melkassa, microdosing of 53 + 53 kg ha^{-1} fertilizer generated the maximum GM, increasing GM by 53 and 42%, respectively, over the control. All of the remaining fertilizer rates also increased GM considerably compared to the control at Ziway and Melkassa. Overall, lower fertilizer rates in microdosing were more economically attractive than the highest rates, as there was no significant improvement in GM with increasing fertilizer rates (Table 4). The banding method also improved GM over the control. At Hawassa, the banding method did not significantly increase GM compared to the control, but increased GM over the 80 + 80 kg ha^{-1} fertilizer in microdosing. At Ziway and Melkassa, banding increased GM by 43% and 29%, respectively, over the control.

Table 4. Average gross income (GI) and gross margin (GM) of fertilizer rates in the microdosing and banding methods at the Hawassa, Ziway and Melkassa sites over the 2011/2012 and 2012/2013 cropping seasons.

Fertilizer	Hawassa		Ziway		Melkassa	
rate	GI (US$ ha^{-1})	GM (US$ ha^{-1})	GI (US$ ha^{-1})	GM (US$ ha^{-1})	GI (US$ ha^{-1})	GM (US$ ha^{-1})
0	1393 b	1272 bc	932 c	813 c	839 c	719 c
27 + 27	1659 a	1442 a	1346 ab	1132 a	1224 ab	1009 a
53 + 53	1589 a	1333 abc	1396 a	1143 a	1275 a	1022 a
80 + 80	1559 a	1263 c	1327 b	1036 b	1178 b	887 b
100 + 100	1680 a	1400 ab	1344 ab	1069 b	1202 ab	928 b
LSD	*134*	*133*	*55*	*56*	*73*	*74*

Means in the same column with same letter are not significantly different at p-value <0.05.

4. Discussion

4.1. Maize Yield and Yield Characteristics Response to Fertilizer Microdosing and Banding

Irrespective of differences in agro-ecological conditions in the three study sites, all of the fertilizer rates in microdosing and the fertilizer rate in banding increased yields compared to the control. This shows that there is a need for applying fertilizer in maize production at all of the study sites. A fertilizer application method that is efficient with a smaller amount of fertilizer is what is most important for marginal farmers in the central rift valley. Such a method will have high potential to increase farmers' interest, economic viability and sustainability with respect to applying fertilizer in maize. In this respect, results from this study showed that the microdosing method of fertilizer application was found to improve maize yields with smaller quantities of fertilizer. The 27 + 27 kg ha^{-1} fertilizer rate, the lowest fertilizer rate, in microdosing was able to improve maize yield more than the higher rates in microdosing and banding across the three sites. It increased yield by 19%, 45% and 46% at Hawassa, Ziway and Melkassa, respectively, compared to the control. Previous studies have also shown similar effects that lower fertilizer rates increased crop yields more than the higher rates in microdosing [19–21] in sub-Saharan countries.

On top of that, the lower yield response in maize to the highest fertilizer rate (80 + 80 kg ha^{-1} fertilizer) in microdosing indicated that there is a limit to the dose of fertilizer that can be applied through microdosing. In this respect, the 80 + 80 kg ha^{-1} fertilizer rate in microdosing was found to depress pocket seed germination and lower plant population at harvest. These negative effects on maize performances might be attributed to the burning effects of high doses of fertilizer in the microdosing method of application. These effects are favored by a previous report that higher doses of fertilizer in the microdosing method of application may have a burning effect on seed germination and other growth stages [19]. A similar result was also obtained with spot application of fertilizer at Hawassa in maize [27]. However, the higher dose of fertilizers (100 + 100 kg ha^{-1}) in the banding method was found to have less burning effects than the variable doses of fertilizer in the microdosing method. This might be accredited to the pattern of placement of fertilizers and seeds, which affects the dose of fertilizers coming in contact with the seeds. In the microdosing method, to increase the fertilizer use efficiency, fertilizer is more precisely placed adjacent to seeds, only in the planting stations. In the banding method, however, fertilizers are placed in the entire furrows, leaving some of the fertilizer outside planting stations, which reduces the dose of fertilizers coming in close contact with seeds. As a result, the microdosing method of fertilizer application becomes more efficient in increasing maize yields than the banding method of fertilizer application. This might be due to the fact that placing fertilizer close to the seed in soils increases fertilizer uptake by crops [19,20,28].

Apart from that, a declining tendency in maize yields with increasing fertilizers doses in microdosing corresponds to an earlier report that maize agronomic responses declined beyond 46 kg ha^{-1} phosphorous fertilizer under spot application in Hawassa [27]. Although the recommended fertilizer rate (100 + 100 kg ha^{-1}) in banding was able to improve yield in maize (compared to no fertilizer application), it has a high cash outlay and is therefore more risky for the resource poor farmers, increasing their reluctance in applying fertilizers. This high rate can be one of the reasons why farmers in Ethiopia generally apply lower rates of fertilizer than national recommendations [23]. Other reports [29] also indicated that the average amount of fertilizer rate used by farmers in Ethiopia is 21 kg N ha^{-1}, which is much lower than the national recommendation rate of 60 to 100 kg N ha^{-1} [30]. The result from this study therefore revealed microdosing of fertilizers at 27 + 27 kg ha^{-1} (which corresponds to a reduction of 73% of DAP or urea compared to the national recommendation at 100 kg ha^{-1} DAP or 100 kg ha^{-1} urea) to be a low cost, low risk and an efficient dose of fertilizer across sites. Therefore, if the farmers are practicing microdosing, they can obtain a good yield at a low rate of fertilizer application. Yet, further study based on long-term data is imperative to rectifying optimum fertilizer rates for the different sites depending on soil quality and other governing agro-ecological conditions.

In relation to sites, the spatial variations in yield responses to fertilizers doses may be attributed to differences in agro-ecological conditions among the sites, namely in soil quality, degree of variability of seasonal rainfall, length of growth period and land use and land management systems. There is spatial variation between Hawassa and the other two sites (Ziway and Melkassa) in these agro-ecological conditions and land use and land management systems. Hawassa has better soil quality (for instance, higher OC, P, as well as well-drained loam soil with slightly acidic pH suitable for maize), owing to better land use and management systems, as well as higher rainfall and length of growing seasons. Among other factors, it was reported that different land management systems were found to differently affect soil quality and agricultural production in Ethiopia [1]. There was spatial variability in soil nutrients even within farms, due to different soil management systems [9], and such variability affects nutrient use efficiency and crop productivity [10]. In this respect, therefore, there is a need for considering soil fertility gradients and nutrient management to improve resource use efficiency and crop production on smallholder farms [9,10]. The lower maize yield response to fertilizer application at Hawassa (with better soil quality) can also be supported with the report that yield response to fertilization decrease with increasing soil quality [10,31].

The average total annual rainfall in Ziway, Melkassa and Hawassa over the past 12 years ranges from 518 to 1002 mm (average 815 mm), 549 mm to 1093 mm (average 877 mm), 776 mm to 1145 mm (average 988.1 mm), respectively. Apart from that, Hawassa lies in the mid-altitude zones in Ethiopia with longer growing seasons. The seasonal variability in rainfall is also lower compared to Ziway and Melkassa. Therefore, despite the better soil quality, better rainfall conditions at Hawassa might be the likely reasons for the higher maize performances, but with lower responses to fertilizer doses. Similarly, the existence of more similar agro-ecological conditions in the other two sites might be the reasons for their similarity in maize performances and responses to fertilizers. An association between spatial and temporal variation in crop responses to climate variability has been observed in East Africa [13]. The high spatial variability in rain and the high variability in the length of the growing season (late onset and early termination) between years was reported to affect crop production in the central rift valley [11,12]. Several previous studies have indicated that although the agricultural extension program in Ethiopia has promoted fertilizer application over the last few decades, its success in increasing agricultural productivity has been constrained principally by unpredictable rainfall patterns [14,15]. Moreover, in this study, Ziway and Melkassa were assumed to have similar agro-ecologies, which can represent most other semiarid areas in the Ethiopian rift valley. Therefore, the findings obtained from this study can be extrapolated to other areas in the central rift valley with similar socioeconomic and agro-ecological conditions.

4.2. Fertilizer Use Efficiency, Value Cost Ratio and Profitability of Fertilizer Microdosing and Banding

Microdosing of fertilizers gave higher FUE (kg kg^{-1}), VCR and GM (US$) compared with the recommend rate. The FUE varied from five to 23 at Hawassa, 11 to 34 at Ziway and 10 to 31 at Melkassa for the microdosing fertilizer rates, respectively. For the banding rate, the FUE value was 7, 9 and 8 at Hawassa, Ziway and Melkassa, respectively. Other studies in Ethiopia have found that nutrient use efficiency (kg yield per kg nutrient) of maize ranges between nine and 17 [32]. This indicates that the application of the smallest microdosing rate is more efficient than the highest microdosing rate.

In microdosing, VCR ranged from one to seven at Hawassa, three to 11 at Ziway and three to 10 at Melkassa. Except for the 53 + 53 and 80 + 80 kg ha^{-1} at Hawassa, the VCR was the above the recommended level. A VCR above two and preferably above four is needed under conditions of risk as in the Sahelian region [33]. Studies from Mali and Sudan in pearl millet and sorghum have shown that the VCR of microdosing is generally very favorable [19,21]. In Ethiopia, previous reports showed VCR for fertilizer maize ranging between 2.5 to 9.0 between the 1980s and 2000s [34]. In Ethiopia, case studies conducted on Sasakawa Global 2000 (SG 2000) fertilizer promotion programs have shown VCR of 9.0 in maize in the mid-1990s [35]. In Ethiopia, the return to the recommended fertilizer application rate has been generally positive in recent years, with VCR around the threshold of two [36].

In this study, microdosing with lower fertilizer rates was able to improve VCR beyond the threshold, thereby minimizing the financial risk for farmers. The optimum rates in microdosing were able to improve VCR above the threshold. The VCR obtained from banding at 100 + 100 kg ha^{-1} was around the threshold. The microdosing rate at 80 + 80 kg ha^{-1} had similar VCR to banding. The VCR at the threshold value is likely to give an unfavorable VCR in years with low rainfall or unfavorable market conditions. As a result, the banding rate is less attractive to farmers, due to high risks and high cash outlays. Microdosing of a small amount of fertilizer may be a better option for resource-poor smallholding farmers at the study sites [19–21]. The lower rate at 27 + 27 kg ha^{-1} will normally be preferred by farmers, because of its higher VCR. This study shows that microdosing can reduce farmers' cash outlay and risk; thereby making the use of fertilizer more attractive. Previous studies in the Sahelian region also confirmed that crop productivity can be increased at a low cost and very moderate risk to farmers [21].

The lowest microdosing rate at 27 + 27 kg ha^{-1} generated a higher GM than the 80 + 80 kg ha^{-1}, banding rate (except at Hawassa) and control. The application of small quantities of fertilizer with the microdosing method becomes more profitable than the application of large quantities of fertilizers with either the microdosing or banding methods. The maximum increase in GM over the control was 13%, 53% and 42%, at Hawassa, Ziway and Melkassa, respectively. Corresponding to yield responses, the higher GM with small quantities at 27 + 27 kg $ha^{-1}$of fertilizer under microdosing may attract farmers toward applying fertilizers in maize. Unlike at Ziway and Melkassa, the banding method did not improve GM over the control at Hawassa, having a lower response to fertilizer. This may be related principally to the better soil quality, seasonal rainfall and the length of the growing season at Hawassa.

This indicates that under a better soil management system and favorable seasonal rainfall conditions, farmers can still get reasonable yields from crops.

Although the labor demand in microdosing (4.8 man-days ha^{-1}) is nearly twice that in banding (2.3 days ha^{-1}) for the application of fertilizers, the microdosing method still appears attractive and viable. Like in several other areas in Ethiopia, the opportunity cost for labor is low in the central rift valley.

4.3. Limitations and Opportunities in Using Fertilizers

The unpredictable climatic conditions in timing and severity—drought and prolonged dry spells—in the central rift valley escalate the risk-averse conditions of the marginal farmers and inhibit investment in high cost fertilizers and technologies [11,12], because the downside risk for marginal farmers is extremely high. Therefore, the microdose method appears to be particularly interesting to farmers having access to only small quantities of fertilizer in risk-prone areas and to the poorest farmers. For the poorest farmers, it is far less risky to use microdosing than the banding method. Particularly, it appeared attractive for boosting the productivity and incomes of maize by using fertilizer rates that are 73% lower than the recommended rate. On top of that, as the use of the microdosing method brings entire changes to the existing fertilizer application methods, there is a need for a strong linkage among researchers, farmers, and policy makers. The knowledge transfer would be more productive if it becomes part of the national agricultural extension system.

5. Conclusions and Recommendations

Microdosing in maize is an interesting option for farmers, because it gives a high yield, VCR and FUE; as well as favorable gross margins. Both fertilizer microdosing and banding improves yields. The lowest fertilizer rates improve yields as much as higher rates under both microdosing and banding. At Hawassa, the gross margin in microdosing was similar to banding, but it required 47% to 73% less fertilizer. However, at Ziway and Melkassa, these lower fertilizer rates under microdosing gave higher GM than higher rates under microdosing and banding. The higher FUE in microdosing shows that it is more efficient than banding, which may increase farmers' interest in applying fertilizer with the microdosing method. Microdosing has a higher VCR than banding and is therefore a less risky and more affordable method for farmers. In conclusion, lower fertilizer rates under microdosing are more productive and profitable than higher rates under microdosing or banding methods. Based on the results from these experiments, application of 27 kg DAP ha^{-1} at sowing and 27 kg urea ha^{-1} at jointing in maize could be an option for the marginal farmers across the sites. Yet, as the findings from this study are based only on two years of data, we suggest further investigation (based on long-term data) for rectifying the optimum rates for the microdosing method of fertilizer application in the study areas.

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Author Contributions

Getachew Sime was responsible for planning, designing, site selection and executing all the experiments, analysis and interpretation of results. He has prepared the first draft of the paper and wrote the final version in collaboration with Jens B. Aune, he also had substantial contribution in the planning, analysis and interpretation of results. He visited all the experiments at Ziway and Melkassa in Ethiopia. Overall, he was the main supervisor of this paper.

Conflicts of interest

The authors declare no conflicts of interest.

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