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RESEARCH ARTICLE

Micro-dosing as a pathway to Africa's Green Revolution: evidence from broad-scale on-farm trials

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Abstract Next to drought, poor soil fertility is the single biggest cause of hunger in Africa. ICRISAT-Zimbabwe has been working for the past 10 years to encourage small-scale farmers to increase inorganic fertiliser use as the first step towards Africa's own Green Revolution. The program of work is founded on promoting small quantities of inorganic nitrogen (N) fertiliser (micro-dosing) in drought-prone cropping regions. Results from initial on-farm trials showed that smallholder farmers could increase their yields by 30–100% through application of micro doses, as little as 10 kg Nitrogen ha^{-1}. The question remained whether these results could be replicated across much larger numbers of farmers. Wide scale testing of the micro-dosing (17 kg Nitrogen ha^{-1}) concept was initiated in 2003/2004, across multiple locations in southern Zimbabwe through relief and recovery programs. Each year more than 160,000 low resourced households received at least 25 kg of nitrogen fertiliser and a simple flyer in the vernacular explaining how to apply the fertiliser to a cereal crop. This distribution was accompanied by a series of simple paired plot demonstration with or without fertiliser, hosted by farmers selected by the community, where trainings were carried out and detailed labour and crop records were kept. Over a 3 year period more than 2,000 paired-plot trials were established and quality data collected from more than 1,200. In addition, experimentation to derive N response curves of maize (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Pennisetum glaucum* (L.) R.Br.) in these environments under farmer management was conducted. The results consistently showed that micro-dosing (17 kg Nitrogen ha^{-1}) with nitrogen fertiliser can increase grain yields by 30–50% across a broad spectrum of soil, farmer management and seasonal climate conditions. In order for a household to make a profit, farmers needed to obtain between 4 and 7 kg of grain for every kg of N applied depending on season. In fact farmers commonly obtained 15–45 kg of grain per kg of N input. The result provides strong evidence that lack of N, rather than lack of rainfall, is the primary constraint to cereal crop yields and that

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micro-dosing has the potential for broad-scale impact on improving food security in these drought prone regions.

Keywords Fertiliser · Nitrogen · Semi-Arid · Smallholder · Sorghum · Maize · Pearl Millet · Southern Africa · Zimbabwe

Introduction

Throughout the 1980s and 1990s, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) primarily targeted the development and dissemination of earlier maturing varieties of sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Pennisetum glaucum* (L.) R.Br.), as means to improve productivity and reduce the risks of drought in semi-arid agro-ecologies of southern Africa (Heinrich 2004). Farmers liked the new varieties for their early maturity and large grain size; adoption rates were favorable. However, limited gains were achieved in crop yields and productivity. This is because of the low inherent fertility of most soils in the region (Giller et al. 2006; Tittonell et al. 2005; Zingore et al. 2007). Even so, farmers are reluctant to risk investments in fertilizer, particularly at the recommended rates (Mafongoya et al. 2006). The main problem with most current fertility management recommendations is that they target maximization of yields or profits without consideration of the agricultural risks and resource constraints faced by many smallholder households. The levels of inorganic fertilizer, manure and rotations demanded are far beyond the capabilities of all but the wealthiest of households (Mapfumo and Giller 2001; Giller et al. 2006; Mafongoya et al. 2006; Zingore et al. 2007). Surveys in southern Zimbabwe, for example, indicated that less than 5% of farmers commonly used fertiliser (Ahmed et al. 1997; Rusike et al. 2003). Sixty percent of households owning cattle did not even use cattle manure as an amendment for crop production. Current and past use of inorganic fertiliser and manure and average rates of application for Malawi and Zimbabwe are summarized in Table 1. Similar data have been reported for elsewhere in Zimbabwe and other countries in sub-Saharan Africa (Hilhorst and Muchena 2000; Mafongoya et al. 2006; Morris et al. 2007; Zingore et al. 2007).

Table 1 Current and past use of inorganic fertiliser and manure and average rates of application, Malawi and Zimbabwe

Country	Practice	Proportion of farmers using technology (minimum and maximum for villages surveyed %)	Rate of application (kg N ha^{-1})	Official recommendation (kg N ha^{-1})
Malawi	Using inorganic fertiliser	4–31	17 kg/ha compound 23-21-0+4S (3.5 kg N ha^{-1})	100–150 kg ha^{-1} compound 23-21-0+4S soon after germination and 100–150 kg of CAN (28% N) or urea (42% N) two weeks after germination (50–105 kg N ha^{-1})
	Ever used inorganic fertiliser	99		
	Using manure	30–40	1.5 t ha^{-1}	10 t ha^{-1}
Zimbabwe	Using inorganic fertiliser	5–75	Less than 50 kg ha^{-1} mostly ammonium nitrate (34% N) (17 kg N ha^{-1})	150–200 kg ha^{-1} compound D 8-14-7+6.5S and 100–150 kg ha^{-1} ammonium nitrate (55–79 kg N ha^{-1})
	Ever used inorganic fertiliser	21–50		
	Manure	6–60	Less than 4 t ha^{-1}	20–40 t ha^{-1}

Source: Twomlow and Ncube (2001)

In the late 1990s, ICRISAT began to use crop simulation models as a tool for more effective analysis of technology responses under conditions of high rainfall variability and low inherent soil fertility. In 1999, ICRISAT began a series of modeling workshops in conjunction with the International Maize and Wheat Improvement Center (CIMMYT) and the Agricultural Production Systems Research Unit (APSRU) in which research and extension officers used a simulation model (APSIM—Agricultural Production Systems Simulator model (Keating et al. 2003)) to evaluate the type of resource allocation questions faced by resource-poor farmers in semi-arid regions of southern Africa (i.e. under conditions of uncertain rainfall and with the objective of achieving household food security). A common theme started from the proposition that farmers may, at best, initiate investments in small quantities of fertiliser (Rohrbach 1999).

The robustness of the simulated responses to small quantities of nitrogen (N) fertiliser, was surprising, and contrary to much of the documented fertility research results in the region which start with at least 25 kg N ha^{-1} (Mafongoya et al. 2006; Mushayi et al. 1999). Simulation results for a 1951–1999 rainfall period in southern Zimbabwe, suggested that farmers could increase their average yields by 50–100% by applying as little as 9 kg N ha^{-1} (no spatial ability for N application in model). These results indicated farmers were better off applying lower rates of nitrogen on more fields, than concentrating a limited supply of fertiliser on one field at the recommended rates (Carberry et al. 2004). However, if the household could only afford a very small quantity of fertilizer, less than 25 kg of inorganic fertilizer, it should be targeted in the first instance on the homestead plots at a micro-dose rate. Unlike the fertility ring management systems of West Africa (Ruthenberg 1980), in smallholder farms of East and Southern Africa the homestead plots, irrespective of the resource status of the household, are the most fertile, with soil fertility declining as one moves away from the household (Giller et al. 2006; Tittonell et al. 2005; Zingore et al. 2007).

On-farm experimentation was then initiated with farmers on micro-dosing alone or in combination with available animal manures (Ncube et al. 2007). The on-farm trial results confirmed that farmers could increase their yields by 30–100% by applying approximately 10 kg N ha^{-1} (Rusike et al. 2006). Larger average gains could be obtained by combining the nitrogen fertiliser with a basal application of low grade manure (Ncube et al. 2007). The question remained whether these results could be replicated across much broader spectrum of farmers and soil types.

Scaling out of micro-dosing was initiated in 2003/2004 in the context of national drought relief programs. Donors were already distributing seed and fertiliser inputs to drought affected farmers. Support was obtained from the Department for International Development (DFID) and the European Commission Humanitarian Aid Office (ECHO) to encourage the application of the micro-dosing of ammonium nitrate (AN) fertiliser by more than 160,000 farmers (Rohrbach et al. 2005; Twomlow et al. 2007a).

This paper reports the results from three related studies on low-input soil fertility management practices for the cereal production systems in southern Zimbabwe. The first two studies were designed to provide direct field evidence to local extension staff on the benefits of small quantities of nitrogen compared to seed, as it is a commonly held belief amongst the relief and development communities that it is better to provide a vulnerable household with seed, rather than fertiliser (Rohrbach et al. 2005; Twomlow 2006). The third study was the wide scale testing of the micro-dosing concept across multiple locations in southern Zimbabwe through relief and recovery programs.

Materials and methods

Rainfall characteristics

On-farm trials were conducted across a total of 16 districts in southern Zimbabwe that covered Natural Farming Region III, IV and V (Vincent and Thomas 1961) from 2003 to 2006. These natural farming regions are characterized by semi-arid climatic conditions and annual uni-modal rainfall of between 450 and 750 mm. The duration of the rainy season is from October/November to March/April and is typically characterized by sporadic, heavy rainstorms, with periodic dry spells. It is followed by a cool to warm dry season from May to September. The length of a typical wet season is between 130 and 140 days for southern Zimbabwe, with Hwange District having the shortest at 107 days.

Soils

The soils of southern Zimbabwe range from deep (>150 cm) Kalahari sands (Eutric-Aridic Arenosol—93% sand, 4% clay, 3% silt, in the 0–11 cm layer) originating from aeolian sand parent material through granitic sands (Eutric Arenosol—93% sand, 3% clay, 4% silt, in the 0–11 cm layer) to clay loams (Eutric-Leptic Cambisol—61% sand 32% clay, 7% silt, in the 0–11 cm layer) (Moyo 2001). The typical pH-value (0.01 M $CaCl_2$) of the soils is slightly acidic (5.5 in the 0–11 cm layer and 5.8 in 11–30 cm layer), organic carbon content less than 1%, and cation exchange capacity (CEC) less than 5 cmolc kg^{-1}. Base saturation is typically less than 20% in the 0–11 cm layer, increasing to over 50% below 75 cm depending on the parent material (Moyo 2001).

Farming system

The farming systems in southern Zimbabwe are semi-extensive mixed farming, involving goat and cattle production, and cultivation of drought resistant crops. Both crop and livestock productivity in the smallholder-farming sector is poor, with farm sizes varying from less than 2 ha in the east of the country to more than 5 ha in the south west (Ahmed et al. 1997; Hikwa et al. 2001; Ncube et al. 2008). The farmers grow maize (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Pennisetum glaucum* (L.) R.Br.) as the major cereal grain crops. Maize and sorghum are normally planted with the first rains from around mid-November and harvest from March onwards. Typical yields are frequently less than 500 kg ha^{-1} (FAOstat), with few if any households meeting basic households' food security needs (900 kg of cereal grain for an average household of six people) from one season to the next (Ahmed et al. 1997; Ncube et al. 2008; Zingore et al. 2007). Normal fertility management practice is to apply amendments (mainly manure) to the maize crop, and plant sorghum the following season (Carberry et al. 2004). Groundnut (*Arachis hypogaea* L.), bambara groundnut (*Vigna subterranea* (L.) Verdc.) and cowpea (*Vigna unguiculata* L. Walp. ssp. unguiculata) are the three legumes grown. But areas sown to legume each season are generally small (Ahmed et al. 1997; Twomlow 2004), and legumes receive less than 5% of the applied nutrients (Mapfumo and Giller 2001), and yields are less than 300 kg ha^{-1} (Hilderbrand 1996; Ahmed et al. 1997; Nhamo et al. 2003). To combat these low crop yields smallholder households pursue a combination of strategies/development pathways together or sequentially to meet their livelihood objectives and reduce their vulnerability. These include livestock enterprises, off farm employment and remittances—strategies common to smallholder communities throughout sub-Saharan Africa (for example: Twomlow 2004; Giller et al. 2006; Pender et al. 2006).

On-farm study 1—maize, sorghum and pearl millet nitrogen response curves

The N response curve for maize (var. SC403 or OPVZM421), sorghum (var. Macia) and pearl millet (var. PMV3 or Okashana) were determined using results from nine on-farm trial sites in southern Zimbabwe in 2003/2004, 2004/2005, and only for maize in 2005/2006. Nitrogen levels of 0, 8.5, 17, 25.5, 34 and 42.5 kg ha^{-1}, applied as ammonium nitrate (AN, 34%N), were evaluated to determine the response curve. The two highest nitrogen levels were applied as split dressing, the first at the 5-to-6-leaf-stage and the second three weeks later. Each on-farm site had a single set of treatments for each crop, with an individual plot size for each treatment of 100 m^2. The trials were located on the homestead field plot in each season, and the host farmer determined all management practices, including the date of planting. Composite soil samples were taken for the top 0.20 m of each on-farm trial site in 2006 and used as covariates in a pooled analysis.

On-farm study 2—maize variety by micro-dosing

Maize yields obtained from changing seed varieties, and adding a small dose of AN fertiliser (equivalent to 17 kg N ha^{-1}) were determined using results from nine on-farm trial sites in southern Zimbabwe in 2003/2004, 2004/2005, and 2005/2006. These were the same nine farmers that hosted trials for Study 1. Each season farmers were asked to prepare three 200 m^2 plots and plant their recycled maize seed, and open pollinated variety (var. Zm421) and a commercial hybrid (SC403). At the 5-to-6-leaf-stage the plots were split in half, one half receiving no nitrogen top dressing, and the other half receiving a small dose of AN fertiliser equivalent to 17 kg N ha[1]. The trials were located on the homestead field plot in each season, adjacent to the trials in study 1, and the host farmer determined all management practices, including the date of planting. Composite soil samples were taken for the top 0.20 m of each on-farm trial site in 2006 and used as covariates in a pooled analysis.

On-farm study 3—wide scale promotion and testing of micro-dosing

Between 2003 and 2006, under a series of recovery programs funded by DFID and ECHO, more than 160,000 farmers each cropping season, across 16 districts of southern Zimbabwe, Natural Farming Regions III, IV and V, were provided with 25 kg of AN along with a 1-page pamphlet in the local language advising on how to apply it to a growing crop. The fertiliser inputs were primarily distributed free, with the aim of improving food security of vulnerable households (see Table 2 for selection criteria for the vulnerability), typically 40–50% of households in most communities in southern Zimbabwe. The agricultural relief and recovery programs aimed at strengthening the capacity of these vulnerable households to produce their own food and produce some surplus for stabilization of national food supplies (Rohrbach et al. 2004).

In each of the three seasons between 300 and 1,200 farmers (more than 50% women in each season) were taught how to establish simple paired demonstration plots of approximately one acre (0.2 ha) in close collaboration with partner non-governmental organizations (NGOs) and local extension staff from the department of Agricultural Research and Extension (AREX). Half of the plot (0.1 ha) would receive approximately 10 kg of AN fertiliser and half of the plot received no fertiliser. The farmers applied the AN to any cereal grain they planted each season. They were advised to apply the AN using 1 beer bottle cap (4.5 g of AN fertiliser) for every three plants. This works out to a rate of about 17 kg N ha^{-1} (approximately 25% of recommended levels). It was recommended that this be applied when the cereal plant was at the 5-to-6-leaf-stage. All other crop management decisions (planting date and method, time of weeding, etc.) were the responsibility of the farmer. The total number of trials planned for each season along with the identity of the collaborating NGOs, and the trials that were successfully harvested in each season is summarized in Table 3. Throughout the on-farm evaluations women were encouraged to participate.

Table 2 Targeting criteria for beneficiaries under the Agricultural Relief and Recovery Programs in Zimbabwe

1. Households[a] without (or with limited) draught power and with limited small stock.
2. Female headed (dejure) households
3. Households with limited cash income, no pension, no formal employment and with little or no remittances
4. Households with high dependency ratio e.g. high numbers of children, orphans, handicapped, terminally ill and the elderly
5. Male headed households with limited assets

[a] Households were selected in public community meetings with representatives from donor NGOs, with the community leaders (village heads and chiefs endorsing the process). The recipients were deemed to be able to fully utilise the agricultural inputs they had received; source: Rohrbach et al. 2004)

Quantifying the long term sustainability of micro-dosing using simulation modeling

The simulation tool used was the Agricultural Production Systems Simulator (APSIM) model (Keating et al. 2003). The model is useful in capturing the interactions between climatic conditions, soil types and nutrient dynamics, and has been successfully used the in cereal based farming systems of southern Africa (Delve and Probert 2004; Robertson et al. 2005; Shamudzarira and Robertson 2002; Whitbread et al. 2004).

Analyses have been done for a sandy loam soil type typical of southern Zimbabwe using a 25 year weather record (1980–2005) record collected by the national Weather Bureau for Matopos Research Station that was extrapolated to 2015 by taking a random selection of weather records from the 45 year record (1960–2005). A short duration maize variety (SC403) was used to simulate maize growth and development to various crop production scenarios. The scenarios simulated are as follows:

1. Farmer practice-crop planted using overall spring ploughing in mid to late December, followed by

Table 3 Distribution of micro-dosing trials across southern Zimbabwe and collaborating NGO over the three seasons from 2003 to 2006

District	Natural region[a]	NGO	Number of paired micro-dosing plots targeted per seasons		
			2003/2004	2004/2005	2005/2006
Bikita	IV/V	CARE	80	ND	ND
Binga	IV/V	Save The Children	ND	ND	21
Buhera	III/IV				6
Chirumhanzu	III	OXFAM GB	ND	ND	15
Chivi	V	Zishavane Water Project	ND	ND	25
Gokwe	III	CARE	80	ND	ND
Hwange	IV/V	COSV	400	98	104
Inziza	IV	World Vision	ND	ND	17
Lupane	IV/v		ND	ND	22
Mangwe	IV/V	World Vision	ND	ND	9
Masvingo	III/IV	CARE	ND	13	ND
Matobo	IV/V	World Vision	400	ND	26
Mberengwa	IV/V	CARE	80	ND	ND
Nkayi	IV	COSV	ND	1	47
Zaka	III/IV	CARE	80	ND	ND
Zishavane	III/IV	OXFAM GB	80	ND	16
Total number of paired plots successfully harvested each season			915[b]	112[c]	308

ND = No demonstrations in that season

[a] Zimbabwe is divided into five agroecological regions, also known as Natural Regions I–V. Natural Region I and II receive the highest rainfall (at least 750 mm per annum) and are suitable for intensive farming. Natural Region III receives moderate rainfall (650–800 mm per annum), and Natural Regions IV and V have fairly low annual rainfall (450–650 mm per annum) and are suitable for extensive farming. Adapted from Vincent and Thomas (1960)

[b] 444 male, 471 female

[c] 49 male, 63 female

at least 2 weedings (Typical scenario for farmers with limited or no access to draught animals).

2. As for farmer practice with a micro-dose (17 kg N ha^{-1}) of fertilizer applied at the 5–6 leaf stage from 2005 onwards to show what contributions microdosing might have towards helping achieve the millennium development goal of increased food security (UN Millennium Project 2005).

For full details of the models parameterization for this soil type please refer to Carberry et al. (2004).

Data collection and analyses

Simple record books in the local vernacular (either Ndbele or Shona) were provided to each collaborating farmer that summarized the trial (Study 1–3) they were hosting and allowed them to record crop planted, date of planting, date and number of weedings, date of fertiliser application, yield information and any other observations they wished to make. We also collected data on basic household resource levels such as draught animal ownership. Field assistants were recruited in each locality to assist the farmers with record keeping, the collection of rainfall records from simple daily catch gauges located in each village for the host farms in Study 1 and 2, and at the individual farms in Study 3, harvesting of the plots and recording crop yields. Given the number of demonstrations undertaken in any one season, it was not possible to physically weigh the threshed grain yield from every plot. Where this was not possible, the yield from each sub plot was placed in 50 kg sacks, and the number to the nearest half sack was recorded. Spot checks were made throughout the districts where on-farm testing was undertaken in each season to quantify the weight of threshed grain that a 50 kg sack contained, in order to convert the number of sacks recorded into grain yield per ha on a dry weight basis. Typically, a 50 kg bag of maize cobs contained 21.6 kg of grain, a 50 kg bag of pearl millet heads contained 18.4 kg of grain, and with sorghum it was 20.7 kg of grain per 50 kg bag (Twomlow et al. 2007a).

Various national surveys have been undertaken since 2004, to assess impacts of the relief and recovery programs large scale distributions of seed and fertilisers. Full details of these surveys are reported in Rohrbach et al. (2005); Rohrbach and Mazvimavi (2005) and Woolcock and Mutiro (2007), and provide the necessary socio-economic inputs to allow a cost-benefit analyses of the micro-dosing intervention.

Statistical analyses

The cereal yield data was analyzed using the method of residual maximum likelihood (REML) included in the statistical software package GENSTAT version 9. The choice of REML was based on the fact that the model includes fixed and random factors, accounts for more than one source of variation in the data and provides estimates for treatments effects in unbalanced treatment designs. Season was included in the fixed model for Study 1 so that differences between seasons could be tested. Between seasons differences for Study 3 are not presented in this paper as locations of the trials varied from season to season, depending on the collaborating NGOs in that season (Table 3).

Gender, draught animal power ownership, household labour, number of weedings, field type (homestead plot/main field) and soils analyses (where available) were tested as fixed variables, but found to be not significant in accounting for any of the unexplained variability or significant interactions with fertiliser.

Therefore, the linear mixed model, used to analyze the seasonal effects on Studies 1–3, had the following components and terms:

Response variate: Yield
Fixed model: Constant + Fertiliser * (Season – included for studies 1 and 2)
Random model: District + Ward

Results

Rainfall patterns over the 3 years of observation varied considerably both within and between seasons, depending on location. Rainfall was found to have a statistically significant effect on cereal yield in the different districts ($P < 0.001$), but was however, found not to have any significant interaction with fertiliser application ($P = 0.697$) in each season. For the purposes of this paper it is sufficient to say that the 2003/2004 experienced below average seasonal rainfall (most districts receiving less than 550 mm), 2004/2005 experienced average seasonal rainfall (most districts receiving between 550 and 600 mm), whilst the 2005/2006 season experienced above average rainfall in all localities (Table 4).

On-farm study 1—maize nitrogen response curve

Figure 1 shows that 1.5–2 bags of ammonium nitrate (25–34 kg N ha^{-1}) are optimum for maize in dry regions, but also shows strong linear response at

Table 4 Maize yields obtained from changing seed varieties and adding a small dose of ammonium nitrate fertiliser (equivalent to 17 kg of N ha^{-1}) in semi-arid regions of Zimbabwe; measurements are the average from 9 farmers' fields, 2003/2004, 2004/2005 and 2005/2006 seasons

Season	Seasonal rainfall mm	Maize seed variety and nitrogen top dressing regime						e.s.e[a]
		Farmers retained seed		OPV ZM421		Hybrid SC403		
		Zero N	17 kg N ha^{-1}	Zero N	17 kg N ha^{-1}	Zero N	17 kg N ha^{-1}	
2003/2004	443	894	1,060	912	1,378	1,093	1,585	179.7
2004/2005	548	880	1,190	1,360	1,706	1,440	1,973	90.6
2005/2006	806	1,120	1,330	1,546	1,741	1,513	2,084	121.6

[a] e.s.e—experimental standard error

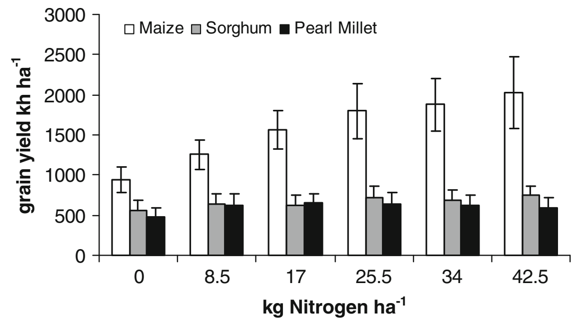

Fig. 1 Grain response of maize, sorghum and pearl millet to increasing levels of N fertiliser under farmer management. Mean of results from 9 sites since 2003 for three seasons for maize, and two seasons for sorghum and pearl millet. Error bars represent standard errors of differences between the predicted means of the nitrogen by crop yield by season

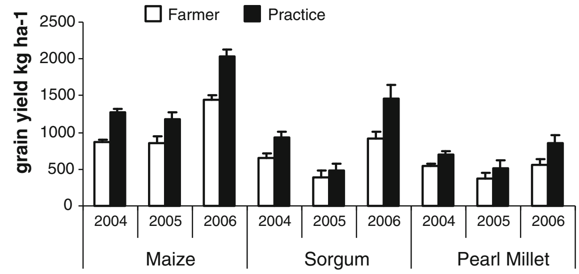

Fig. 2 Grain responses of cereals to a targeted application of 50 kg of ammonium nitrate fertiliser (17 kg N ha^{-1}) under farmer management. Mean of results across multiple sites for 2003/2004, 2004/2005 and 2005/2006 cropping seasons. (Grain increases due to each kg of N applied were between 18 and 35 kg for maize, 5 and 32 kg for sorghum, 8 and 16 kg for pearl millet). Error bars represent standard errors of differences between the predicted means of the micro-dosing by crop yields

lower application rates. It is worth noting that evidence for the linear maize response at low N rates is usually implied in published fertiliser response curves, which typically start at 30 kg N ha^{-1} or higher (e.g. Benson 1998; Mushayi et al. 1999). The slope of the maize response curve at the lower rates in Fig. 1 is about 11 kg of grain per kg of fertiliser input, and the economic returns to fertiliser investments at these sub-optimal levels have been shown to be quite profitable (Woolcock and Mutiro 2007). For example, the 25 kg of AN fertiliser commonly distributed through relief programs cost approximately US$ 2 kg^{-1} to deliver to the crop. This includes the estimated costs of labour used in applying this input. This compares with a post-harvest farm gate price for maize grain of US$ 0.4 kg^{-1}. In order to break even, farmers would have to obtain 5 kg of grain for every kg of fertiliser applied. This is easily surpassed by the grain response at low N rates in Fig. 1. In fact, at 11 kg of grain per kg of fertiliser input, the value cost ratio (VCR) exceeds 2:1, the commonly accepted threshold required to encourage risk-averse farmers to invest in fertiliser technology (Benson 1998; Morris et al. 2007). For N application rates above 25.5 kg ha^{-1}, the VCR falls below 2:1 and is approximately 1.6 for the highest rate applied in Fig. 1 (42.5 kg N ha^{-1}). However, this rate is well below the 46–76 kg N ha^{-1} promoted in current extension recommendations for these regions (Table 1).

The 3 years of on-farm experimentation in drier regions of Zimbabwe show consistent grain yield response and profitability of maize to low rates of nitrogen fertiliser, either alone (Fig. 1) or in combination with manure (Ncube et al. 2007). What is of concern, and requires more detailed study, are the poor responses of sorghum and pearl millet to nitrogen fertiliser shown in Fig. 1. It is speculated that some of these poor responses are due to poor root development and capability of sorghum and millet to extract P under low P conditions as observed in these soils (Vadez personal communication), despite the fact that the trials were located on homestead plots that are traditionally considered to be more fertile (Ncube et al. 2008). However, this lack of response by sorghum and pearl millet was not so evident in the broad-scale testing in farmers fields (Figs. 2 and 3).

On-farm study 2—maize variety by micro-dosing

Table 4 summarizes the three seasons' responses of different varieties of maize to micro-dosing. Improved OPV seed alone appears to give a significant increase in maize grain yield over the farmers retained seed in average to above average rainfall seasons, but not in below average seasons. In addition, the data suggests that the hybrid response to N was consistently about 500 kg, whereas that for farmer seed or OPV was less and more variable. The retained seed response to N was between 100 and 300 kg, whereas the OPV seed response was between 200 and 400 kg, depending on the rainfall received.

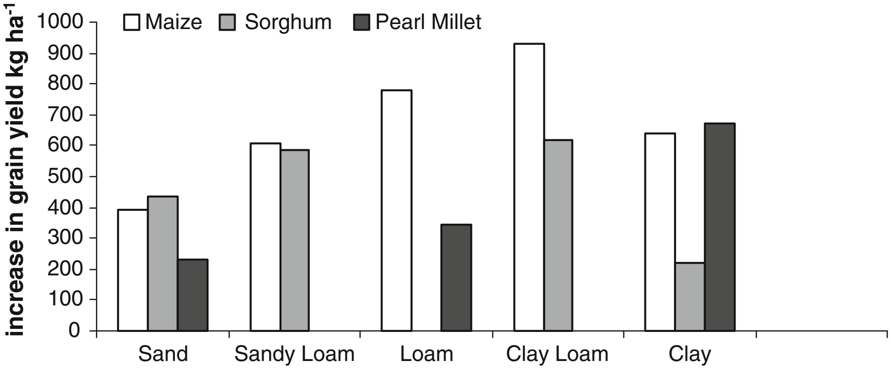

Fig. 3 Observed increases in cereal grain yield (kg ha^{-1}) for 323 households from 13 districts across southern Zimbabwe in response to a targeted application of 50 kg of ammonium nitrate fertiliser (17 kg N ha^{-1}) under farmer management for five different soil types in 2005/2006 season (Grain increases due to each kg of N applied were between 15 and 45 kg

On-farm study 3—wide scale promotion and testing of micro-dosing

Three years of wide scale testing in numerous districts across southern Zimbabwe with farmers has confirmed that small amounts of nitrogen fertiliser (17 kg ha^{-1} compared to recommended rates of 55 kg ha^{-1}) applied as targeted topdressing can give significant increases ($P = 0.001$) in cereal grain yield (Fig. 2), irrespective of farmers ability to manage the crop (Table 5) or soil type (Fig. 3). Despite the high variability shown in Table 5 for the timing of fertiliser application and weeding dates, which was observed to occur each season despite the flyers and training that were given, the response to small doses of N proved remarkably robust (Fig. 4). Only 7 of the 89 farmers (7.8%) in Fig. 4 either failed to obtain a yield gain with N micro-dosing or witnessed a decline in yield. A households' failure to achieve positive yield increases was, based on the farmers own record books and site visits attributed to either late planting, late or zero application of the fertiliser and poor weed management. At the same time, the few very high yield gains in Fig. 4 (those exceeding 850 kg or 50 kg grain/kg of N applied) are probably the result of unaccounted additional nutrient inputs (e.g., manure applications or extra fertiliser).

The observed efficacy of the grain response to low doses of N in this study is noteworthy and is an important result from the perspective of improving the food security of smallholder farmers in these dry regions. Even from the perspective of a breakeven yield (85 kg grain), the consistent gains exhibited in Fig. 4 are impressive-only 22 of the 89 farmers (25%) failed to achieve the necessary yield gain. In other words, 75% of farmers achieved a yield gain that would translate into a profit margin (over the input cost) when N was applied at a low rate.

Table 5 Timing of fertiliser application and weedings relative to planting dates for seven districts in southern Zimbabwe in 2003/2004

District	Days after planting		
	Fertilization (minimum–maximum)	First weeding (minimum–maximum)	Second weeding (minimum–maximum)
Bikita	58 (18–101)	27 (4–68)	57 (28–103)
Gokwe	42 (6–72)	22 (6–49)	38 (18–87)
Hwange	42 (0–74)	27 (3–105)	39 (21–97)
Matobo	52 (3–120)	33 (4–96)	50 (16–136)
Mberengwa	61 (25–111)	25 (1–80)	50 (16–96)
Zaka	54 (22–84)	21 (2–54)	25 (24–86)
Zishavane	39 (27–52)	25 (19–36)	75 (38–105)

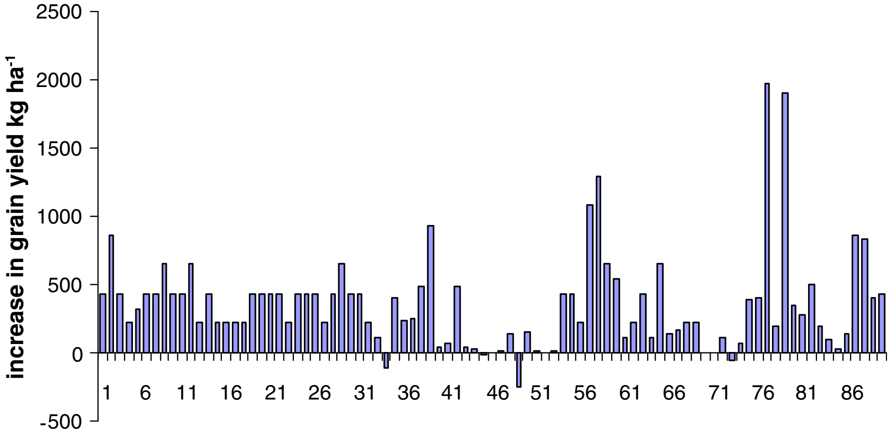

Fig. 4 Observed increases in maize grain yield (kg ha^{-1}) for 89 households from Hwange, Lupane, Masvingo and Nkayi Districts in response to a targeted application of 50 kg of ammonium nitrate fertiliser (17 kg N ha^{-1}) under farmer management in 2004/2005

Discussion

The drought relief program that was the platform for the research studies reported here facilitated widespread distribution of seed and fertiliser across southern regions of Zimbabwe. The innovation in the relief program was that it included fertiliser distribution into dry regions and that it promoted small doses of N fertiliser. The decision to do this was based on ICRISAT's results from a small number of on-farm trials in conjunction with output from crop simulation analysis. The question on whether the response to small doses of N could be replicated for much larger numbers of farmers with varied soil and management conditions and rainfall regimes remained. We pursued this question through trials that establish fertiliser response curves in dry regions (in the process helping to fill a research gap as such data are largely non-existent for these regions), comparing technology investments in N and improved seed, and broad-scale testing of small N doses under farmer management conditions.

Results from three seasons of extensive testing clearly show that response to small doses of nitrogen is measurable in on-farm trials for a wide range of soils, farmer management and seasonal rainfall conditions. This reflects the inherent low fertility (Mapfumo and Giller 2001; Ncube et al. 2007) of these cropping systems and the fact that nitrogen is more of a constraint to production than lack of soil moisture in most seasons. The grain yield increases achieved in the broad-scale studies are also consistent with the level of yield responses first suggested by the crop modeling analysis of the smallholder cereal production systems in southern Zimbabwe (Dimes et al. 2003; Carberry et al. 2004).

It is particularly remarkable that micro-dosing benefits accrued to almost all the farmers applying this technology, irrespective of season or resource status, as is shown in Fig. 4. Usually there are leaders and laggards in technology adoption. Often technologies are initially applied well by only a subset of better-than-average farmers. It is well known that fertiliser response depends on the application of complementary practices such as timely planting, timely weeding, timely fertiliser application, the starting quality of soils, and incidence of diseases and pests. Yet such a wide range of farmers have obtained significant yield gains from micro-dosing, even in drought years. The strong and consistent responses in Fig. 4 are further evidence of the inherently low N supply capacity of soils across the dry regions in Zimbabwe and that widespread yield responses to N can be generally expected (Mushayi et al. 1999; Mapfumo and Giller 2001; Zingore et al. 2007; Ncube et al. 2008).

The 2003/2004 and 2004/2005 seasons when micro-dosing was widely promoted were relatively poor rainfall years (Table 4), compared to the 2005/2006 season. Even so, the vast majority of fertiliser recipients achieved strong positive returns to this investment. With the aid of simulation modeling, Fig. 5 highlights the gains likely to be achieved if farmers continue to pursue micro-dosing in the

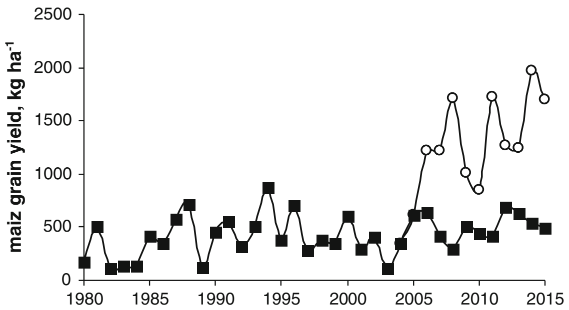

Fig. 5 Maize grain yields obtainable in drought prone semi-arid parts of Zimbabwe under current farmer practices without ammonium nitrate fertilizer (■) and with small doses of ammonium nitrate fertiliser (17 kg N ha^{-1}) post 2005 (○), based on crop simulation modeling using APSIM and confirmed by farmer managed demonstration trials

future. The initial data series (■) summarizes the levels of yields to be expected when farmers apply no fertiliser—the common current practice in semi-arid areas of the country. The second series (○) highlights the gains achievable with sustained use of as little as 17 kg N ha^{-1}, equivalent to one 50 kg bag of ammonium nitrate per hectare.

If the use of small quantities of AN can be continued after the relief programs stop handing out free fertiliser, these farmers can achieve a sustained set of higher grain yields and a sustained improvement in food security, thus meeting the first of the UN millennium goals (UN Millennium Project 2005). Even if severe drought occurs farmers will be better off than in previous drought years. On the other hand, if rains are more favorable, farmers will have appreciably higher yields as the N inputs contribute to higher water productivity in either situation.

The challenge remains, however, to move farmers from a dependence on free handouts toward a willingness to purchase fertiliser each year in a local retail shop. Currently, farmers are unaccustomed to purchasing fertiliser. Local retailers remain with the view that most of these farmers will not make this investment because it is too risky. Further, the willingness of fertiliser companies and retailers to pursue this market has been undermined by the continuing distribution of free seed and fertiliser directly to farm households. At a minimum, this sort of distribution should be through vouchers redeemable at local retail shops.

Some have questioned the logic of micro-dosing, claiming this is such a small quantity of fertiliser and that it is not sustainable. Some argue it is wrong to encourage farmers to adopt second best solutions. Some state that other nutrients such as phosphorous will quickly become limiting if only ammonium nitrate is promoted or low levels of organic matter will eventually restrict yield gains.

Yet the majority of farmers being assisted by the various donor programs in Zimbabwe did not use any fertiliser prior to the initiation of this effort. Extension recommendations calling for larger doses were consistently ignored as they were viewed to be impractical and too risky. The micro-dosing promoted by ICRISAT and many NGOs offers vulnerable households the first opportunity to lift their average yields to a new threshold. To apply only one 50 kg bag of AN offers a substantial improvement on food security that otherwise would not have been available. Extensive crop systems modeling data indicates this gain can be sustained in southern Zimbabwe for many years (Fig. 5). Importantly, however, the success of micro-dosing demonstrations has encouraged many farmers to begin to experiment with alternative improvements in crop management—combining organic and inorganic fertiliser, applying higher rates, and attempting conservation farming (Mazvimavi and Twomlow 2007; Twomlow et al. 2007b). In effect, this simple technology is renewing farmers' interest in exploring new options for technological change.

The 25 kg of AN fertiliser commonly distributed through the relief programs cost approximately US$ 2 kg^{-1} to deliver to the crop. This includes the estimated costs of labour used in applying this input. This compares with a post-harvest farm gate price for maize grain of US$ 0.4 kg^{-1}. In order to obtain a profit, farmers would have to obtain only 5 kg of grain for every kg of fertiliser applied. In fact, farmers more commonly obtained 15–45 kg of grain per kg of fertiliser input (Figs. 3 and 5).

Conclusions

This research set out to establish the efficacy of cereal crop responses to low doses of N fertiliser across dry regions of southern Zimbabwe. The results have provided strong evidence that N micro-dosing has the potential for broad-scale impact on food security for a large section of the rural poor. For example, Rohrbach et al. (2005) estimate DFID's support for the distribution of 25 kg of ammonium nitrate fertiliser to each of 160,000 farm households contributed 40,000 additional tons of maize production, valued by the World Food Program at 5–7 million USD. A further question now arises for national research and extension agencies with a mandate for dry land cropping regions—is it rational and acceptable to recommend levels of fertiliser use lower than current recommendations? Our results from three years of observations in dry land areas say yes.

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