MAIZE-NITROGEN RESPONSE IN MALAWI'S SMALLHOLDER PRODUCTION SYSTEMS

Sieg Snapp, T.S. Jayne, Wezi Mhango, Todd Benson and Jacob Ricker-Gilbert[1]

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[1] Snapp is Professor of Soils and Cropping System Ecology, Michigan State University; Jayne is Professor, Agricultural, Food and Resource Economics, Michigan State University; Mhango is Senior Lecturer, Department of Crop and Soil Sciences, Lilongwe University of Agriculture and Natural Resources; Ricker-Gilbert is Assistant Professor, Department of Agricultural Economics, Purdue University; and Benson is Senior Research Fellow, International Food Policy Research Institute.

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1. Introduction

Sustainable intensification is the foundation for smallholder agriculture to adapt to a changing world, to address poverty reduction, and food security in sub-Saharan Africa. Substantial gains have been made in crop genetics, but these do not translate into production without complementary investments in soil, water and pest management. Nitrogen is the key driver for cereal crop performance across most environments, both in terms of yield and stability of yield (Vanlauwe et al., 2013). Understanding nitrogen use efficiency (NUE) thus becomes an urgent project that underlies success in climate change adaptation and agricultural development. Indeed, nitrogen has been identified as one of the grand challenges of the 21st Century given its pivotal role in food production, and nowhere is this more important than in sub-Saharan Africa where fertilizer manufacture infrastructure is non-existent and landlocked countries face fertilizer costs five to ten-fold higher than in the Global North.

Maize is the staple food crop of smallholder farmers across Southern and East Africa, with the potential to produce large amounts of calories if supplied sufficient nitrogen. Other nutrients are required in modest amounts and only occasionally limit production. Raising the efficiency of nitrogen use by maize is therefore crucial for the sustainability and economic feasibility of land intensification in the region.

It is well known that the efficiency of fertilizer use on maize in sub-Saharan Africa is considerably higher on experiment station plots and researcher-managed farm trials than on plots managed exclusively by smallholders. Nitrogen use efficiency on maize plots following researcher management protocols can be in the range of 14 to 50 kg maize per kg nitrogen (N) and even higher in some cases (Whitbread et al., 2012; Vanlauwe et al., 2011).[2]

By contrast, estimates of NUE on maize plots derived from nationally representative and site-specific farm survey data in Malawi are typically in the range of 7 to 14 kg (Ricker-Gilbert et al., 2011; Chibwana et al. 2012; Snapp et al., 2013; Wiyo and

[2] The vast majority of studies reviewed by Whitbread *et al.,* (2012) were from researcher-managed on-station or on-farm experiments using hybrid maize varieties.

Feyen, 1999).[3] It is well accepted that NUE on researcher-managed plots should be higher than those achieved by smallholder farmers on their own plots, given the myriad constraints on limited-resource farms. However, the magnitude of the difference between estimated NUEs on researcher-managed and farmer-managed plots as reported in survey data have led to questions on the reliability of survey data as a means for generating such estimates. It is also possible that the wide gap in NUEs observed between researcher-managed plots with non-random farmer participation and nationally-representative farmer-managed plots are real and signal the magnitude of constraints faced in smallholder production systems, and that a holistic approach of education and integrated management is needed to support policies aimed at enhancing access to fertilizer. A number of reviews of maize and fertilizer technology in the region have recommended investment in improving NUE, and we take up that challenge here (Heisey and Smale, 1995; Snapp, et al., 1998; Vanlauwe et al., 2013).

This paper has two objectives. Our first objective is to review the research evidence on the factors known to be affecting the efficiency with which Malawian farmers use nitrogen fertilizer on maize. It is our position that such factors, along with non-random aspects of most trials, might explain the large gaps observed between researcher-managed plots and farmer-managed fields.

Our second objective is to provide practical guidance to Malawian policy makers and the national extension system for helping farmers to raise the efficiency with which they use fertilizer. In so doing, we emphasize that crop diversification and soil management practices that raise soil fertility, while often viewed as "alternative" forms of agriculture, may be more accurately characterized as major components of an input-intensive and efficient production system that is both profitable and sustainable.

2. Research evidence on response rates from farm surveys in Malawi

Table 1 reports mean NUEs for <u>farmer-managed</u> maize plots based on survey data in Malawi. Some of the studies report a range of NUEs, since even mean NUEs for a

[3] Peer-reviewed published work from the following farm surveys consistently produce estimates of N-use efficiency in the 7 to 14 kg range: The nationally representative Integrated Household Survey II (2003/04) collected by the National Statistical Office, the nationally representative Integrated Household Survey III (2009/10) collected by the NSO, each of the three rounds of the Agricultural Inputs Support Surveys (2007, 2009, 2011), collected by the NSO in 2007 and by Wadonda Consult in 2009 and 2011.

particular farming population can be meaningfully disaggregated according to the type of seed used, weather, soil types, and whether the plot was intercropped or monocropped. Most of the crop seasons covered by these studies were either normal or favorable growing seasons in most of Malawi, although localized problems were reported by a sizeable proportion of farmers in every year.

Several studies based on farmer interviews and computations of value-cost ratios report that a large proportion of Malawian farmers found fertilizer to be of limited profitability or negative profitability when costed at its full commercial price (Wiyo and Feyen, 1999; SOAS (2008); Ricker-Gilbert et al., 2011; Kamanga et al., 2014).[4] Whether fertilizer is profitable for farmers to use at full commercial prices depends greatly on the efficiency with which they use fertilizer. Farmers vary in their management skills, and studies estimating household-specific NUE find that even within fairly concentrated geographic areas with similar elevation and growing conditions in the same season, NUE can vary enormously, owing to differences in management ability, soil conditions, labor constraints, and exogenous shocks such as drought, pests and disease (see Figure 1 for an example from Zambia). Soil quality heterogeneity has been shown to be a factor in NUE on smallholder production fields, with much lower NUE in 'outfields' which are extensively management and sometimes associated with low soil organic matter (Vanlauwe et al. ,2011).

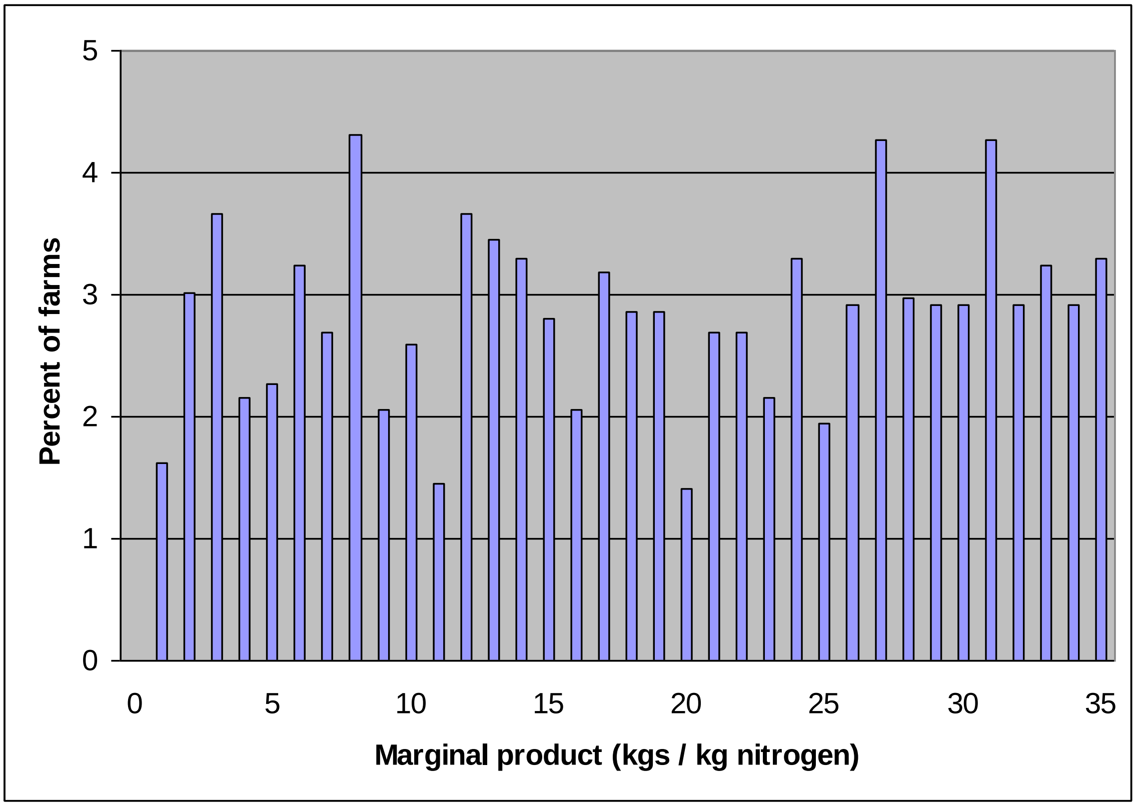
For these reasons, the mean NUE's reported in Table 1 are expected to mask considerable variation across farmers and within fields. More research is necessary in Malawi to understand the extent of this variation. If it is found to be rather large in Malawi, as found to be the case in neighboring countries, then efforts to raise the fertilizer use efficiency of the bottom half of farmers to that of the mean could raise national maize production by as much as 8 to 11 percent without any additional use of fertilizer (Xu et al., 2009).

[4] For example, SOAS (2008) reports that "this analysis suggests that profitability of fertiliser use on maize is a constraint to its use on maize grown for sale at or near harvest. Where maize is grown for own consumption then it may be valued more highly, using peak post-harvest prices and with VCRs greater than 2" (p. 13).

Table 1. Microeconomic studies reporting nitrogen use efficiency on farmer-managed maize fields in Malawi

Study	Year(s) of survey	Data sets (yield measurement)	Geographic coverage	Estimated N-use efficiency
Wiyo and Feyen, 1999	1984-1995	Annual Sample Survey of Agriculture (ASSA) maize yield database, Malawi Ministry of Agriculture (yield sub-plot measurement)	Nationally representative	14-18 for hybrids; 9.5 – 16.5 for local varieties; 14.1 overall.
Chibwana et al	2002, 2006, 2009	Farmer-managed field data of 375 households across three seasons	Kasungu and Machinga Districts in central and southern Malawi	9.6 to 12.0
Dorward and Chirwa, 2013	2009, 2010	Nationally representative IHS-II and IHS-III, and AISS-I and -II surveys (farmer recall, with exception of 2009 which also contained yield sub-plot measurement)	Nationally representative for IHS-II and IHS-III; nationwide for AISS-I and AISS-II	Negative to 9.0 [b]
Ricker-Gilbert and Jayne, 2011, 2012	Same as with Dorward and Chirwa			6.6 to 11.5
Snapp et al. 2013	Same as with Dorward and Chirwa			5.33 for monocropped maize; 8.84 for intercropped maize
Holden and Lunduka, 2010	2006, 2007, 2009	Random sample of 450 farmers collected in Central and Southern Malawi		9.1

[b] Dorward also estimated NUEs using the nationally representative data from IHS2 and IHS3 as well as from the various AISS surveys using both yield sub-plot and farmer recall data, and reported low NUEs comparable to those obtained by Ricker-Gilbert and Jayne (2011), and Snapp et al (2013) but concluded that the data from these various surveys were problematic and unacceptably low (Dorward, 2010).



Note: Agroecological zone IIa with acrosol soil type is generally considered among the most suitable for intensive maize production in Zambia. Mean NUE for the sample of 690 plots among farmers in this specific area was 16.5, whereas the mean NUE for the entire nationally-representative sample was estimated at 9.7 (Burke, 2012). Source: Xu et al (2009).

Figure 1. Variation in efficiency of fertilizer use on maize fields among smallholder farmers in Agroecological Zone IIa with predominantly acrosols soils, Zambia, 2007/08.

3. Factors affecting nitrogen use efficiency on maize plots in Malawi

Maize response to nitrogen fertilizer has been the focus of agronomic research for over fifty years. We highlight five factors that, according to published research evidence, significantly affect the efficiency with which many Malawian farmers use inorganic fertilizer. These are inadequate weeding and other pests, limited use of crop rotation and intercrops, late fertilizer application, the levels of active organic carbon in the soil, and other chemical properties of the soil. In addition to these five factors, we also highlight several factors about the design and implementation of researcher managed trials that create problems of external validity in extrapolating their NUE estimates to a nationally representative smallholder population.

1. *<u>Inadequate weeding and other pests:</u>* Weeding improves the uptake and utilization of N and P by the crop. Farmers that weed their maize plots only once can experience major weed build-up which may result in a 26–34% yield reduction (FAO, 2000). While Malawian smallholders understand the importance of multiple weedings in raising their maize yields and efficiency of inorganic fertilizer applications, there are usually good reasons why they often cannot devote as much labor to weeding as they would like. For example, more than half of the farmers interviewed by Kamanga et al. (2014) reported being unable to devote more than one weeding to their maize plots due to obligations such as harvesting their tobacco, *ganyu* labor (casual work done for other farmers for food or cash), funerals and illness.[5] Kamanga *et al* (2014) report that when fertilizer is obtained at highly subsidized prices through the Farm Inputs Support Programme (FISP), the financial returns to labor were generally high when farmers performed two weedings compared to one. However, when valuing fertilizer at market prices, they found that neither one nor two weedings generated returns to labor that exceeded the prevailing *ganyu* labor wage rate. National survey data from the 1980s indicated a strong location effect on the intensity of weeding undertaken by Malawi farmers, with the highest levels invested in the South where the rural population density is highest (Heisey and Smale, 1995). Further, the survey data were consistent with farmer knowledge of weed-fertilizer interactions, as early weeding was preferentially applied to fertilized maize: 70-97% compared to 30 to 60% early weeding applied to unfertilized local maize.

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[5] Weeding intensity also affects NUE. While many farmers may report having weeded two or three times, they may not be able to devote enough time to clear the field of weeds as sufficiently as they would want.

Table 2 suggests that during 2006/07 and 2007/09 65-70% of plots were weeded 2 times. Zero or one weedings were reported on 25-27% of plots, while only 3-10% of plots were weeded 3 or more time. These data indicate that the majority of households in Malawi find it optimal to weed their maize field 2 times, given the constraints they face. However, there is still a substantial portion of the plots that receive limited attention and are weeded fewer than 2 times.

Weeding intensity and timing is likely to differ substantially on researcher-influenced farm trials relative to farmer fields, due to the small size of trial plots. The preferential location of trial plots on farms that are relatively well resourced could also influence the investment of weeding in these plots. On this basis, some differences in NUE among these two groups should be expected.

Pests such as the parasitic weed striga[6] and insect infestation are other challenges faced by smallholders in Malawi. These tend to be location specific (e.g., striga build ups in maize grown in central Malawi upland soils), or weather related and episodic in severity. We note from the national survey data that 13.7 percent in 2006/07 and 17.3 percent in 2008/9 of smallholders reported yield loss due to crop disease and pests (Table 2).

2. *<u>Crop rotation and intercropping:</u>* A factor that consistently influences maize response to nitrogen is rotation with a legume crop. Legume residues are N-enriched (3 to 5% N compared to cereal residues of 1 to 2% N), due to biological N fixation capacity, although after the N-enriched grain is removed at harvest from food legumes a net benefit is not always achieved in terms of building the soil N supply (Giller and Cadisch, 1995). Longer-duration legumes that produce copious amounts of vegetative matter over 6 to 10 months are much more likely to fix appreciable amounts of N, compared to 3 to 4 month food legumes such as common bean and soybean (Snapp et al., 1998). There is considerable debate in the literature regarding the amount of N that can be fixed by legumes grown under smallholder conditions, where plant population densities tend to be low, and where soil fertility is generally depleted, but bushy and viney long-duration food legumes have been shown to fix 30 to 100 kg of N, and to build soil N pools (Cadisch et al., 1998; Snapp et al., 2010). Table 2 indicates that in 2002/03 and 2003/04 50.1% of maize plots had some legumes grown on them. This percentage consistently declined across

[6] Striga is not just a weed that competes with the maize plant for soil nutrients; it is produces toxic chemicals that stunt maize root development and is parasitic in that it attaches to the maize roots to deplete it of nutrients, hence its impact on maize yield and NUE can be particularly severe.

following surveys, and in 2008/09 and 2009/10 maize and legumes were intercropped on 37.9% of plots.

There are also unique contributions that legumes make via what is often termed the ‘rotation effect’. This is not well defined but generally associated with building of active soil organic matter and associated microbial diversity (Turco et al., 1990). The yield response of maize to nitrogen when grown after soybean is considered to be about 15 to 20% higher, compared to response of continuous maize. This was recently shown to consistently increase the calculated net returns for maize producers in a Tennessee study in the USA Midwest (Boyer et al., 2013). In Malawi, maize response to N fertilizer has been shown to be 35-125% higher than continuous maize when grown in a rotation after a ‘best bet’ legume such as shrubby pigeonpea, which has substantially more potential to fix nitrogen and improve soil than the shorter lived annual food legumes (Snapp et al., 2010). This large-scale study also provided support for improved stability in maize yield response, as well as gains in NUE.

As population pressures cause a gradual shrinking of farm sizes over time, smallholder farmers respond by more continuously cropping their fields every year. As Table 2 presents, the IHS3 data suggests that only 1.1% of plots were left entirely fallow in 2008/09 and 2009/10, and that 95.7% of plots had never been fallowed. More than half of Malawi’s smallholder farms are smaller than 0.8 hectares. Most production systems in densely populated Africa are so heavily prioritized to meeting the next year’s staple food needs that crop rotations and the use of green manures or agroforestry systems are difficult to adopt. One surprising change in land use is the marked decrease from over the last four decades of maize-legume intercropping, which has declined from almost 100% in 1968/69 to 25 to 39% in 1980/81 (Heisey and Smale, 1995; Table5.11) and see continuing reductions in intercropped land in recent country wide surveys (Table 2). Government policies have promoted sole cropped production of hybrid maize, which may have contributed to the decline of intercropping as adoption of hybrid maize has increased markedly in recent years, although other factors have been hypothesized to contribute to this decline as well (Heisey and Smale, 1995)

Less surprising is the preferential practice of crop rotations by better-off farmers with larger landholdings (Snapp et al., 2002). On very small farms, households cannot afford to sacrifice a whole year by crops for which there is limited consumption value because they need to produce as much food as possible for the coming year. Many households therefore continue to grow maize on the same fields year after year, continuing to obtain very low efficiency of inorganic fertilizer application. Systematic differences in crop rotation may therefore be another source of variation in NUEs between researcher-influenced farm trials vs. nationally-representative farm survey data, and research could be directed at market or policies that enhance farmer utilization of rotations.

Table 2. Selected indicators of farming conditions in Malawi, various surveys between 2002 and 2010

	IHS2 Panel Survey Wave 1 2002/03&2003/04	AISS1 Panel Survey Wave 2 2006/07	AISS2 Panel Survey Wave 3 2008/09	IHS3 2008/09 & 2009/10
% of plots left entirely fallow	--	--	--	1.1
% of plots NEVER left fallow in the past	--	--	--	95.7
Average area left uncultivated in ha (unconditional)	0.192	0.154	0.237	--
By Region:				
North	0.411	0.181	0.520	
Center	0.195	0.217	0.296	
South	0.056	0.099	0.062	
% of maize plots intercropped w/legume	50.1	46.1	45.4	37.9
% of maize plots using organic manure	15.2	--	--	12.7
% of maize plots receiving zero or one weeding[1]	--	25.5	27.2	--
% of maize plots receiving 2 weedings[1]	--	65.3	69.7	--
% of maize plots receiving 3 or more weedings[1]	--	10.2	3.2	--
% of maize plots where area harvested was less than area planted[1] (generally due to adverse weather)				54
% of HH experiencing lower yields due to poor soil fertility in past 2-3 years	--	32.2	39.6	--
% of HH experiencing lower yields due to bad weather or rainfall in past 2-3 years	--	27.3	29.9	--
% of HH experiencing lower yields due to crop disease or pests in past 2-3 years	--	13.7	17.3	--
Median yield (kg/ha)	576	576	691	1,289[2]
Median yield if hybrid or composite (kg/ha)	691	691	864	1,373[2]
Median yield if local variety (kg/ha)	518	513	657	1,210[2]

Sources: Authors' calculations based on IHS2, AISS1, AISS2, and IHS3 datasets.
Notes: Estimates use original data and are unweighted; [1]includes intercropped maize plots; [2] IHS3 plots are measured using GPS, farmer recall in other surveys; ' -- ' means data not available in particular survey wave.

3. *Late delivery and application of fertilizer:* According to Jones and Jacobsen, (2003) timing of fertilizer application is essential for optimizing both yield and quality. They further indicate that proper timing of fertilizer application reduces nutrient losses, increases the efficiency of nutrient usage, and prevents damage to the environment. It is essential that fertilizer be available in a timely manner so that farmers can apply it when they need it. Though the surveys from Malawi do not clarify exactly when households acquire their FISP fertilizer, according to the 2006/07 and 2008/09 AISS surveys, the majority of households apply their first dose of fertilizer 3 or more weeks after planting. This is especial true in the 2008/09 season, when 57.4% of household applied their first dose of fertilizer to maize 3 or more weeks after planting. Late application of fertilizer could be due to various factors, such as late delivery of fertilizer, lack of available labor to apply fertilizer, and lack of knowledge about appropriate use of fertilizer. By contrast, most farmers participating in trials would need to follow timely fertilizer application protocols as a condition of participation. Therefore, late application of fertilizer may be yet another source of observed differences in NUEs reported between farm trials and survey data.

Table 3. Weeks After Planting of First Fertilizer Application in Malawi

	2006/07 season			2008/09 season		
Weeks late	N	%	Cum %	n	%	Cum %
Less than 1	126	4.3	4.3	3	0.1	0.1
1	504	17.2	21.6	192	6.7	6.8
2	735	25.1	46.7	592	20.7	27.5
3	683	23.4	70.1	857	29.9	57.4
4	561	19.2	89.3	816	28.5	85.9
5	135	4.6	93.4	233	8.1	94.0
> 5 weeks late	179	6.2	100.0	171	6.0	100.0
Total	2,923	100		2,864	100	

Source: AISS surveys, 2006/07 and 2008/09.

4. *Low soil organic matter and soil quality:* A cornerstone to sustainable intensification in Africa is soil organic carbon (SOC). Crops require a healthy, functioning soil environment in order to grow rapidly and respond to inputs. Soil quality is a key regulator of crop yields in a variable rainfall environment, as both excess and insufficient precipitation can reduce crop yield in the absence of good infiltration or water holding capacity (Shaxson and Barber, 2003). Thus,

maintaining soil quality is a major concern now and in the future, given climate change and the highly variable rainfall patterns that farmers face in Malawi. Over a quarter of farmers surveyed in the 2006/07 and 2008/09 Agricultural Inputs Support Surveys (AISS) reported yield loss due to adverse weather conditions (Table 2).

Soil organic matter is particularly important in smallholder tropical agriculture as amendments such as lime, irrigation and micronutrient fertilization are rare. Paradoxically, it is difficult to enhance total SOC on tropical smallholder farms. However, not all SOC is the same: biophysical fractionation of C pools has shown that it is the *active* fraction of SOC that regulates nutrient release, aggregation and soil function as a media for plant growth and response to fertilizer (Beedy et al., 2010). Fortunately, biologically active soil C can be improved through additions of mixed quality residues, even at the modest levels of biomass (3 to 5 tons, including roots) that are practical to produce in the sub-humid tropics through growing leafy types of multipurpose legumes or manure transfers (Barrios et al., 1996; Snapp et al., 1996). If the active soil C pool is enhanced, there is evidence that soil inorganic N availability will increase from almost nil to 35 kg of N per ha, with associated maize yield response due to good establishment and early growth (Chikowo et al., 2004). This requires broader testing, and is the subject of ongoing analysis.[7]

To build total soil C and the active pool requires a combination of residues from cereals, legumes, or compost – although the latter is difficult to source in Malawi (Snapp et al., 1998). As presented in table 2, the IHS2 data indicates that only 15.2% of all maize plots had organic fertilizer applied to them in 2002/03 and 2003/04, which declined to 12.7% in 2008/09 and 2009/10. This may be due to limited livestock production in Malawi, and labor constraints that make it difficult to engage in composting. There are varying perceptions of the extent to which low SOC poses limitations on NUE in Malawi; more evidence is needed on this topic.

5. *Soil chemical properties – acidity and low phosphorus (P).* Although contentious, there is evidence that soil acidity is a constraint to crop production in some locations in Malawi, particularly in high rainfall and high altitude areas (Kabambe et al., 2012). There is almost no trial evidence that maize responds to application of lime which is indicative of soil pH not being an important soil

[7] Interdisciplinary analysis among researchers from the Lilongwe University of Agriculture and Natural Resources, Africa Rising and the Guiding Investments in Sustainable Agricultural Intensification (GISAIA) are currently examining the efficacy of various strategies for augmenting soil fertility and their effects on the response rates and profitability of inorganic fertilizer in maize production.

constraint to this crop. There is however evidence that extension campaigns that have promoted compost use have been successful in groundnut production intensified area such as Mchinji -- potentially due to soil acidity and calcium deficiency amelioration properties of composted manure which have made returns to compost investments profitable in this enterprise.

Important nutrients to consider in crop production across Malawi are generally considered to be phosphorus, and in some locations sulfur and zinc (Heisey and Smale, 1995; Kumwenda, et al., 1997). Soil phosphorus status is tremendously variable in Malawi, with inorganic phosphorus varying both within and between fields, reflecting the role of management history in regulating phosphorus availability (Snapp, 1998). The promotion of high analysis N-containing fertilizer (Urea at 44% N) versus a fertilizer such as 23:21 that contains P and N in major proportions and is mixed with 4% S in some formulations has been an on-going debate in Malawi. There is evidence since the 1960s that for some crops (particularly legumes) the highland regions of Malawi have soil types that supply insufficient P (Kumenda et al., 1997). Thus, the generally recommended combination to apply a basal fertilizer (such as 23:21 +4S) followed by a side-dress of high analysis N fertilizer may be appropriate for most soil types in Malawi. However, in the short-term, if maize is the focus without considering other crops grown on the farm, then urea may be the only profitable fertilizer in the absence of fertilizer subsidies (MPTF, 1999).

6. *Fertilizer use is endogenous*: Few farmers will pay the full commercial price of fertilizer unless they feel that they can use it profitably. Therefore, households paying for commercial fertilizer on average tend to be relatively productive users of fertilizer (and hence have higher NUE on maize plots) than households not paying for it. Access to working capital may confound this relationship to some extent, but in general we find a positive correlation in smallholder survey data between access to credit, asset wealth, maize production and NUE (Ricker-Gilbert and Jayne, 2012). If fertilizer is distributed to a large proportion of farmers at a highly subsidized price, then survey data would tend to include some proportion of fertilizer users who would not have demanded it at commercial prices for fear of not breaking even, but whom would be glad to acquire it at 10% of the full price. The probability of breaking even are obviously considerably higher when paying 10% of the full price even among relatively inefficient users of fertilizer, hence the subsidy program may put downward pressure on NUEs observed in survey data where a large proportion of maize plots are fertilized with subsidized fertilizer. Recall the data in Figure 1 showing the wide variation in NUE among farmers even in the same area.

7. *The "observer effect," , and other sources of trial bias*

Also (erroneously) referred to as the Heisenberg Principle, this principle holds that measurements of a system cannot be made without affecting the system itself. Applied to the case of farm trials in Malawi, farmers participating in trials may have subtle incentives to apply more intensive labor and management oversight to their trial plot than to their ordinary plots, as a matter of pride, social standing in the community, etc. For these reasons, NUE as reported in farm trials may be expected to be somewhat higher than in non-trials, other conditions held constant.

Another factor that leads to over-estimates of crop yields and treatment response is that of plot size. In researcher-influenced trials, whether conducted on-farm or on research-stations, resource constraints and interest in comparing a large number of treatments makes it necessary to limit the size of plots, compared to real world fields. This often leads to small plot sizes of 10-100 m^2 whereas farmer fields are often orders of magnitude larger in Malawi. This introduces a biological bias, as 'edge effects' can dominate in small plots which have a large boundary area where plants experience minimal competition – that is, plants can access light and other resources to a much greater degree than in the middle of a plot. An example of the magnitude of plot size effects was recently illustrated in a literature review of biomass potential estimated from field trials of biofuel species: annual aboveground biomass in switchgrass was 4 - 35 T/ ha but decreased to 2-3 T/ha in more realistic field-scale tests (Searle and Malins, 2014). This plot size effect on biomass measurements held across the five species reviewed, and was primarily associated with edge effects according to the authors.

Non-random sampling of farmers and plots is expected to influence differences observed between researcher-influenced farm trial studies are based on farmers willing to take part in the study. These farmers also tend to be connected to extension staff, and this can result in on-farm trials over-sampling of 'master farmers' with superior management skill, despite efforts to overcome such bias. Studies with large numbers of randomly selected farmers (as with nationally representative surveys) provide an opportunity to sample a wider range of variation on-farm (especially those recording yield sub-plot measurements), but many researcher-influenced trials involve few and non-randomly selected observations.[8]

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[8] Of course, researcher managed trials have various objectives and often are not designed to measure mean NUE prevailing under actual smallholder conditions.

There is also expected bias from researcher-managed on-farm trials of crop yield response to applied nutrients that report NUEs after having excluded crop yield data from trial sites that were subject to crop damage or other factors that confounded the nutrient response in the crop planted at the trial site (e.g., MPTF, 1999). However, over half (54%) of the Malawian farmers surveyed in the nationally representative 2010 IHS3 survey reported that they harvested less than the area that they planted due to various exogenous shocks (see Table 2).

Non-random sampling and the exclusion of some plots experiencing damage from analysis are appropriate under certain study objectives, such as when a better understanding of crop yield response to nutrient application is sought. However, findings from such studies cannot be extrapolated to provide valid estimates of actual NUE achieved by the full cross-section of Malawian farmers given the serious challenges that they face in their farming systems. In contrast to studies attempting to measure NUE based on what farmers might achieve under favorable conditions, a more accurate estimate of actual NUE obtained by entire sample of farmers would be:

$$NUE = \alpha NUE_{ncd} + (1-\alpha)NUE_{cd}$$

where α is the proportion of sampled farmers experiencing little or no crop damage and $1-\alpha$ is the proportion experiencing significant crop damage, and NUE_{ncd} and NUE_{cd} are those obtained on fields experiencing no crop damage and some damage, respectively. If, for example, 75 percent of the plots in the trials had no reported crop damage, while the other 25 percent of plots did, and the nitrogen use efficiency of the 'no crop damage' group was 24, while the N use efficiency of those experiencing crop damage was 6, then researchers interested in what a particular plot would achieve under relatively favorable conditions would report NUE=24 while researchers interested in reporting NUE by all farmers would be 0.75*24 + 0.25*6 = 19.5. Therefore, we conclude that different treatment of cases of crop damage as well as non-randomness with respect to farmer selection for study trials may also account for some of the observed difference in NUEs between trials and nationally representative survey data.

4. Discussion: the way forward

There is broad agreement that, whatever the current level of efficiency with which Malawian farmers use fertilizer, great benefits can come from helping them to use it more efficiently. Toward this end, we identify the following proposals for consideration:

First steps

1. Diagnose key regulating factors that determine NUE on farmers fields, as vital input for policy recommendations, and to prioritize among investments;
2. Attention to planning and FISP logistical supply chain to ensure timely delivery to farmers. This is a widely supported recommendation of past FISP reviews that requires action.
3. Extension messages on targeting fertilizer to responsive soils and plants:
   - Fertilizer use based on good agronomy, following the **4R** Nutrient Stewardship (**R**ight Source, **R**ight rate, **R**ight time, Right place);
   - Target fertilizer to fields where there is good response (fields with sufficient soil quality/meet minimum thresholds, where plants grow well and can utilize fertilizer);
   - Target fertilizer to improved crop varieties, and apply directly to crop roots (application of doses directly to crops as microdoses to planting stations or band along rows), using moderate doses of high analysis-N fertilizer (e.g., 30 kg of N as Urea) which is widely the most profitable fertilizer for maize production on most soil types, use even lower amounts for dry areas (e.g.., 10 kg of N);
   - Apply moderate doses of fertilizer that contain N and P (e.g. basal fertilizer, 23:21) to maize grown in rotation or intercropped with food legumes, and to soil types that show P-deficient symptoms (purple leaves in seedlings, observations that crops respond to P fertilizers);
   - For poorer quality soils and striga infested areas: grow 'best bet' legumes as described below, in combination with compost and small doses of fertilizer, to suppress striga and build soil productive capacity.

Next steps

1. Provide agronomic advice in tandem with FISP. Building on the starter pack and ASWAP demonstrations, support good agronomy through building farmer knowledge and capacity to innovate with inputs. Extension staff activities, radio campaigns and collaboration with the Ministry of Education are important means to add value to the FISP as opportunities to enhance farmer experimentation and capacity. Agronomic topics include:

- Improved weed management through integrated approaches, promote crop diversification to reduce crop-specific weed build ups, correctly timed and targeted application of fertilizer directly to crops for maximum uptake efficiency and reduced weed competition. High crop populations with well-timed early weeding.

– Promote broader use of best bet legumes through education and market policies to maximize N fixation, P solubilization and active soil organic matter for sustainable intensification. These include pigeonpea, doubled up legumes (pigeonpea intercropped with food legumes), long-duration varieties of soybean, cowpea and climbing bean, grown using good quality seed at high plant population densities, with targeted use of inputs.

- Integrated pest management techniques, particularly for striga and stem borer in maize and weevils in food legumes and tubers. Farmer field school and related extension approaches should be used to promote pest life cycle knowledge and the introduction of combined approaches, such as compost, rotations, intercrops and targeted spraying with botanical or chemical pesticides.

2. Allow flexible vouchers so that farmers can choose which inputs they feel would be in their best interests to purchase. For market-oriented farmers, access to both input and output markets for growing cash crops with low-toxicity herbicides may be appropriate – to the extent that labor constraints impede the number of and intensity of weeding. Because few farmers currently use herbicides, training in the pesticide mode of action and safe use combined with access to appropriate application equipment and safe modes of storage are all essential if herbicides are to be introduced in a safe and effective manner.

3. Improve soil production capacity long-term through educational activities on diagnosis of soil problems, and amelioration through investment by farmers and society. Use FISP to incentivize soil and water conservation/fertility enhancement and investment in legumes, compost and fertilizers to address persist problem soils with striga, acidity, compaction or other issues. Propose a 'conditional universal subsidy', i.e. any farmer of any size can qualify for subsidised fertiliser provided he/she adopts soil quality-enhancing investments to reverse the cycle of land degradation in densely populated farming areas. As many as 30% of farmers in the Central Region suffer from striga. The spread of striga is symptomatic of the growing problems associated with continuous maize cultivation grown with minimal inputs, and needs to be addressed particularly in

view of a changing climate with associated rainfall variability. This makes managing FISP in conjunction with education on building soil production capacity of vital importance to food security and building the nation.

5. Conclusions

Raising the efficiency with which farmers use fertilizer is crucial for achieving sustainable agricultural productivity growth, food security and poverty reduction in Malawi. Survey data indicate that NUE on maize fields managed by Malawian farmers is variable but low on average. Interventions to raise NUE will be crucial for enabling farmers to use fertilizer profitably, thereby raising the commercial demand for fertilizer and contributing to sustainable forms of land intensification.

NUE from researcher-involved farm trials tend to be 2 to 3 (or more) times higher than NUEs obtained from smallholder farm surveys where yields are measured by either yield sub-plot data or farmer recall of harvest from the plot. Reasons for the major differences in NUE between farm trials and survey data include differences in weeding intensity, late application of fertilizer, non-random selection and self-selection of farmers to participate in trials, the tendency for farmers to provide different levels of effort on plots where their maize yield is being recorded by outside observers. We also point out the bias associated with edge effects on small plots, and the tendency of nationally representative survey data to include a higher proportion of farmers using fertilizer with below-average management skills compared to farmers participating in trials.

In recent years, 50% or more of the Government of Malawi's expenditures on agriculture have been devoted to subsidizing the cost of fertilizer. Sustainable agricultural productivity growth in Malawi may be more effectively achieved by a shift of emphasis that elevates efforts to help farmers use fertilizer more efficiently in addition to the current emphasis (as per the composition of public expenditures) on raising the quantity of inorganic fertilizer and hybrid seed used. Greater use of fertilizer and hybrid seeds in the absence of programs and interventions to raise the efficiency of input use will continue to depress the positive impacts of the FISP program.

Toward this end, the paper identifies the need for investment in understanding the factors that influence the variation of NUE observed on smallholder fields. This can be used to inform policies and complementary investments to subsidy programs.

We contend that near-term improvements in NUE can be made through prioritizing timely availability of inputs, and investment in educational activities to support widespread knowledge of how to manage nitrogen fertilizer for maximum returns. Longer term and important investments include support for soil management practices that increase active SOM and rainfall-use efficiencies, through extension education and market infrastructure that enhances farmer adoption of legumes and soil diagnosis and rehabilitation practices. While often viewed as "alternative" or "low-input" forms of agriculture, these may be more accurately characterized as important components of a holistic system approach that enables an input-intensive production system to be both profitable and sustainable in a rapidly changing world.

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