

Variable Returns to Fertilizer Use and the Geography of Poverty: Experimental and Simulation Evidence From Malawi

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Abstract

We use large-scale, panel experimental data from maize field trials throughout Malawi to estimate the expected biophysical returns to fertilizer use conditional on a range of agronomic factors and weather conditions. Using these estimated returns and historical price and weather data, we simulate the expected profitability of fertilizer application over space and time. We find that the fertilizer bundles distributed under Malawi's subsidy program are almost always profitable for improved hybrid seeds at retail and farmer-reported maize and fertilizer prices. Our results on the profitability of fertilizer under Malawi's subsidy program are robust to a tripling of fertilizer prices, to a 50% decrease in the maize price, and to drought conditions. We also correlate the estimated expected returns to fertilizer use with geographically disaggregated estimates of headcount poverty rates. We find a very weak positive correlation between poverty and the expected returns to

fertilizer, which calls into question whether fertilizer subsidies are spatially distributionally progressive in helping to reduce poverty among Malawian farmers.

Many observers ascribe much of sub-Saharan Africa (SSA)'s relatively low agricultural productivity to African farmers' limited use of fertilizers (Gregory and Bumb 2006, Kelly 2006, Morris et al. 2007). In 2005, SSA farmers applied only 9 kg of fertilizer per hectare (ha), on average, compared to 73 in Latin America and 100-135 in Asia, where as much as 50% of the Green Revolution yield growth is attributed to fertilizer use (IFDC 2006). Low fertilizer application rates among SSA farmers are often attributed to problems associated with thin markets as well as weak infrastructure and institutions that impede fertilizer distribution and demand in spite of its expected profitability (Omamo et al 2001, Kherallah et al 2000, Jayne et al 2003, Gregory and Bumb 2006, Poulton et al 2006). In response, several African heads of state committed to fertilizer subsidies in the 2006 Abuja Declaration on Fertilizer for An African Green Revolution, and especially after the 2007-2008 food price crisis (Jayne and Rashid 2013, Kelly et al 2011).

In response to a severe drought in 2004-2005, the government of Malawi implemented a large-scale Farm Input Subsidy Program (FISP) distributing hybrid or improved open pollinating seeds and 50 kg of basal fertilizer and 50 kg of urea to targeted recipients, approximately 50% of the population. Aggregate maize production doubled in 2006, then tripled in 2007, going from a 43% national deficit in 2005 to a 53% surplus in 2007 (Denning et al 2009). In a nation where inhabitants consume approximately 1,193 kilocalories from maize per day and grew maize on approximately 40% of cultivated land in 2005 (FAOSTAT 2005), the fertilizer subsidy scheme's apparent success in dramatically improving Malawi's food security attracted widespread attention and helped turn fertilizer subsidies into a high-level political issue. In part due to the subsidy scheme, Malawi is one

of a number of sub-Saharan African countries where inorganic fertilizers are now used by a majority of farm households (Sheahan and Barrett 2014).

Yet there remain lingering questions as to whether low and variable soil fertility, frequent drought and high fertilizer prices render fertilizer unprofitable for large subpopulations of African farmers, at least in periods of unfavorable weather (Waithaka et al 2007, Zingore et al 2007, Marenya and Barrett 2009a, 2009b). Furthermore, published studies typically rely on observational data that are difficult to control effectively for unobserved farmer and location attributes that may jointly affect fertilizer use and output. This shortcoming has limited researchers' ability to make rigorous, general statements about the expected profitability of fertilizer use at the national scale at which policies are made. Given the considerable sums expended by cash-strapped governments on fertilizer subsidies – starting at US \$ 50 million in 2005-2006 and growing to US \$ 265 million in 2008-2009 in Malawi's case – this evidence gap is striking.

In this study, we use a large-scale, repeated, nationwide experimental, plot-level data set from Malawi, merged with detailed soils and weather data, to generate flexible maize production function econometric estimates of the marginal physical returns to fertilizer use. Randomized assignment of fertilizer applications combined with detailed agronomic controls enable us to identify the causal effects of fertilizer application on maize yields. We then use the estimated maize production function and historical weather and price data to simulate the distribution of the expected profitability of fertilizer use over space in the face of uncertain weather given prevailing retail and farmgate output and input prices during the subsidy period in Malawi. Finally, we correlate those estimated expected benefits of fertilizer use with local poverty rates so as to establish whether yield gains

reasonably attributable to fertilizer accrue primarily in poorer or richer areas of the country. Fertilizer subsidies are often touted as a poverty reduction policy in low-income economies dominated by small farms. If fertilizer subsidies are to offer a distributionally progressive instrument for reducing widespread poverty among small farmers in SSA, then fertilizer not only needs to increase yields but those gains should ideally also be concentrated in regions of higher initial poverty.

Our study offers three main contributions. First, we overcome the endogeneity of input selection by farmers by using experimental, agronomic field trial data. Second, we take into account the distribution of weather conditions to examine how fertilizer use interacts with past temperature and rainfall conditions so as to simulate the distribution of marginal profitability of fertilizer use. Finally, we link the estimated profitability of fertilizers to geographic patterns of poverty. We know of no prior published evidence on how the spatial patterns of the expected returns to fertilizer correlate with the geographic distribution of poverty. We find that the fertilizer bundles distributed under Malawi's subsidy program are almost always profitable for improved hybrid seeds, even if fertilizer prices triple, maize prices decrease by 50%, and under drought conditions. When we correlate estimated expected returns to fertilizer use with geographically disaggregated estimates of headcount poverty rates, we find a very weak positive correlation. Fertilizer subsidies may encourage uptake and expand output among all farmers, but within the farming community the gains are not likely concentrated among the poorest. This implies that the poverty reduction effects, if any, of fertilizer subsidies are more likely to result from increased aggregate output inducing agricultural wage and market price effects that benefit poor workers and consumers, as was true of the Green Revolution (David and

Otsuka 1994, Evenson and Gollin 2003), than from direct productivity gains concentrated among the poor.

Data

The data used in this study come from multiple sources.

Experimental field trials data

We use on-farm experimental field trial data conducted by the Maize Productivity Task Force (MPTF) in 1995-1996 and again in 1997-1998 after the Ministry of Agriculture called for fertilizer verification trials to determine which fertilizer combinations would be best suited to different soil types throughout Malawi (Snapp *et al.* 2010, Benson 1999a). Six treatments of different fertilizer bundles were randomly assigned across 1,677 sites nationwide in 1995-1996. Experiments with four of those treatments were repeated on 1,407 sites in 1997-1998, with 1,205 overlapping locations across the two years (table 1). The experimental sites were managed by full-time farmers who were chosen based on the criteria of being reliable, intelligent, and well-respected in the community. Because farmers were not randomly selected, however, potential selection bias concerns exist, as explained in the discussion below.

At each site, the different treatments were conducted on 4-6 (depending on the year) adjacent trial plots, each plot measuring 6.3 m x 9 m, consisting of seven ridges spaced 90 cm apart. The net harvest plot size was five full ridge lengths, or 1/247 ha (0.00405 ha). The basal application of fertilizer was done before planting using the banding method. Two different maize varieties were used. The shorter duration hybrid, MH18, was planted at

about two-thirds of all sites – those in lowland areas and in rain-shadow areas in the uplands. The taller, longer duration hybrid, MH17, was planted at the remaining sites. The maize was planted at a rate of three seeds per station, with planting stations spaced 75 cm along the ridge. The top-dressing application of fertilizer was done by the banding method when the maize had reached 45 cm in height. Plots were weeded at least twice (Sauer and Tschale 2009, Benson 1999).

To ensure the plots were managed as uniformly as possible (except for the amount of fertilizer application), the farmers were carefully trained and closely monitored by regional field assistants (FAs) who themselves were monitored by development officers (DOs). The FAs made sure that all of the major cropping activities were carried out on the same day on all plots in each site. FAs and farmers worked together to apply fertilizers to all the plots (except for the no-fertilizer plot) at the same time, following the same guidance. Farmers were responsible for keeping all the plots free of weeds throughout the growing season, under FAs' supervision. FAs were also responsible for either harvesting themselves or closely supervising farmers to do so. The DO hosted four inspection visits with local farmers and their FA at each site. The first visit was carried out after the land was prepared, the treatments were randomly assigned at the plot and the basal fertilizer was applied. The second visit was executed after the top dressing was applied. The third visit was planned for when the maize was fully grown, but still green, and the final visit occurred after harvest when the grain yield had been weighed. The DO collected several types of data including soil samples, farmer comments, crop growth stage dates, incidence of pest attack, and harvest data.¹ The FAs received two payments (of 195 MK/field day) for

¹ Soil samples were collected on a small share of the experimental plots, effectively precluding their use in the estimation below.

successfully implementing the trials: the first payment was given after the maize was fully grown, and the second after harvest. Sites where the trial was improperly executed were abandoned and FAs were not paid (Sauer and Tschale 2009, Benson 1999b).² Because all the plots were rain-fed, farmers reallocating water in favor of heavily fertilized plots is not a concern. Although we cannot completely eliminate the possibility that farmers reallocated labor among plots based on fertilizer application, we consider it less of a concern, because the major labor-intensive activities, such as planting, fertilizer application, weeding and harvesting, were closely monitored so that we can control for them.

Differences in soil characteristics between sites observed in both years are statistically significantly but not substantively different than those observed in only one of the years (Appendix 1). As expected, yields increase with the nitrogen (N), phosphate (P) and sulphur (S) contents of a fertilizer application (table 1). Interestingly, treatment 5 leads to statistically significantly higher (at the 1% level) mean yields than treatment 6, which has a higher N and phosphate content but no S. Yields in 1995-1996 were statistically significantly higher (at the 1% level) than yields in 1997-1998 for each treatment, likely reflecting differences in weather conditions. Farmers selected field sites on which fertilizer had not been applied and that had been fallow for at least two years. The 1997-1998 trials were in the same location as the 1995-1996 trials, but not at the exact same sites, so as to ensure that the preceding treatments did not affect subsequent trial's yields.³

² Reasons for which the trial might be abandoned include: trial was laid out wrong, wrong fertilizer applied to a plot, wrong cup size used in applying fertilizer, animals destroyed some of the plot, bad management, no data recorded, harvests were not kept separate, some of the harvest was lost before it was weighed.

³ We use *location* to refer to the same geographic area at which one or more *site* was chosen at which to perform the field experiments. Therefore, up to two different *sites* (one for the 1995-1996 trials and one for the 1997-1998 trials) were chosen at one location.

Table 2 shows the mean striga and termite infestation by year at each site, as reported by farmers overseeing the plots. Farmers were asked to observe whether the site was infested by striga, differentiating between infestation on less than 50% of planting stations (some infestation) or more than 50% (high striga infestation). Between 21-28% (6-7%) of sites suffered moderate (high) infestation each year. Termites were observed on approximately 40% of sites in both years.⁴ We have no reason to believe that pest infestation rates are endogenous to the fertilizer treatments.

Soils data

To control for soil heterogeneity that may affect the marginal physical product of fertilizer on maize, we use soil maps generated by the Land Resources Conservation Board at the Ministry of Agriculture in Malawi in collaboration with FAO and UNDP in the 1980s and 1990s (Eschweiler *et al.* 1991). The maps contain soil characteristics, including soil type, slope, cation exchange capacity (CEC), soil N, P and K content. We extract soil characteristics at each site, with mean values shown in Table 3. The terrain is flat (steep) on 48% (3%) of sites. The soils are on average acidic. Given the proximity in location of the trial plots in both seasons, we can reasonably assume that the sites shared similar agro-ecological characteristics, although there is surely unobserved plot-level variation in soil conditions. Nonetheless, we can estimate the marginal impact of fertilizer on maize yields because application rates were randomized across plots, plot management was

⁴ Pest infestation is not chronic: the correlation between striga infestation between both years is 0.19; the correlation between high striga infestation is 0.12 between both years; and the correlation between termite infestation is 0.10 between both years.

standardized, and we can control for a host of agronomic conditions that might also affect the marginal physical product of fertilizer.

Climate controls

We control for weather variability by using daily rainfall and temperature time series data from 23 weather stations distributed throughout Malawi as collected by the Malawi Meteorological Service (Figure 1). The first year of available rainfall data differs by district, ranging between 1903-1976, and ending in 2009 for all districts. The temperature data also differ in the starting year, ranging between 1956 and 1984 and ending between 2002 and 2008.

We build three weather variables to control for temperature and rainfall. First, we calculate the number of growing degree days (GDD) between 8 and 30 degrees Celsius between the reported planting and harvest dates to predict maize development rates (Lobell et al. 2011). Second, we calculate the number of growing degree days above 30 degrees Celsius to control for high temperatures that might harm maize growth. Finally, we calculate the total precipitation for the 21-day period centered on the silking date, to control for anthesis, the period when maize flowers and is particularly susceptible to drought. Appendix 2 includes a more thorough description of the construction of these weather variables. Each experimental field site was linked to the three nearest weather stations and a single average value was calculated using inverse distance weighting.

Figure 2 shows these weather measures from 1972 to 2004. As expected, a high GDD 30+ corresponds with past drought years, notably seasons 1982-1983, 1991-1992, and 1994-1995. Figure 2 also includes total maize yields (FAOSTAT 2013). High GDD

30+ and low precipitation years are, as expected, generally accompanied by low maize yields.

Fertilizer and maize prices

District-level median fertilizer prices were calculated from the agriculture module data in the third Integrated Household Survey (IHS3) for Malawi (NSO 2012). In the surveys, respondents were asked the quantity and value of unsubsidized fertilizer purchased. Our analysis, therefore, examines the market cost of fertilizer, not the subsidized cost to farmers nor the cost to the government. District-level median retail maize prices were calculated using the Ministry of Agriculture's monthly maize prices between December 2009 and March 2010 (the range of dates for which fertilizer prices were reported). In table 4, we compare the Ministry of Agriculture's monthly maize prices with farmer reported prices from the IHS3 data. As expected, farmers report lower prices than retail prices, with a mean of 34.5-36.5 MK/kg for maize compared to 46.4 MK/kg retail prices reported by the Ministry of Agriculture. Typical total transportation costs associated with crops sales vary between 0.23 – 0.52 MK/kg. Because the majority of reported transport costs are 0, we can assume that the majority of reported prices represent farm-gate prices where buyers came to farmers' households to make purchases. Appendix 3 shows the breakdown of prices by district.

Poverty maps

Finally, in order to correlate our spatially-explicit estimates of the expected marginal benefit/cost ratio for fertilizer application with local poverty rates we use the suite of

poverty measures reported for each of Malawi’s 28 districts in the 1998 poverty map (CIESIN 2013): mean daily household consumption per capita, the Gini index of consumption inequality, the poverty headcount rate (percent of the population living below \$1.25 per capita/day in purchasing power parity), the poverty gap, the poverty severity index, maximum education level attained, and the travel time to the nearest market per enumeration area. These estimates were generated using standard poverty mapping methods (Elbers *et al.* 2003). We use poverty maps from 1998 as these are the most close to when the field trial data were collected.

Methods

Using the MPTF data, we estimate a generalized quadratic production function of the form

$$y_{kit} = \alpha_0 + \sum_w \alpha_w x_{kitw} + \sum_w \sum_v \beta_{wv} x_{kitw} x_{kitv} + \eta_i + \delta_t + \varepsilon_{kit} \quad (1)$$

where y_{kit} represents the yield for treatment k on site i in year t , x_{kitw} and x_{kitv} represent all variables (indexed by v and w , respectively) potentially affecting yields: nutrient amounts in the fertilizer, soil characteristics, temperature and rainfall, η_i is a site-level random effect,⁵ δ_t is a year-specific fixed effect, and ε_{kit} represents the independently and identically distributed, mean zero, regression error. α_0 , α_w and β_{wv} are the production function parameters of interest. More specifically, we control for site-specific field characteristics, i.e., whether the site was infested by striga or termites, as well as site-level soil quality characteristics extracted from national soil maps, i.e., the slope, soil texture,

⁵ The panel data are unbalanced, but the field trial site selection was random and therefore the remaining unobservables should be uncorrelated with the regressors. We therefore estimate a random effects model.

pH, CEC, and N, P and potassium (K) contents, and weather. The full regression estimation results are reported in Appendix 4⁶ and average partial effects in Appendix 5. The data do not include observations for any inputs that were not controlled experimentally, so we cannot control for factors such as labor applications per plot. We must therefore assume that farmers optimally apply labor so that the marginal return estimates for fertilizer include the associated induced changes in the labor allocation, not merely the biochemical effects of the nutrient amendments. We correct for heteroskedasticity and spatial autocorrelation by clustering standard errors at the site level.⁷

The nutrients applied to the field trial sites are as explained above: nitrogen, sulfur, and phosphate. In sub-humid environments like Malawi, nitrogen is known to be the main driver of cereal yield response in soils with low organic matter. However, applying only nitrogen as fertilizer (in the form of urea) can lead to sulfur and phosphate deficiencies in the longer term (van der Velde et al. 2013). Potassium is less deficient in Malawian soils except perhaps for the intensive cultivation of tobacco. Zinc and other micronutrients also contribute to soil fertility but are rarely deficient except perhaps in small, localized areas of Malawi (Benson 1999a, 1999b). Chilimba and Liwimbi (2008) do conclude, however, that generally a basal dressing including zinc or potassium, or both, is superior to a basal application without them.

Although both sulfur and phosphate are known to contribute to maize yields, we cannot control for both because there is insufficient variation between treatments. Because sulfur more consistently showed yield responses than phosphate in the field trials, NPK

⁶ Sensitivity analysis revealed that our quadratic regression results were consistent in relative elasticity magnitude and sign with a Cobb-Douglas specification. Details available from the lead author by request.

⁷ A Breusch-Pagan /Cook- Weisberg test rejects the null hypothesis that all conditional variances are equal.

23:21:0+4S (N = nitrogen; P = phosphate; K = potassium; S = sulfur) was promoted as the basal dressing in Malawi's FISP. We therefore choose to control for nitrogen and sulfur in the production function estimation.

Given the estimated maize production function, we can compute the expected marginal physical returns to fertilizer, $E[dy]$, which equals the sum of the marginal products of each element in the fertilizer bundle, N and S, multiplied by the percent of the nutrients in the specific fertilizer:

$$E[dy] = \gamma_n \frac{\partial y}{\partial n} dn + \gamma_s \frac{\partial y}{\partial s} ds \quad (2)$$

For example, NPK (23:21:0+4S) contains 23% N, 21% P, 0% K and 4% S, so $\gamma_n = 23\%$ and $\gamma_s = 4\%$ while urea contains 46% N so that $\gamma_n = 46\%$ and $\gamma_s = 0\%$. Given the estimation results from equation (1), the expected marginal return to fertilizer f is:

$$E[dy] = \gamma_n (\alpha_n + \sum_v \beta_{nv} x_{kitv}) + \gamma_s (\alpha_s + \sum_v \beta_{sv} x_{kitv}) \quad (3)$$

Using historic district-level weather data along with the regression results, we estimate the distribution of expected returns for the FISP bundle, NPK and urea at each site for each available year. We calculate the growing degree days above 30C (GDD 30+), GDD from 8-30C (GDD 8-30) and rainfall (mm) weather variables for each year for each site by using the silking, planting and harvest dates from the 1995-1996 field trials (Lobell et al. 2011). We use the joint distribution of the observed weather variables to simulate the expected returns for each available year for the trial sites. The availability of data varies by

trials site and ranges between a start date of 1971 and an end date of 2004.⁸ We have to assume that soil characteristics remain constant as we do not have annual soil characteristics.

Given the distribution of expected returns to fertilizer, as well as fertilizer and maize prices, we then estimate the expected benefit/cost (EBC) ratios for each plot and the probability that fertilizer is profitable for a given plot. While weather conditions may affect maize prices and, to a lesser degree, fertilizer prices, data limitations keep us from controlling for the variation in prices over time. We therefore use district-level median maize and fertilizer prices from the third Integrated Household Survey (IHS) data for Malawi from 2009-2010 (NSO 2012), a year during which FISP was in effect. The expected change in profit, $E[\Delta\pi]$, from fertilizer application is

$$E[\Delta\pi] = E[\Delta y \cdot p_y] - f \cdot p_f \quad (4)$$

where p_y is the price of maize and p_f is the price of fertilizer, the first of which is unknown when farmers make fertilizer purchase decisions, and therefore subject to uncertainty, hence the expectations operator.⁹ The price of fertilizer, however, is known at the time of purchase. f is fertilizer application, Δy represents the change in yields resulting from fertilizer application. Here, we estimate the change in yields between applying the FISP bundle (50 kg urea + 50kg NPK) relative to applying no fertilizer. Fertilizer application

⁸ Because we match each trial site to three stations, we use the set of years available at each of the three stations per site.

⁹ Lacking data with which to establish the joint distribution of maize prices and the marginal physical product of fertilizer, we assume these are statistically independent, thus $E[\Delta y \cdot p_y] = E[\Delta y] \cdot E[p_y]$.

will be profitable in expectation so long as $E[\Delta\pi] > 0$, which constitutes a necessary condition for fertilizer application.¹⁰

Finally, we correlate the entire set of simulated EBC ratios, by district with 1998 poverty map (NSO 2012) using multiple poverty measures: mean daily household consumption per capita, the Gini index of consumption inequality, the poverty headcount rate (i.e., the percent of the population living below \$1.25 per capita/day in purchasing power parity terms¹¹), the poverty gap, the poverty severity index, maximum education level attained, and the travel time to the nearest market per enumeration area. These estimates were generated using standard poverty mapping methods (CIESEN 2005). The number of observations per district varies between 44 and 3,439.

Results

Maize production function and marginal returns to fertilizer

Using on-farm experimental field trial data collected by Malawi's Maize Productivity Task Force (MPTF) on 1,677 sites in 1995-1996 and again in 1997-1998 on 1,407 sites (with 1,205 overlapping sites) and controlling for soil characteristics, rainfall and temperature, we estimate a generalized quadratic maize production function. The full regression estimation results of the maize production function, equation (1), are reported in column 1 of appendix 4. Because we are interested in the marginal effects of fertilizer, we demean

¹⁰ This is not a sufficient condition because risk aversion, liquidity constraints that force the farmer to borrow funds at a positive interest rate in order to purchase fertilizer, and other factors can still make fertilizer use unattractive even with $E[\Delta\pi] > 0$.

the data both to make the generalized quadratic an exact second-order approximation of the unknown true production function and to make the interpretation of the coefficients more straightforward.

As expected, nitrogen and sulfur each have a statistically significant positive effect on yield that diminishes with the application rate. The interaction of nitrogen with sulfur is also statistically significantly positive, indicating that each is limiting, leading to complementarities in combining the two nutrients. The estimated marginal yield effect of nitrogen fertilizer also varies statistically significantly with weather, increasing (decreasing) with precipitation (high temperatures, reflected in GDD 30+). Likewise, the marginal yield effects of sulfur vary statistically significantly with soil phosphate content and slope. The clear implication is that the marginal returns to fertilizer vary predictably across growing seasons and over space, so that any benefits of Malawi's subsidy program will necessarily be heterogeneous. The key questions are how big those benefits are, how (un)evenly they are spread, and whether that variation is distributionally progressive or regressive. That is, are the expected marginal gains to additional fertilizer application positive and are they positively or negatively correlated with poverty headcount rates?

The coefficient estimates on the other control variables are as one would expect. The regression estimates also indicate that yields in the 1995/1996 season were higher. Independently, GDD 8–30 and rainfall both have a positive, albeit statistically insignificant, effect on yields, while GDD 30+ has a negative and significant effect. Yields were higher with the shorter-stature MH18 hybrid variety and in higher pH soils, since most of Malawi's farmland is moderately to mildly acidic. High levels of *Striga* and termite infestation and steeply sloped sandy soils are associated with lower yields. Given an overall

R^2 of 0.34 with nearly 11,000 observations, the regression does a reasonably good job of explaining variation in maize yields. We have no reason to expect a significant change in the production function over a short time, especially over the course of the field trial sites (1995/1996 and 1997/1998) and FISP (2005–). However, there may be slight differences due to the different seed varieties distributed under FISP (hybrid, OPV) relative to those used in the field experiments (M17, M18). Furthermore, more recent data would more accurately depict current expected returns, as soil quality likely will have changed over time due to the number of years a plot has been cultivated and/or left fallow. Although using these somewhat dated data to measure the production function is not ideal, it is the most accurate feasible estimation of these parameters we are aware of for Malawi at nationwide scale, especially using experimental rather than observational data. Moreover, it is unclear why one might expect any change over time in the biophysical response of essentially-unchanged seed varieties to the same chemical fertilizer blends.

We ran robustness checks on these estimates using both a Hausman-Taylor estimator (model II in Appendix 4), which allows some of the regressors to be correlated with the unobserved individual effect, η_i , and a random effects model estimated only on the balanced panel subset of data observed in both years (model III). The results are generally quite consistent across specifications, especially as regards the central parameters of interest relating to the estimated marginal effects of fertilizer application on maize output. The sign of the estimated effect differs only for the second-order effects of pH where it is negative (as expected) for model I but positive in models II and III.

Based on the estimated maize production function, we compute the expected marginal physical returns to fertilizer following equation (2). We find expected marginal

returns of 25.2 kg maize per kg nitrogen for the FISP bundle when the fertilizer application rate is zero and applied in conjunction with hybrid seeds. The expected marginal returns decrease to 23.2 kg (21.1 kg) maize per kg nitrogen when the fertilizer application rate increases to 10 (20) kg nitrogen, which falls within the upper end of the wide range of maize responses to fertilizer found in the literature, which typically range between 8 kg and 24 kg maize per kg nitrogen applied (Jayne and Rashid 2013), depending in part on the underlying quantity of fertilizer applied at which the marginal products are evaluated.

Profitability of the FISP bundle

Given 2009-2010 maize and fertilizer prices and our estimated maize production function, we find that the fertilizer bundle recommended under Malawi's FISP is almost always and everywhere profitable in expectation, at least when applied with hybrid seeds by farmers comparable to those in the sample. These results are consistent when using both retail and farmer-reported prices, as shown by the probability of profitability of 1 in tables 5A and 5B.

We compare the FISP bundle with fertilizer applications comprised uniquely of urea and NPK of the equivalent value as the FISP bundle, i.e., 97 kg NPK and 103.2 kg urea, the equivalent to 100kg of the FISP bundle in monetary value (tables 5A and 5B). While we find that the EBC ratio of urea is higher than that of NPK and the FISP bundle, if the experimental design had allowed us to control for phosphate, the EBC for NPK might be higher, as we must implicitly put zero value on P since S appears more limiting and the experimental design unfortunately rendered them perfectly collinear. Furthermore, while the application of urea may increase yields in the short term it may lead to the depletion of

other nutrients in the longer term (van de Velde *et al.* 2013). The three last columns of tables 5A and 5B show that the expected mean return of urea, NPK, the FISP bundle and N for the entire set of simulated data are close to the in-sample means (columns 2, 3 and 4).

We examine how the expected probability of profitability and EBC ratios might vary with changing fertilizer and maize prices, which are notoriously volatile.¹² Holding maize retail and farmer-reported prices fixed, we first increase the price of the fertilizer for the treatment bundle by 50%, 100%, 200% and 500% (tables 6A and 6B). The expected profitability of fertilizer application is robust to increases in fertilizer prices up to 200% using retail prices and 100% using farmer-reported maize prices. But fertilizer use becomes widely – but not everywhere – unprofitable with fertilizer price increases of 500%, as occurred between 2004 and 2008. Similarly, we estimate the expected probability of profitability and EBC ratios when maize retail and farmer-reported prices decrease, holding fertilizer prices at 2009-2010 levels. Even with a 50% decrease in the retail (farmer-reported) price of maize, the probability of profitability remains high at 0.998 (0.974) and the EBC ratio decreases only to 2.025 (1.497) (tables 6A and 6B).

We also compare how expected benefits/costs and the probability of expected profitability of fertilizer application vary with changing weather conditions. We compare results estimated for a drought year, 1991, and for a year with favorable rainfall and temperatures, 1984. The likelihood of profitability of the FISP bundle decreases only to 97.3% (97.0%) in a drought year using maize retail (farmer-reported) prices. The expected

¹² For example, international DAP and urea prices increased roughly six-fold from 2004-2008 before retreating sharply by 2009-10 and settling at roughly two to three times the 2004 prices by 2012-13 (<http://www.africafertilizer.org/Data-Centre/Monthly-International-Prices-for-Fertilizers.aspx>).

profitability of fertilizer irrespective of growing conditions is a striking result. EBC ratios are greater than 2.5 in all cases (tables 7A and 7B).

As indicated above, given that we use just two years of data, close together in time, these results assume the production function remains constant. We cannot account for potential change in maize response to fertilizer over time. But the weather observed during these experiments were broadly representative of the period from which we draw data for simulation. The mean GDD 8 – 30 (GDD 30) index for the 1995-1996 growing season was of 56,505 (309.7) and 59,332 (437.0) for the 1997-1998 growing season compared to the mean values of 56,644 (479.8) observed for all other years. Therefore the range of weather variables observed during our period of study – 1995-1996 and 1997-1998 -- fall within the range observed for all other years.

Because the Ministry of Agriculture has retail prices for each of the 23 districts, whereas the IHS data is missing median values for 6 of the 23 districts, we use the retail prices in the subsequent analysis. However, the results do not substantively change since the EBC ratios remain high even under significant fertilizer and maize price changes as described above. Maps of the profitability expressed in expected benefit/cost (EBC) ratio terms offer strong indications as to where the gains from fertilizer use induced by subsidies are concentrated: in the northern region of Karonga and the west of the country (Figure 3). These areas of higher profitability benefit from more favorable weather conditions, higher soil quality and/or higher maize prices.

Poverty

While FISP does appear to favorably affect maize yields and farm profitability, on average, we find that the spatial pattern of those gains is largely uncorrelated with headcount poverty rates, calling into question the extent to which Malawi's fertilizer subsidies are distributionally progressive across space among farmers. The expected gains from increased fertilizer use do not appear concentrated in regions populated by more poor farmers.

Figure 4 shows the correlation coefficients between the expected benefits/costs of a FISP fertilizer ratio and various poverty measures. The mean correlation between FISP EBC and the headcount poverty rate is 0.0309 over the entire data set ($n = 28,751$), statistically significantly different from zero at the one percent level but very small in magnitude. These very slightly positive correlations indicate that regions with higher poverty levels are very weakly associated with higher expected fertilizer returns, making the benefits of fertilizer subsidies essentially spatially neutral in the distribution of gains among farmers. Nevertheless, the values are negative for many districts (Figure 4), indicating that higher (lower) poverty levels are associated with lower (higher) returns in some parts of Malawi. The districts of Balaka and Mchinji display high positive estimated correlations between poverty rates and expected marginal returns to fertilizer, while other districts, such as Ntcheu and Thyolo, exhibit large negative estimate correlations. The results are generally consistent for other poverty measures – such as mean daily household per capita income, poverty gap and education levels – and when uniquely isolating the profitability in 1998, the year for which the poverty map was estimated (Table 8).

Discussion

Our results indicate that the fertilizer bundle distributed under Malawi's FISP – 50 kg NPK (23:21:0+4S) and 50 kg urea – appears profitable in expectation for this large sample of farmers, across years with strikingly different growing conditions, and across sub-regions with markedly different soils and other attributes. Even if fertilizer prices were to rise by as much as 200% or maize prices fall by half, the EBC ratio would still exceed one.

However, our estimated EBC ratios may represent an upper bound for a few reasons. First, while farmers managed the plots on which the maize fertilizer trials were conducted, farmers were not randomly selected and likely had greater-than-average ability. Second, the planting and application of fertilizer followed a clear guidance with the help of FAs so the farming practice used are likely to be superior than average. Furthermore, farmers may have made a greater effort to manage the experimental plots knowing that they were participating in a study and being followed by an extension agent. Such selection or Hawthorne effects, if they exist in these data, would likely bias upwards the estimated productivity effects. Third, land constraints make fallowing uncommon in Malawi. The sites selected had been left fallow for at least two years. This might have made their soils slightly more fertile, with higher organic matter content, than continuously cultivated plots, although any such effects are likely small given the lack of consistent cereals yield gains from traditional fallows of such short duration (Hall et al. 2006). Finally, our results estimate the returns to fertilizer application rates conditional on the use of improved hybrid seeds, which are expected to be higher than fertilizer application used in conjunction with unimproved seed.

As previously mentioned, many past studies estimating marginal physical returns to nitrogen using household survey data suffer from endogeneity since factors unobserved

by the researcher may affect farmers' fertilizer decisions, thereby biasing production function parameter estimates. While these studies attempt to identify the marginal returns using various econometric techniques, e.g., instrumental variables or correlated random effects models, there remain outstanding endogeneity concerns. Observed and unobserved heterogeneity among both farmer attributes (for example, patience, skill) and soil characteristics affect fertilizer profitability (Foltz et al. 2011). For example, Marenya and Barrett (2009a, 2009b) show that fertilizer yield responses vary with soil organic matter content, making fertilizer application less profitable on poorer quality soils, and that farmer fertilizer application behavior responds accordingly. Low quality of fertilizer in the retail markets provides another possible reason of lower returns to fertilizer found in the studies using household survey data. For instance, Bold et al. (2015) find that on average, retail fertilizer contained 31% less nutrient than authentic fertilizer in Uganda. At the other end of the spectrum, there are studies that use data from researcher-managed plots, which tend to report higher returns, ranging between 14 to 50 kg maize per kg nitrogen (Snapp et al. 2014). There is therefore a tradeoff between well-identified estimates versus estimates measured from a representative population. Our data uniquely fall somewhere in between both types of study, using nationally representative field trial sites conducted on fallow land and managed by smallholder farmers with extension agents' supervision. Therefore, our results should be interpreted as an upper bound on farmers' returns to nitrogen use or, alternatively, the expected returns among a large sample of what may be some of the nation's best farmers.

The high expected profitability of fertilizer we estimate begets understanding the relatively low and variable observed fertilizer adoption rates among smallholder farmers

in Africa. There are several possible reasons why farmers may not apply fertilizers despite high expected payoffs. First, the costs associated with accessing fertilizers and complementary agricultural inputs and practices, such as improved seeds, irrigation, frequent weeding, that increase the returns to fertilizer, may be excessive (Foltz et al. 2011). Indeed, Suri (2011), explains the low adoption of a technology, improved seeds, by the heterogeneous benefits and costs of the technology, rendering it profitable only for a subset of the population, those who adopt it. Second, soils are heterogeneous and thus fertilizer returns will not be equal across farmers. Given limited access to soil testing and labs, farmers do not know what fertilizers they should apply to their plots, given their underlying soil quality, nor necessarily how to apply it (Marenya and Barrett 2009a, 2009b, Duflo et al. 2008). Third, Duflo et al. (2011) hypothesize that behavioral biases of procrastination helps explain the low adoption of fertilizer. They find that offering farmers small, time-limited discounts on fertilizer purchases could yield higher yields than heavy subsidies or laissez-faire policies. Fourth, low and uncertain quality of retail fertilizer may result in lower adoption of fertilizer than the optimal level (Bold et al. 2015). Finally, highly volatile fertilizer and crop prices cause the profitability of fertilizer application to vary with prices over space and time and may induce risk-averse farmers to forego fertilizer use (Dercon and Christiaensen 2011; Morris et al. 2007). Likely, a combination of these reasons helps explain why we observe such low adoption of fertilizers. However, while adoption is low, recent studies show an increase in fertilizer use in Malawi, suggesting that the subsidy program has successfully taught farmers how to profitably apply fertilizers (Sheahan and Barrett 2014).

Our results also show that the expected benefits of fertilizer use vary significantly across space, and not always in ways that concentrate in the poorest regions the gains to farmers from increased fertilizer use. Fertilizer subsidy programs are often motivated by governments' objective to reduce poverty and food insecurity, especially among smallholder farmers. But if poorer farmers live in areas where growing conditions are less favorable or cultivate soils that do not respond as well to fertilizers as do those of better-off farmers, subsidies might not be a distributionally progressive instrument for poverty reduction, at least not within the subpopulation of farmers (Kelly et al. 2011, Marenya and Barrett 2009a). Furthermore, there may be tradeoffs between targeting poor farmers to generate direct income gains among that sub-population, versus targeting better-off farmers who typically produce greater yields and might thereby generate greater aggregate supply gains that may generate agricultural wage increases or price reductions that benefit poor workers and consumers, respectively, effects we cannot take into account. Ricker-Gilbert et al. (2013), however, find that doubling the size of Malawi's subsidy program only reduces maize prices marginally, by 1.2-2.5% on average.

We find a very mildly positive overall correlation between location-specific estimated poverty headcount rates and expected returns to fertilizer, leaving it unclear whether fertilizer subsidies really are pro-poor and distributionally progressive among growers. Geographic targeting of poor regions with high expected marginal returns could ensure that a government's subsidy program is pro-poor (Lang et al. 2012), not only concentrating gains in the poorest areas but also prospectively reducing the potential crowding out effect of fertilizer subsidies on commercial input markets (Jayne et al. 2013, Ricker-Gilbert et al. 2011). Furthermore, targeting the poor who otherwise might not

purchase their own fertilizer would give them the opportunity to learn about the benefits of fertilizer application (e.g., which fertilizer to apply and how/when to apply it), increasing their likelihood of continued fertilizer use.

The sustainability of fertilizer subsidy programs remains precarious due to high associated costs and heavy logistical demands. Alternative programs could perhaps help alleviate poverty even more effectively, e.g., by constructing roads, investing in agricultural research and design and education programs (Jayne et al. 2013). Targeting regions with soils that respond especially strongly to fertilizer application and that are populated by the poorest farmers can help increase the efficiency of the program and reduce costs while more effectively promoting its goals of poverty reduction and increasing food security. However, given the high expected profitability of fertilizer used in conjunction with improved seeds, still more work is needed to better understand reasons for low observed fertilizer use and whether a fertilizer subsidy is the optimal tool to address these constraints.

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Figures

Malawi - Districts and Climate Stations

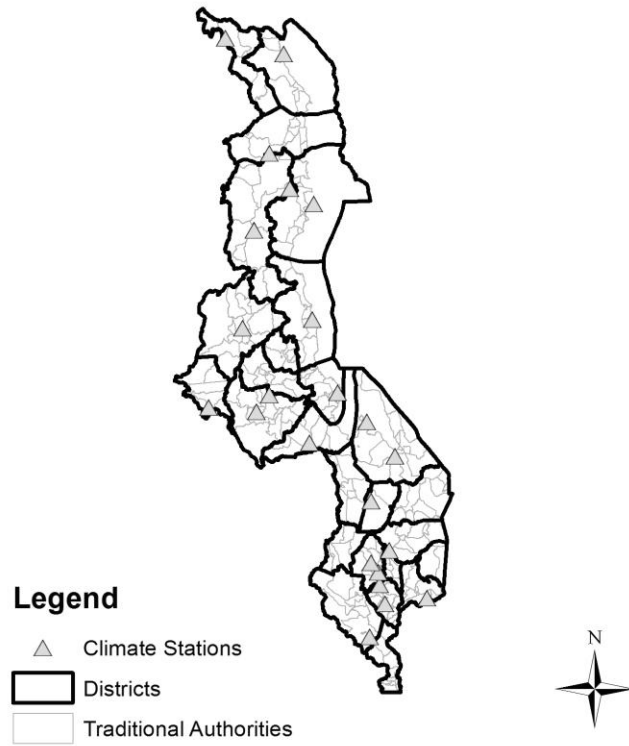


Figure 1. Meteorological stations

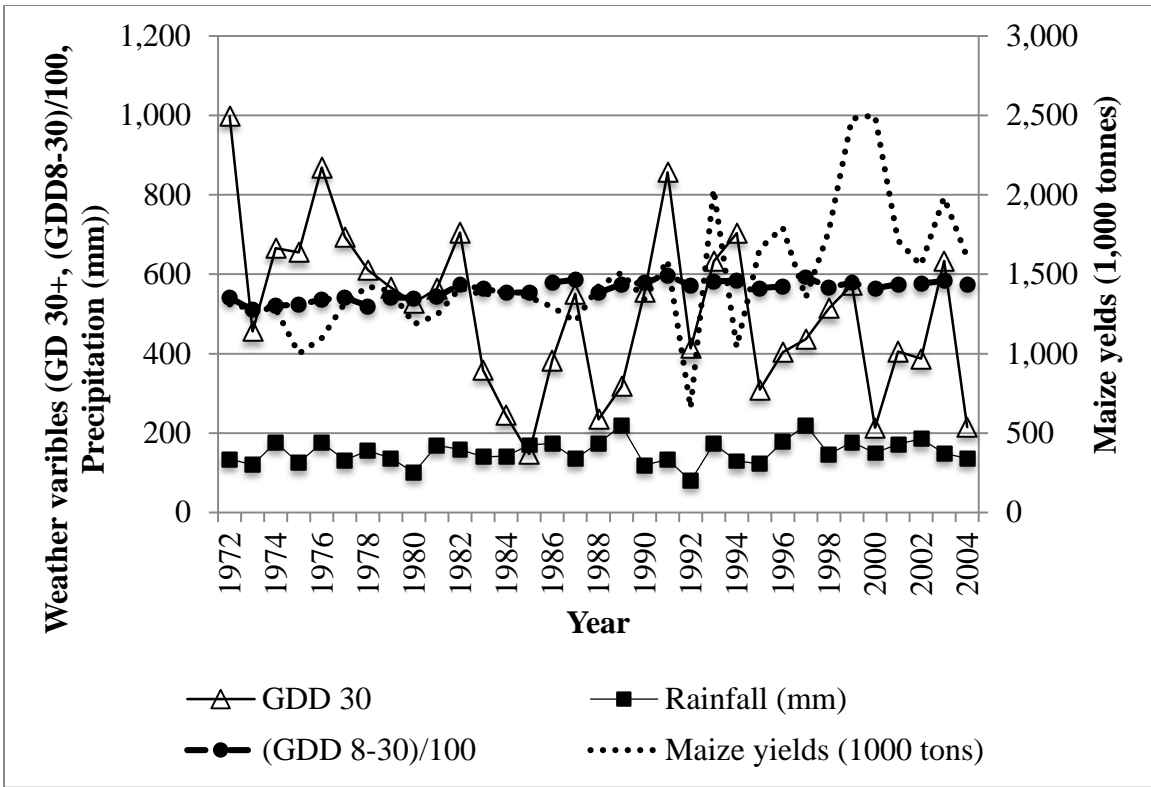


Figure 2. Weather and maize yields, 1972-2004

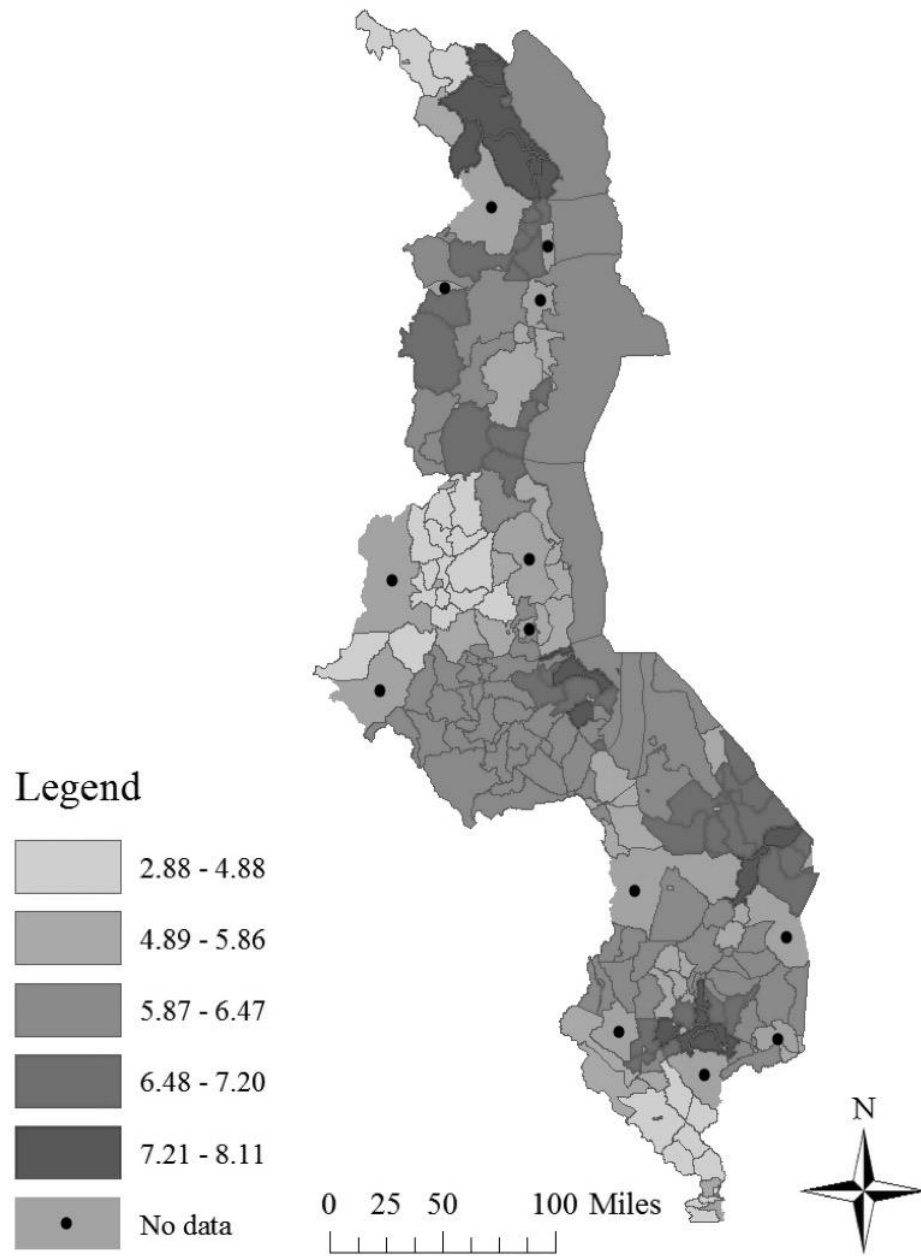


Figure 3. Expected benefit/cost ratio of FISP bundle

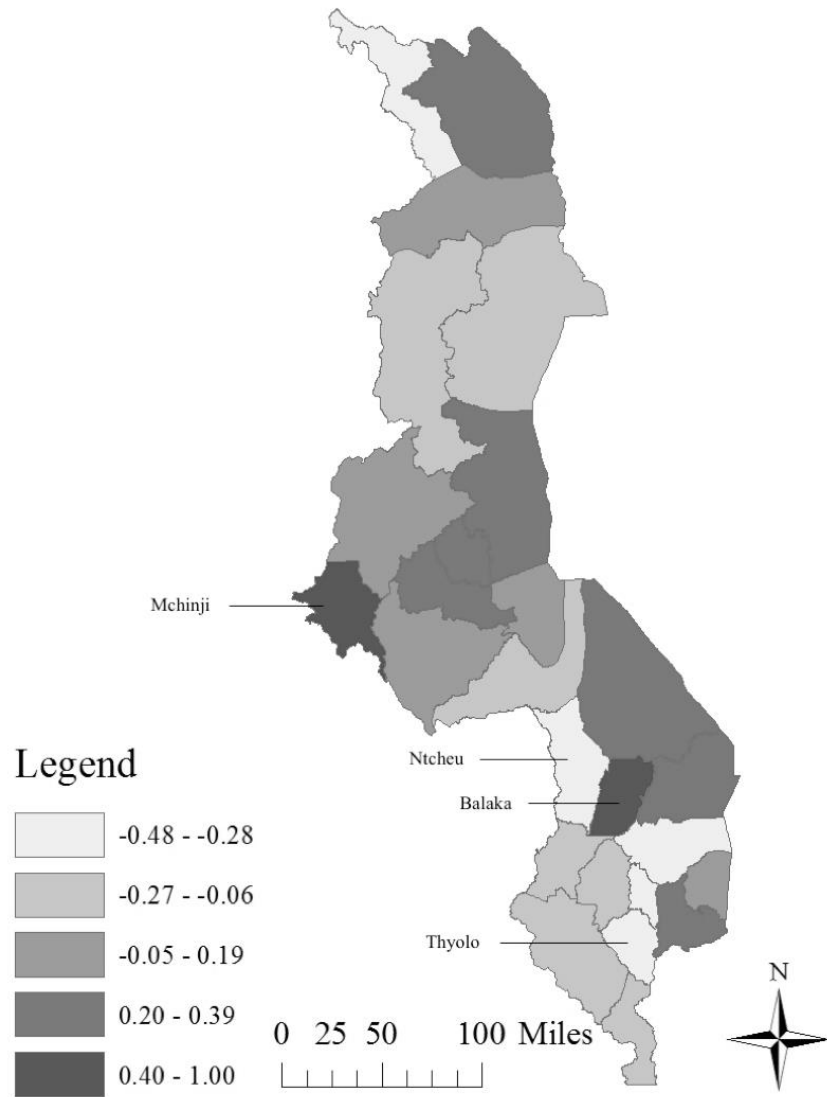


Figure 4. Correlation coefficients between poverty headcount rates & FISIP expected benefit/cost ratio

Tables

	Nutrients (kg/ha)			Fertilizer		Mean Yields (kg/ha)	
	<i>N</i>	<i>P</i>	<i>S</i>	<i>Basal (50 kg bags/ha)</i>	<i>Top dressing (50 kg bags/ha)</i>	<i>1995-1996 Trial</i>	<i>1997-1998 Trial</i>
1	0	0	0	0	0	1,410	1,124
2	35	0	0	0	1.5 Urea	2,183	-
3	35	10	2	1 x 23:21:0+4S	1 Urea	2,358	1,997
4	69	21	4	2 x 23:21:0+4S	2 Urea	2,882	2,523
5	92	21	4	2 x 23:21:0+4S	3 Urea	3,147	2,915
6	96	40	0	1.75 DAP ⁺	3.5 Urea	2,947	-

⁺ DAP: di-ammonium phosphate

Table 1. Treatments. Note: Differences in mean yields between all treatment combinations are statistically significant at the 1 % level except for treatments 2 and 3, which are not statistically significantly different.

	<u>1995-1996</u>	<u>1997-1998</u>
Striga infested	27.80%	21.00%
High striga infestation	6.40%	6.70%
Termite infested	39.80%	38.80%
GDD 8-30C	57207	58180
GDD 30+	261	421
Rainfall (mm)	182	163

Table 2. Summary statistics, striga and termite infestation

	<u>Mean</u>	<u>Std. Dev.</u>
Maize variety (D, 1 = MH18)	0.666	0.472
Terrain is flat (D)	0.476	0.5
Terrain is steep (D)	0.026	0.16
Soil is sandy (D)	0.053	0.225
Soil is sandy/clay (D)	0.021	0.144
pH	5.881	0.41
Soil has high cation exchange capacity	0.253	0.435
Soil has high N content	0.021	0.142
Soil has high P content	0.061	0.239
Soil has high K content	0.881	0.324

Table 3. Summary statistics, soil characteristics by trial site (from soil map, n=1,891)

	<u>Mean</u>	<u>Std. dev.</u>	<u>Min.</u>	<u>Max.</u>
Retail maize price	46.39	6.68	32.67	63.28
Farmgate local maize price	36.52	10.71	24.00	59.17
Farmgate hybrid maize price	34.54	8.71	25.00	61.11
Transport cost local maize	0.52	0.84	0.00	2.50
Transport cost hybrid maize	0.23	0.45	0.00	1.86
CAN price	103.03	23.74	30.00	157.33
DAP price	106.19	10.89	90.00	153.00
NPK price	102.32	8.45	80.00	120.00
UREA price	97.52	5.28	89.47	110.00

Table 4. Summary statistics prices (n = 23 districts) (MK/kg)

Expected B/C	In-sample			Full weather distribution		
	<u>FISP</u>	<u>NPK</u>	<u>UREA</u>	<u>FISP</u>	<u>NPK</u>	<u>UREA</u>
<i>Mean</i>	4.120	2.154	4.384	4.051	2.125	4.259
<i>Median</i>	4.140	2.156	4.400	4.110	2.156	4.342
<i>Std. Dev.</i>	0.584	0.471	0.628	0.702	0.519	0.873
Prob. Of Profitability	1.000	0.981	1.000	0.998	0.962	0.990
<i>N</i>	2,763			34,885		

Table 5A. Expected benefit/cost (EBC) ratios using retail maize prices and expected probability of profitability for 97 kg/ha NPK (23:21:0+4S), the FISP bundle (50kg/ha urea and 50kg/ha NPK) and 103.2 kg/ha urea.

Expected B/C	In-sample			Full weather distribution		
	<u>FISP</u>	<u>NPK</u>	<u>UREA</u>	<u>FISP</u>	<u>NPK</u>	<u>UREA</u>
<i>Mean</i>	3.082	1.591	3.296	2.994	1.550	3.146
<i>Median</i>	3.004	1.604	3.180	2.879	1.604	3.096
<i>Std. Dev.</i>	0.744	0.454	0.847	0.774	0.480	0.965
Prob. Of Profitability	1.000	0.960	1.000	0.997	0.942	0.989
<i>N</i>	2,763			34,885		

Table 5B. Expected benefit/cost (EBC) ratios using farmer-reported maize prices and expected probability of profitability for 97 kg/ha NPK (23:21:0+4S), the FISP bundle (50kg/ha urea and 50kg/ha NPK) and 103.2 kg/ha urea.

	FISP EB/C			FISP Prob. Of
	<i>Mean</i>	<i>Median</i>	<i>Std. Dev.</i>	Profitability
Fertilizer price increase:				<i>Mean</i>
50%	2.701	2.740	0.468	0.994
100%	2.025	2.055	0.351	0.988
200%	1.350	1.370	0.234	0.936
500%	0.675	0.685	0.117	0.123
Maize price decrease:				
25%	3.038	3.082	0.527	0.996
50%	2.025	2.055	0.351	0.988

Table 6A. Expected probability of profitability and expected benefit to cost ratio with 50-500% fertilizer price increases and 25-50% maize price decreases from 2009-2010 prices (n = 34,885).

	FISP EB/C			FISP Prob. Of
	<i>Mean</i>	<i>Median</i>	<i>Std. Dev.</i>	Profitability
Fertilizer price increase:				<i>Mean</i>
50%	1.996	1.919	0.516	0.992
100%	1.497	1.439	0.387	0.974
200%	0.998	0.960	0.258	0.691
500%	0.499	0.480	0.129	0.432
Maize price decrease:				
25%	2.246	2.159	0.580	0.994
50%	1.497	1.439	0.387	0.974

Table 6B. Expected probability of profitability and expected benefit to cost ratio with 50-500% fertilizer price increases and 25-50% maize farmer-reported price decreases from 2009-2010 prices (n = 34,885).

	1984			1991		
	<u>FISP</u>	<u>NPK</u>	<u>UREA</u>	<u>FISP</u>	<u>NPK</u>	<u>UREA</u>
Expected B/C						
<i>Mean</i>	4.183	2.185	4.474	3.774	2.022	3.816
<i>Median</i>	4.145	2.165	4.411	3.947	2.104	4.041
<i>Std. Dev.</i>	0.619	0.481	0.676	0.950	0.593	1.347
Prob. Of Profitability						
<i>Mean</i>	1.000	0.977	1.000	0.973	0.936	0.955
<i>n</i>		1309			1301	

Table 7A. Expected probability of profitability and expected benefit/cost for a drought year (1991 conditions) and a favorable growing year for maize (1984 conditions) (using maize retailer prices)

	1984			1991		
	<u>FISP</u>	<u>NPK</u>	<u>UREA</u>	<u>FISP</u>	<u>NPK</u>	<u>UREA</u>
Expected B/C						
<i>Mean</i>	3.113	1.598	3.354	2.729	1.446	2.731
<i>Median</i>	2.959	1.623	3.225	2.749	1.508	2.879
<i>Std. Dev.</i>	0.717	0.445	0.808	1.013	0.561	1.420
Prob. Of Profitability						
<i>Mean</i>	1.000	0.960	1.000	0.970	0.915	0.953
<i>n</i>		1309			1301	

Table 7B. Expected probability of profitability and expected benefit/cost for a drought year (1991 conditions) and a favorable growing year for maize (1984 conditions) (using farmer-reported maize prices)

	FISP bundle		NPK		Urea	
	<u>All years</u>	<u>1998</u>	<u>All years</u>	<u>1998</u>	<u>All years</u>	<u>1998</u>
<i>Hh</i>						
<i>consumption</i>	0.0043	0.0271	0.0003	0.0125	0.0068	0.0394
<i>Gini index</i>	0.0706***	0.1686***	0.0862***	0.1324***	0.0397***	0.1627***
<i>Poverty</i>						
<i>headcount</i>	0.0309***	-0.0348	0.0835***	0.0565*	0.0149**	-0.0853***
<i>Poverty gap</i>	0.0324***	-0.0031	0.0958***	0.0900***	0.0036	-0.0644**
<i>Poverty</i>						
<i>severity</i>						
<i>index</i>	0.0284***	0.0099	0.0964***	0.1019***	-0.0057	-0.0541*
<i>Travel time</i>						
<i>to nearest</i>						
<i>market</i>						
<i>center</i>	-0.0097*	-0.0465	-0.0955***	-0.1072***	0.0375***	-0.0111
<i>Max</i>						
<i>education</i>	0.0974***	0.1165***	0.1097***	0.0964***	0.1288***	0.1967***
<i>n</i>	32,692	1,217	32,692	1,217	32,692	1,217

Table 8. Correlation coefficients between poverty indices and the expected benefit/cost ratio for fertilizer bundles. ***p<0.01, ** p<0.05, * p<0.10.

Appendices

Appendix 1. Difference in site characteristics between sites observed in both years versus sites observed once

	One year		Both years		Difference	Statistical Significance
	Mean	Std Dev.	Mean	Std Dev.		
MH18	0.692	0.462	0.645	0.478	0.047	***
Striga infestation	0.239	0.427	0.255	0.436	-0.016	*
High striga infestation	0.074	0.262	0.062	0.242	0.012	**
Termite	0.387	0.487	0.401	0.490	-0.014	
Rainfall (mm)	178.0	62.2	173.5	63.0	4.486	***
GDD (8-30C)	57795	7471	57477	7971	318	**
GDD (30+)	319.3	387.2	320.1	453.2	-0.838	
Yields (ha)	2413.4	1190.8	2338.9	1174.8	74.446	
Yield (ha, log)	7.639	0.608	7.596	0.637	0.043	***
Nitrogen	53.107	34.535	52.300	34.626	0.807	***
Phosphate	14.74	12.89	14.40	12.21	0.342	
Sulfur	1.878	1.799	2.000	1.789	-0.122	***
Slope is flat	0.469	0.499	0.480	0.500	-0.011	
Slope is steep	0.030	0.169	0.024	0.153	0.006	**
Clay soil	0.006	0.077	0.015	0.123	-0.009	***
Sandy soil	0.048	0.214	0.058	0.234	-0.010	**
Loamy soil	0.005	0.073	0.005	0.069	0.001	
Sandy clay soil	0.026	0.158	0.019	0.137	0.007	**
pH	5.882	0.375	5.882	0.437	0.000	
CEC is medium	0.235	0.424	0.266	0.442	-0.031	***
Medium N	0.018	0.134	0.022	0.146	-0.004	
Medium P	0.059	0.236	0.059	0.236	0.000	
Medium K	0.896	0.305	0.868	0.338	0.028	***

Appendix 2. Construction of the weather variables, following Lobell *et al.* (2011)

First, we calculate the number of growing degree days (GDD) between 8 and 30 degrees Celsius between the reported planting and harvest dates to predict maize development rates. Second, we calculate the number of growing degree days above 30 degrees Celsius to control for high temperatures that might harm maize growth. Finally, we calculate the total precipitation for the 21-day period centered on the silking date, to control for anthesis -- the period when maize flowers and is particularly susceptible to drought. Growing degree days were calculated at each field trial site as:

$$GDD_{base,opt} = \sum_{t=1}^N DD_t \quad DD = \begin{cases} 0 & \text{if } T_t < T_{base} \\ T - T_{base} & \text{if } T_{base} \leq T_t \leq T_{opt} \\ T_{opt} - T_{base} & \text{if } T_t > T_{opt} \end{cases}$$

where t is an hour within the growing season. T_t is the average temperature during the hour and is determined by interpolating a sine curve between the minimum and maximum temperatures in a day. N is the number of hours between planting and harvesting. Therefore, the $GDD_{8,30}$ corresponds to $T_{base} = 8$ degrees Celsius and $T_{opt} = 30$ degrees C and GDD_{30+} corresponds to $T_{base} = 30$ degrees C and $T_{opt} = \text{infinity}$.

Precipitation is controlled for by summing the total precipitation 10 days before and 10 days after silking, controlling for anthesis, the period of time during which a flower is open and functional and most susceptible to drought.

Lobell D, Manziger M, Magorokosho C, Vivek B (2011) Nonlinear heat effects of African maize as evidenced by historical yield trials. *Nature Climate Change* 1: 42-45.

Appendix 3. Farmer-reported versus market maize prices

	Farmer-reported prices				Retail prices
	Median local maize price (MK/kg)	Mean transport cost local maize (MK/kg)	Median hybrid maize price (MK/kg)	Mean transport cost hybrid maize (MK/kg)	Maize price (MK/kg)
Balaka	50.00	1.00	40.00	0.00	44.65
Bolero					51.63
Bvumbwe					48.73
Chichiri	40.00	0.11	31.00	0.33	47.16
Chileka	34.00	0.00	40.00	0.00	40.03
Chitedze	30.00	1.25	35.00	1.86	44.07
Chitipa	59.04	0.46	44.44	0.37	38.12
Dedza	30.00	0.00	32.00	0.20	41.38
Kia					44.13
Karonga	59.17	0.00	61.11	0.00	63.28
Kasungu	24.00	0.00	30.00	0.15	32.67
Makoka					44.13
Mangochi	30.00	2.50	30.00	0.00	55.35
Mimosa					44.13
Monkey Bay	30.00	2.50	30.00	0.00	47.23
Mzimba	24.17	0.53	25.26	0.00	48.38
Mzuzu	35.00	0.00			37.35
Ngabu	34.00	0.00	40.00	0.00	45.66
NkhataBay	29.00	0.00	25.00	0.34	53.01
Nkhota Kota	43.89	0.00	33.33	0.00	42.22
Salima	32.50	0.50	30.00	0.37	53.83
Thyolo	36.00	0.00	30.00	0.22	47.85
Tembwe			30.00	0.00	52.02

Appendix 4. Quadratic production function estimates

Notes: The dependent variable is yield (kg/ha); model I uses a random effects specification, model II uses a Hausman-Taylor specification, model III uses a random effects specification on the subset of sites with data from both seasons; * $p < 0.05$, ** $p < 0.01$; we demean the data both to make the generalized quadratic an exact second-order approximation of the unknown true production function at the sample mean and to make the interpretation of the coefficients more straightforward

	I. RE	II. H-T	III. RE (balanced panel only)	IV. Treatment dummies
Year (D, 1 = 95-96)	324.869***	335.770***	332.020***	325.25***
	(41.763)	(19.001)	(44.18)	(41.741)
Nitrogen (N) Fertilizer	16.968***	16.963***	17.021***	
	(0.372)	(0.505)	(0.45)	
Sulphur (S) Fertilizer	25.294***	25.488***	28.197***	
	(6.543)	(9.51)	(7.911)	
Growing degree days (8-30C)	0.004	0.009**	0.005	0.003
	(0.004)	(0.002)	(0.004)	(0.004)
Growing degree days (+30C)	-0.213***	-0.246***	-0.219***	-0.203***
	(0.067)	(0.051)	(0.071)	(0.068)
Precipitation	0.198	0.175	0.307	0.209

	(0.387)	(0.174)	(0.408)	(0.387)
pH	280.531***	281.391***	301.756***	276.573***
	(61.358)	(108.381)	(66.65)	(61.356)
Striga infested (D)	-117.528*	-86.966***	-111.992*	-119.736**
	(60.723)	(32.854)	(64.861)	(60.874)
Striga infested (high) (D)	-553.691***	-520.318***	-554.825***	-553.781***
	(94.458)	(53.242)	(101.714)	(94.841)
Termite infested (D)	-250.248***	-296.476***	-268.971***	-249.066***
	(51.31)	(25.625)	(54.706)	(51.359)
Maize variety (D, 1 = MH18)	248.376***	537.560***	237.786***	245.65***
	(53.471)	(123.561)	(60.106)	(53.390)
Terrain is flat (D)	96.284**	210.791	140.251***	93.743**
	(43.059)	(229.628)	(49.034)	(43.123)
Terrain is steep (D)	-328.210***	768.841	-255.978*	-333.197***
	(112.027)	(584.683)	(135.511)	(111.817)
Soil is sandy	-305.931***	-960.572**	-316.540***	-305.254***
	(93.814)	(479.204)	(104.356)	(93.699)
Soil is sandy/clay	-491.878***	-933.141	-520.000***	-490.025***
	(156.995)	(784.6)	(187.215)	(157.324)
Squared: N fertilizer	-0.103***	-0.103***	-0.096***	
	(0.008)	(0.011)	(0.009)	
Squared: S fertilizer	-35.856***	-35.934***	-35.773***	
	(3.968)	(6.236)	(4.589)	
Squared: precipitation	0	0.002	0.001	0

	(0.004)	(0.002)	(0.004)	(0.004)
Squared: pH	-12.381	-1.359	26.555	-17.564
	(58.593)	(115.669)	(61.681)	(58.62)
Interaction: GDD 8-30, pH	0.019**	0.018***	0.018**	0.018**
	(0.008)	(0.004)	(0.009)	(0.008)
Interaction: GDD 30+, pH	-0.017	-0.021	-0.004	-0.008
	(0.086)	(0.048)	(0.089)	(0.086)
Interaction: Precipitation, S	-0.051	-0.06	-0.007	
	(0.092)	(0.083)	(0.12)	
Interaction: Precipitation, pH	-0.562	-0.478	-0.484	-0.59
	(0.998)	(0.408)	(1.048)	(1.006)
Interaction: Precipitation, N	0.009**	0.009**	0.011*	
	(0.005)	(0.004)	(0.006)	
Interaction: N, S Fertilizers	1.260***	1.263***	1.303***	
	(0.197)	(0.282)	(0.237)	
Interaction: N, pH	0.464	0.465	0.544	
	(0.564)	(0.557)	(0.666)	
Interaction: pH, S	-4.119	-4.138	-3.96	
	(12.186)	(11.775)	(14.759)	
Interaction: GDD 30+, S	0.01	0.014	0.008	

	(0.015)	(0.015)	(0.019)	
Interaction: GDD 30+, N	-0.004***	-0.004***	-0.004***	
	(0.001)	(0.001)	(0.001)	
Interaction: S, Flat terrain	-20.247**	-20.025***	-28.733***	
	(8.479)	(7.73)	(10.374)	
Interaction: S, Steep terrain	-47.847***	-49.589**	-62.948**	
	(18.549)	(22.473)	(24.487)	
Interaction: S, Sandy soil	-30.192*	-29.464*	-47.270**	
	(16.625)	(15.733)	(20.092)	
Interaction: S, Sandy/Clay soil	38.9	38.693	24.974	
	(23.982)	(25.579)	(30.427)	
Interaction: S, High CEC	-10.723	-10.393	-14.103	
	(10.296)	(9.499)	(12.82)	
Interaction: S, High N	-19.246	-20.367	-10.227	
	(22.805)	(23.305)	(29.127)	
Interaction: S, High P	-46.513***	-47.623***	-58.273***	
	(16.571)	(14.983)	(20.632)	
Interaction: S, High K	-0.776	-1.629	-9.749	

	(13.275)	(12.04)	(15.697)	
Treatment: 96N:40P:0S				1479.832***
				(23.659)
Treatment: 35N:0P:0S				762.59***
				(18.255)
Treatment: 35N:10P:2S				903.761***
				(14.228)
Treatment: 69N:21P:4S				1426.976***
				(17.197)
Treatment: 92N:21P:4S				1744.425***
				(19.993)
Interaction: GDD 8- 30, 96N:40P:0S				0.001
				(0.004)
Interaction: GDD 30+, 96N:40P:0S				-0.406***
				(0.083)
Interaction: Precipitation, 96N:40P:0S				0.932
				(0.487)

Interaction: pH, 96N:40P:0S				47.782
				(60.276)
Interaction: GDD 8- 30, 35N:0P:0S				-0.009***
				(0.003)
Interaction: GDD 30+, 35N:0P:0S				-0.04
				(0.069)
Interaction: GDD Precipitation, 35N:0P:0S				0.001
				(0.387)
Interaction: pH, 35N:0P:0S				47.787
				(50.336)
Interaction: GDD 8- 30, 35N:10P:2S				0.001
				(0.002)
Interaction: GDD 30+, 35N:10P:2S				-0.163***
				(0.030)
Interaction: Precipitation, 35N:10P:2S				0.262
				(0.207)

Interaction: pH, 35N:10P:2S				25.424
				-36.128
Interaction: GDD 8- 30, 69N:21P:4S				0.005**
				(0.002)
Interaction: GDD 30+, 69N:21P:4S				-0.273***
				(0.037)
Interaction: Precipitation, 69N:21P:4S				0.37
				(0.251)
Interaction: pH, 69N:21P:4S				-12.619
				(43.691)
Interaction: GDD 8- 30, 92N:21P:4S				0.006**
				(0.003)
Interaction: GDD 30+, 92N:21P:4S				-0.369***
				(0.042)
Interaction: Precipitation, 92N:21P:4S				0.498
				(0.3)

Interaction: pH, 92N:21P:4S				36.305
				(49.953)
Constant	220.285***	208.943***	173.224***	28.508
	-30.431	-38.303	-34.734	-27.3
Within R2	0.52	.	0.49	0.52
Between R2	0.1	.	0.12	0.1
Overall R2	0.34	.	0.35	0.34
<i>N</i>	10992	10992	8000	10992

Appendix 5. Estimated average partial effects

	dy/dx
Year (D, 1 = 95,96)	324.87*** 41.76
Nitrogen (N) fertilizer	17.00*** 0.38
Sulphur (S) Fertilizer	22.66*** 6.64
Growing degree days (8-30C)	0.00 0.00
Growing degree days (+30C)	-0.21*** 0.07
Precipitation	0.20 0.38
pH	279.47*** 61.01
Striga infested (D)	-117.53* 60.72
Striga infested (high) (D)	-553.69*** 94.46
Termite infested (D)	-250.25*** 51.31
Maize variety (D, 1 = MH18)	248.38*** 53.47
Terrain is flat (D)	95.77** 43.09
Terrain is steep (D)	-329.43*** 112.06
Soil is sandy	-306.70*** 93.79
Soil is sandy/clay	-490.88*** 157.21

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$