MALAWI
Strategy Support Program

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
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A member of the CGIAR Consortium

WORKING PAPER 9 | October 2014

Maize Yield Response to Nitrogen in Malawi's Smallholder Production Systems

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I. INTRODUCTION

Sustainable intensification in crop and livestock production is the foundation for smallholder agriculture in sub-Saharan Africa to adapt to a changing world, to respond to new economic opportunities, and to address poverty reduction and food security. For crop farmers, substantial gains in potential productivity have been made through 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) – here defined as the amount of additional grain harvested per kilogram of nitrogen applied to the grain crop – thus becomes an urgent project that underlies success in agricultural development in the region. 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 Eastern 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).[1] In the 1995/96 and the 1997/98 cropping seasons, a nationwide research trial in Malawi was implemented on over 3,000 farmers' fields in total by agricultural extension field assistance with relatively close researcher oversight in order to verify the yield performance of a range of inorganic fertilizer packages on hybrid maize. The average linear maize yield response to nitrogen estimated from the trial results was 17.7 kg maize grain per kg N-applied, with somewhat higher levels of around 19.0 seen in the mid-altitude plateau areas of Lilongwe, Kasungu, and Mzimba (MPTF 1999).

By contrast, estimates of NUE on maize plots derived from nationally representative and site-specific household survey data in Malawi are typically in the range of 7 to 14 (Ricker-Gilbert et al. 2011; Chibwana et al. 2012; Snapp et al. 2013; Wiyo and Feyen 1999).[2] 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 as to 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, signalling the magnitude of constraints faced in smallholder production systems and the need for a holistic approach of education and integrated management to support policies aimed at enhancing access to and efficient use of fertilizer. A number of reviews of maize and fertilizer technology in the region have recommended investments to improve 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.

[1] 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.

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

2. RESEARCH EVIDENCE ON RESPONSE RATES FROM HOUSEHOLD SURVEYS IN MALAWI

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

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 (kg maize per kg N applied)
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. 2012	2002, 2006, 2009	Farmer-managed field data of 375 households across three seasons	Kasungu and Machinga Districts in central and southern Malawi	9.6 – 12.0 †
Chirwa and Dorward 2013	2009, 2010	Nationally representative IHS-II, IHS-III, AISS-I, and AISS-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 *
Ricker-Gilbert and Jayne 2011, 2012	Same as with Chirwa and Dorward 2013			6.6 – 11.5
Snapp et al. 2013	Same as with Chirwa and Dorward 2013			5.33 for monocropped maize; 8.84 for intercropped maize
Holden and Lunduka 2010	2006, 2007, 2009	Random sample of 450 farmers	Central and Southern regions	9.0 ϒ

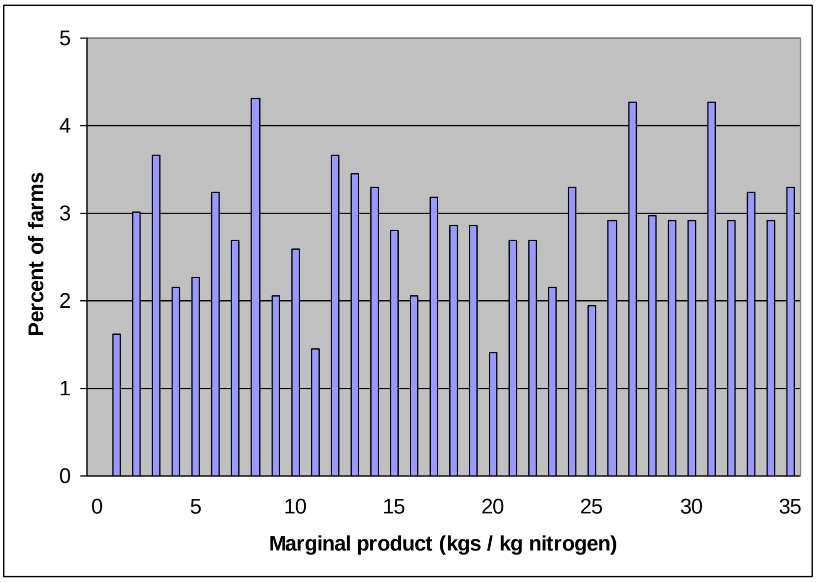
Notes: * Dorward and Chirwa (2010) also estimated NUEs using the nationally representative data from IHS2 and IHS3 and from the AISS surveys using both yield sub-plot and farmer recall data. They reported low NUEs that were comparable to those obtained by Ricker-Gilbert and Jayne (2011, 2012) and Snapp et al (2013). However, the authors concluded that the data from these surveys were problematic and unacceptably low.
† The referenced study did not calculate NUE directly. The NUE estimate comes from Arndt et al. (2014, p. 39). Chirwa and Dorward (2013, p. 131) calculate an NUE of 9-11.5 for the referenced study.
ϒ The referenced study did not calculate NUE directly. The estimate here comes from Chirwa and Dorward (2013, p. 131).

Several studies based on farmer interviews and computations of value-cost ratios report that a large proportion of Malawian farmers find 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).[3] 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 NUEs 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 has been 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).

[3] For example, SOAS (2008) reports that "this analysis suggests that profitability of fertilizer 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).

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



Source: Xu et al. 2009.

Note: Agroecological zone IIa with acrisol soils 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).

3. FACTORS AFFECTING NITROGEN USE EFFICIENCY ON MAIZE PLOTS IN MALAWI

Maize response to nitrogen fertilizer has been the focus of agronomic research in Malawi 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 level 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.

Inadequate weeding and other pests

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 to 34 percent yield reduction (FAO 2000). While Malawian smallholders understand the importance of multiple weedings in raising their maize yields and the efficiency of inorganic fertilizer application, 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.[4] 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 higher 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: The survey results showed that early weeding was applied to between 70 and 97 percent of fertilized maize plots compared to early weeding being done on only between 30 and 60 percent of unfertilized maize plots.

Table 2 suggests that during the 2006/07 and 2007/08 seasons, 65 to70 percent of plots were weeded twice. Zero or one weedings were reported on between 25 and27 percent of plots, while only 3 to 10 percent of plots were weeded 3 or more times. These data indicate that the majority of households in Malawi find it optimal to weed their maize field

[4] 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.

twice, given the labor and other resource constraints that they face. However, there is still a substantial portion of plots that receive more limited attention and are weeded fewer than 2 times.

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
Area left uncultivated, ha (unconditional national avg.):	0.192	0.154	0.237	--
Northern region	0.411	0.181	0.520	
Central region	0.195	0.217	0.296	
Southern region	0.056	0.099	0.062	
% of maize plots intercropped with legume crop	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 two weedings [1]	--	65.3	69.7	--
% of maize plots receiving three 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
Due to poor soil fertility, percent of households experiencing lower yields in past 2-3 years	--	32.2	39.6	--
Due to bad weather or rainfall, percent of households experiencing lower yields in past 2-3 years	--	27.3	29.9	--
Due to crop disease or pests, percent of households experiencing lower yields in past 2-3 years	--	13.7	17.3	--
Median maize yield, kg/ha	576	576	691	1,289 [2]
Median hybrid or composite maize yield, kg/ha	691	691	864	1,373 [2]
Median local variety maize yield, 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 plot area measured using GPS. Farmer recall is the source of plot area data in the other surveys.
' -- ' means data not available in particular survey wave.

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*[5] and insect infestation are other challenges faced by smallholders in Malawi. These tend to be location specific (e.g., striga build up is particularly seen 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 of smallholders in 2006/07 and 17.3 percent in 2008/9 reported yield loss due to crop disease and pests (Table 2).

Crop rotation and intercropping

A factor that consistently influences maize yield response to nitrogen is rotation with a legume crop. Legume residues are N-enriched, containing 3 to 5 percent N compared to 1 to 2 percent N in cereal residues. This is due to the biological N-fixation capacity of most legumes through a symbiotic relationship with rhizobia soil bacteria. Legumes that have a longer-duration growing period and produce copious amounts of vegetative matter over 6 to 10 months are much more likely to fix appreciable amounts of N, compared to food legumes such as common bean and soybean with a shorter 3 to 4 month growing period (Snapp et al. 1998).[6] 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. However, bushy and viney long-duration food legumes have been shown to fix

[5] Striga (*kaufiti* in Chichewa, also called witchweed in English) is not just a weed that competes with the maize plant for soil nutrients. It produces toxic chemicals that stunt maize root development and attaches itself parasitically to maize roots to deplete the plant of nutrients. Hence, striga's impact on maize yield and NUE can be particularly severe.

[6] Moreover, after the N-enriched grain is removed at harvest from food legumes, a net N-benefit is not always achieved to contribute to the soil N supply (Giller and Cadisch 1995).

30 to 100 kg of N/ha, and to build soil N pools (Cadisch et al. 1998; Snapp et al. 2010). Table 2 indicates that between 35 and 50 percent of maize plots in Malawi have some legumes grown with the maize, but that the prevalence of legume intercropping declined over the period the surveys were conducted.

There are also unique contributions that legumes make to maize productivity via what is termed the 'rotation effect'. This is not well defined, but is generally associated with building active soil organic matter and associated microbial diversity (Turco et al. 1990). The yield response of maize to nitrogen when grown after soybean is estimated to be 15 to 20 percent higher than the yield response of continuous maize to applied nitrogen. In a study in Tennessee, USA, this rotation effect recently was shown to consistently increase the calculated net returns for maize producers (Boyer et al. 2013). In a nationwide trial in Malawi on the effects of incorporating legumes into smallholder cropping systems, maize response to N fertilizer was shown to be between 35 and 125 percent 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 shorter lived food legumes (Snapp et al. 2010). This large-scale study also demonstrated improved stability in maize yield response due to the rotation effect, as well as gains in NUE.

As population pressures cause a shrinking of farm sizes in Malawi over time, smallholder farmers respond by continuously cropping their fields. As shown in Table 2, estimates from the IHS3 survey are that only 1.1 percent of plots were left entirely fallow in 2008/09 and 2009/10, and that 95.7 percent 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 of maize-legume intercropping over the last four decades. Intercropping was practiced on almost 100 percent of maize plots in Malawi in 1968/69. By 1980/81, intercropping was observed on only between 25 and 39 percent of maize plots (Heisey and Smale 1995; Table 5.11). Continuing reductions in intercropped land are observed in the results from recent countrywide surveys (Table 2). Government policies have promoted sole-cropped production of hybrid maize. As adoption of hybrid maize has increased markedly in recent years, this may have contributed to the decline of intercropping, although other factors are hypothesized to contribute to this decline as well (Heisey and Smale 1995).

Less surprising is the preferential practice of crop rotation by better-off farmers with larger landholdings (Snapp et al. 2002). On very small farms, households cannot afford to sacrifice using the land for an entire year for crops for which there is limited consumption value. Such households need to produce as much staple food as possible for the coming year. Therefore, many households continue to grow maize on the same field year after year, resulting in declining NUEs when these households apply fertilizer to their maize. Systematic differences in crop rotation therefore may be another source of variation in NUEs between researcher-influenced farm trials vs. nationally-representative household survey data. In order to raise the NUEs such small farmers realize in their use of fertilizer on maize, research could be directed at market or other policies that strengthen the incentives for farmers to use maize-legume crop rotations.

Late delivery and application of fertilizer

Timing of fertilizer application is essential for optimizing both yield and quality. Proper timing of fertilizer application reduces nutrient losses, increases the efficiency of nutrient usage, and prevents damage to the environment (Jones and Jacobsen 2003). It is essential that fertilizer be made available to farmers in a timely manner so that they can apply it when their crops need it.

Table 3—First fertilizer application to maize crop by farmers in Malawi, by weeks after planting

Fertilizer application timing (weeks after planting)	2006/07 season			2008/09 season		
	n	percent	cumulative percent	n	percent	cumulative percent
Less than 1 week	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
More than 5 weeks	179	6.2	100.0	171	6.0	100.0
Total	2,923	100.0		2,864	100.0	

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

Though the surveys from Malawi do not clarify exactly when households acquire their fertilizer through the Farm Input Subsidy Programme, according to the 2006/07 and 2008/09 AISS surveys, the majority of households apply their first, basal dose of fertilizer 3 or more weeks after planting. This was especially true in the 2008/09 season, when 72.5 percent of households applied the first dose of fertilizer to their maize 3 or more weeks after planting. Late application of fertilizer by farmers could be due to various factors, such as late delivery of fertilizer, lack of available labor to apply it, and lack of knowledge about appropriate fertilizer use. By contrast, most farmers participating in on-farm research 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.

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. However, it is difficult to enhance total SOC on tropical smallholder farms. Not all SOC is the same: biophysical fractionation of soil carbon 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 a modest levels of biomass addition (3 to 5 tons, including roots). Such quantities of biomass are practical to produce in the sub-humid tropics through growing leafy types of multipurpose legumes or by 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 improved crop 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, survey data indicates that only 15.2 percent of all maize plots had organic fertilizer applied to them in 2002/03 and 2003/04, which declined to 12.7 percent in 2008/09 and 2009/10. This could be attributed to limited livestock production in Malawi and labor constraints that make it difficult to engage in composting. More evidence on the extent to which low SOC poses limitations on NUE in Malawi is needed.

Soil chemical properties – acidity and low phosphorus

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 constraint to this crop. However, extension campaigns promoting compost use have been successful in areas of Malawi in which groundnut is intensively produced, such as Mchinji. This groundnut yield response to compost may be due to the soil acidity and calcium deficiency amelioration properties of composted manure.

Important nutrients to consider in crop production across Malawi are generally considered to be phosphorus and sulfur and in some locations 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). There is evidence since the 1960s that for some crops, particularly legumes, the highland regions of Malawi have soil types that supply insufficient P (Kumwenda et al. 1997). Thus, the generally recommended combination of apply a basal fertilizer containing phosphorus (and sulfur), such as 23:21:0+4S, followed by a top-dressing of high analysis N fertilizer, such as urea, is appropriate for most soil types in Malawi. However, in the short-term and in the absence of fertilizer subsidies, if maize is the focus without considering the nutrient needs of other crops grown on the farm, then urea may be the most profitable fertilizer for farmers to employ (MPTF 1999).

[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.

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 their 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 who would be glad to acquire it at a cost that is 10 percent of the full price. The probability of breaking even are obviously considerably higher when paying 10 percent of the full price even among relatively inefficient users of fertilizer. Hence, the Malawi Farm Input Subsidy Programme may put downward pressure on the NUEs observed in the survey data, as a large proportion of maize plots of survey households would have been fertilized with subsidized fertilizer. Recall the data in Figure 1 showing the wide variation in NUE among farmers even in the same area.

"Observer effect" and other sources of trial bias

The "observer effect" principle holds that measurements of a system cannot be made without affecting the system itself. Applied to the case of researcher-influenced on-farm trials in Malawi, farmers participating in such 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, or for other reasons. Consequently, NUEs as reported from farm trial plots may be expected to be somewhat higher than from fields in which no trials were sited, other conditions being 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 an 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 in Malawi, although generally small, are often orders of magnitude larger than these trial plots. 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 above ground biomass in switchgrass was estimated at between 4 and 35 mt/ha but decreased to between 2 and 3 mt/ha in more realistic field-scale tests (Searle and Malins 2014). This plot size effect on biomass measurements was primarily associated with edge effects.

Non-random sampling of farmers and plots is expected to influence differences observed in NUE between researcher-influenced farm trial studies and what farmers actually obtain. These are based on farmers' willingness to take part in the study. Farmers involved in such on-farm studies tend to be well-connected to extension staff. This can result in on-farm trials over-sampling 'master farmers' with superior management skill, despite efforts to overcome such bias. Studies with a 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 sub-plot yield measurements). In contrast, most researcher-influenced on-farm trials involve few and non-randomly selected observations. [8]

Bias in results is also expected 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 percent) 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 the actual NUE obtained by a representative sample of farmers would be:

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

[8] Of course, researcher managed trials have various objectives, including nutrient response holding all other factors constant, and often are not designed to measure mean NUE prevailing under actual smallholder conditions.

where α is the proportion of sampled farmers experiencing little or no crop damage and 1-α is the proportion experiencing significant crop damage, and NUE_{ncd} and NUE_{cd} are the nitrogen use efficiencies 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 at household and national levels can come if they are able to use it more efficiently. Toward this end, we make the following proposals:

FIRST STEPS

1. Diagnose the key regulating factors that determine NUE on farmers' fields as a vital input for policy recommendations and to prioritize among public investments in agriculture;
2. Improve the logistical operations of Farm Input Subsidy Programme input supply chains to ensure timely fertilizer delivery to farmers. This is a widely supported recommendation of past FISP reviews that requires action.
3. Strengthen the quality and dissemination of agricultural extension messages on targeting fertilizer to responsive soils and plants:
    - Fertilizer use based on good agronomy, following **4R** Nutrient Stewardship practices of **R**ight source, **R**ight rate, **R**ight time, and **R**ight place;
    - Target fertilizer to fields where there is good response – fields with sufficient soil quality and which meet minimum agronomic performance thresholds, where plants can grow well under good management and can utilize fertilizer effectively;
    - Target fertilizer to improved crop varieties, and apply directly near crop roots (application of doses directly to crops as microdoses to planting stations or band along rows).
    - For farmers that cannot afford the recommended combination of 23:21:0+4S and urea fertilizers, application of moderate doses of high analysis-N fertilizer (e.g., 30 kg N per ha) should prove profitable over the short to medium term on most soil types, using lower amounts in drier areas (e.g., 10 kg N per ha);
    - Apply moderate doses of fertilizer that contain N and P (e.g. basal fertilizer, 23:21:0+4S) to maize grown in rotation or intercropped with food legumes, and to soil types that show P-deficient symptoms (purple leaves in maize seedlings, or observations that crops respond to P fertilizers);
    - For poorer quality soils and striga infested areas, grow 'best bet' legumes in combination with compost and small doses of fertilizer, to suppress striga and build soil productive capacity.
    - Use best agronomic practices for maize production, such as optimum plant densities, proper weed management, and the timing of key cropping operations. To realize the NUEs that on-farm researcher-influenced trials demonstrate are possible to achieve in Malawi, farmers must have information on the best agronomic practices that they are able to employ.

NEXT STEPS

1. Provide agronomic advice in tandem with the Farm Input Subsidy Programme. Building on the Starter Pack and field demonstrations conducted under the Agriculture Sector-wide Approach (ASWAp), 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 up, 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 biological N-fixation, P solubilization, and active soil organic matter for sustainable intensification. These 'best bet' legumes include pigeonpea, doubled up legumes (pigeonpea intercropped with food legumes), long-

duration varieties of soybean, cowpea, and climbing bean; all 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 under the FISP 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 operations. Because few farmers currently use herbicides, training in the mode of action of the herbicide and its 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 the production capacity of soils in the long-term through educational activities on diagnosis of soil problems and their amelioration through investments by farmers and government. The design of the FISP could be altered so that it provides increased incentives for farmers to engage in soil and water conservation and soil fertility enhancement activities, increase their legume production, and use compost and fertilizers to address persistent problem soils with striga, acidity, soil compaction, or other issues. We propose the use of a 'conditional universal subsidy' through which any farmer of any size can qualify for subsidised fertiliser provided that she or he adopts soil quality-enhancing investments to reverse the cycle of land degradation in densely populated farming areas. This makes modifying the FISP so that the program better addresses these issues, in conjunction with education on building soil production capacity through the provision of improved agricultural extension services, 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 two or three times higher than NUE estimates obtained from smallholder household 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 the NUE reported from researcher-influenced on-farm trials and from household survey data include differences in weeding intensity, late application of fertilizer by farm households, 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, and farmers growing maize continuously with no legume break crops, among others. 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 and farming on more degraded soils compared to farmers participating in trials.

In recent years, 50 percent 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 an increased emphasis in public investments to elevate efforts to help farmers use fertilizer more efficiently, in addition to the current emphasis through the FISP 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, this paper identifies the need for investment in understanding the factors that influence the variation of NUE observed on smallholder fields across Malawi. Insights from such research can be used to inform policies and complementary investments to input 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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Acknowledgments

This report has benefited from discussions with numerous individuals including Stephen Carr, Ken Giller, Nicole Mason, and Malcolm Blackie. Funding for this study was provided by the Bill and Melinda Gates Foundation under the 'Guiding Investments in Sustainable Agricultural Intensification' project and by the United States Agency for International Development under the 'Africa Rising' project.

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