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Climate change, chemical fertilisers and sustainable development – panel evidence from Tanzanian Maize farmers

by

Christiane Heisse & Risa Morimoto

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Department of Economics
SOAS University of London
Thornhaugh Street, Russell Square, London WC1H 0XG, UK
Phone: + 44 (0)20 7898 4730
Fax: 020 7898 4759
E-mail: economics@soas.ac.uk
http://www.soas.ac.uk/economics/

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Climate change, chemical fertilisers, and sustainable development – panel evidence from Tanzanian Maize farmers

Heisse, C & Morimoto, R*

Abstract

We study the impact of rainfall risk on fertiliser use by Tanzanian maize farmers using newly available spatially disaggregated agronomic survey data on Tanzanian maize producers. We show that fertiliser use is highly sensitive to rainfall risks. Our discussion embeds these findings into the wider debate around environmental sustainability and mineral fertilisers, thus relating directly to the country's government efforts of climate mainstreaming into their (agricultural) policies. We conclude that chemical fertilisers are useful for agricultural productivity growth but that they should be used to supplement more economically and environmentally sustainable practices.

Keywords: Climate change; fertilisers; sustainable development; Tanzania; Maize farmers; panel analysis.

JEL classification: Q10, Q15, Q56, R15, R28.

*SOAS University of London. Address for correspondence: Department of Economics, SOAS University of London. Russell Square, London WC1H 0XG, UK. Tel: +44 207 898 4730. Email: rm36@soas.ac.uk

Introduction

Maize is Tanzania's main staple crop that is characterised by low agricultural productivity growth. Agronomists associate this with poor soil quality and the low uptake of productivity-enhancing technologies like the application of chemical fertiliser (Morris et al., 2007). Anthropogenic climate change poses a growing threat to Tanzanian smallholder maize farmers, most of whom practice rain-fed agriculture (Luhunga, 2017). This is because anthropogenic climate change, among other things, increases rainfall variability, the frequency of droughts, and is expected to cause significant shifts in the global climatic suitability to maize production away from tropical regions (Ramirez-Cabral et al., 2017).

There is a dual connection between droughts and fertilisers. First, increased rainfall risk makes mineral fertilisers a less viable choice of input for farmers. On the one hand, as droughts reduce the income of rural populations, it will reduce their ability to purchase fertilisers (Alem et al., 2010; Dercon and Christiaensen, 2011). On the other hand, if fertilisers are applied but rainfall is insufficient, the excess Nitrogen (N) can 'burn' the seed and therefore reduce the yield compared to if no fertiliser had been applied (Nyssen et al., 2017; Waithaka et al., 2007). Second, fertilisers are produced from fossil fuels and transported long distances to remote rural locations again using fossil fuels. Therefore, one might argue that they themselves are inherently unsustainable.

Although making agriculture more resilient and productive is crucial for climate change adaptation, the negative externalities resulting from fertiliser production, distribution and use beg the question if promoting fertiliser use for a 'Green Revolution' is indeed a sustainable way forward for developing countries like Tanzania.

In light of this background we study the impact of rainfall risk on fertiliser use by Tanzanian maize farmers using newly available spatially disaggregated agronomic survey data on Tanzanian maize producers. We show that fertiliser use is highly sensitive to rainfall risks. Our discussion embeds these findings into the wider debate around environmental sustainability and mineral fertilisers, thus relating directly to the country's government efforts of climate mainstreaming into their (agricultural) policies.[1] We conclude that chemical fertilisers are useful for agricultural productivity growth but that they should be used to supplement more economically and environmentally sustainable practices.

The rest of the paper is organised as follows: section 2 reviews the empirical literature on what drives fertiliser use in Sub-saharan Africa (SSA), including but not limited to rainfall.[2] Section 3 outlines our methodology, including case study description, data description and panel analysis. Section 4 presents empirical results, followed by a discussion and conclusion in section 5.

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[1] Climate change mainstreaming means that climate change is included in government and development policy making as an overarching theme, rather than being considered only in separate initiatives. Due its weak and broad definition mainstreaming initiatives often face implementation problems (Oates et al., 2011).

[2] Note that fertiliser use (if and how much is applied) is conceptually different from fertiliser adoption (the choice to start using fertiliser, or to (dis-)continue it) and that its analysis requires different statistical techniques. This literature review pertains to both.

Literature review

According to World Bank economists Morris et al. (2007, p. 18), there is "an escalating soil fertility crisis in Africa", driven by decades of soil-degrading agricultural practices like reducing fallow periods, and deforestation to access new farmlands.[3] These led to soil-mining, which happens when nitrogen (N), phosphorus (P) and potassium (K) are removed by crops as they grow, and not replenished through fertilisation (organic or inorganic) and fallow. Soil mining decreases ecosystem resilience to pests and diseases, reduces soil productivity, and can drive further extensification. Morris et al. (2007, p. 18) further argue that low rates of technology adoption are making the problem worse: "low fertiliser use in Africa is part of a wider problem of soil degradation. African soils present inherent difficulties for agriculture [...] and land-use practices during the past several decades have exacerbated those difficulties". Mineral fertilisers boost plant growth by supplying N to the plants at crucial stages in the cropping cycle. They were a key technological component of the green revolution (GR) together with improved seed varieties and intensive irrigation (Morris et al., 2007; Smil, 1991). Though application rates of chemical fertiliser grew at similar rates in SSA and Asia initially, efforts to achieve a GR in SSA were toppled by neoliberal development policies.

The adoption of production technologies depends on availability, accessibility and affordability of the technology. Our review of the literature shows that for mineral fertilisers in SSA, the main underlying drivers are income and profitability, human and social capital, and environmental factors.

First, compared to other inputs to smallholder farming such as rain or unpaid household labour, chemical fertilisers have to be purchased in the market, and their usage is therefore limited by financial resource constraints (Kaliba et al., 2000; Stahley et al., 2012; Waithaka et al., 2007). A study of survey data from over 1000 Tanzanian maize farmers finds that production technologies which require little cash are more widely adopted than costly technologies such as fertiliser and improved seed, which need to bought every year, and that farmers are more likely to apply fertiliser where credit access is better (Kaliba et al., 1998, 2000). Research from Kenya confirms this, finding that fertiliser usage among Kenyan smallholders increases with scale economies for farmers that have a larger farm and higher income (Nambiro and Okoth, 2013; Waithaka et al., 2007). Mineral fertilisers are more widely applied by farmers for cash crops than for food crops, reinforcing the notion that they are a scarce and costly input (Nambiro and Okoth, 2013; Stahley et al., 2012; Waithaka et al., 2007).

According to Liverpool-Tasie et al. (2017, p. 41), existing literature is limited in "the belief that fertiliser use is too low is predicated on the assumption that it is profitable to use higher rates than is currently the case". Profitability depends on both agronomics and economics, that is, the yield response of fertiliser application as well as the relative prices of inputs,

[3] There is a debate about why this has happened. Development economists identified population pressures as the main reason, while some agronomist argue it has to do with technological adaptation in new settlements (see Koning and Smaling, 2005).

outputs and infrastructure. Their analysis shows that in Nigeria, although fertiliser is widely applied in maize production, the profitability of fertiliser use is significantly diminished by low marginal physical product and high transportation costs of the input (Liverpool-Tasie et al., 2017). This points at the importance of including actual input prices when studying technology adoption.

Weak road infrastructure and remote geographical location can further result in low fertiliser use (Kaliba et al., 2000; Waithaka et al., 2007). Fertiliser is a relatively bulky input and transport costs to remote locations can be high. Among Kenyan smallholders, there is a negative impact of the distance to the nearest market on the amount of fertiliser used, although this can be partially offset by owning a means of transport (Waithaka et al., 2007).

Second, mineral fertiliser requires knowledge of how and when to apply it, and in what amount. However, when empirical studies test for human and social capital, the outcomes are ambiguous. Some find that households with higher formal education of the head apply more fertiliser (Waithaka et al., 2007), while others control for schooling but find no significant effect (Alem et al., 2010). Similarly, some show that access to extension services has a positive significant relationship to fertiliser use (Kaliba et al., 2000; Nambiro and Okoth, 2013; Stahley et al., 2012); while others argue that extension services are less important for well-known productivity enhancing technologies like mineral fertilisers (Alem et al., 2010). These contradictory findings could imply that there is no clear role for education in fertiliser adoption, or perhaps that measures like the years of schooling are inadequate proxies for specialist agrarian knowledge. Instead, Isham (2002) places the impact of human capital at the community level over individual characteristics, analysing if local social structures affect the decision of rural households in Tanzania to use fertiliser. He finds that both ethnical ties and participating in formal social activities seem to influence the adoption decision. Furthermore, survey of maize farmers in Tanzania's Kilosa district revealed that farmers who have mobile phones widely perceive them to have a positive impact to their business, which could suggest that digital networks are a more important channel through which technology is diffused than formal schooling (Kiberiti et al., 2016).

Third, the interaction of agrochemicals like fertiliser and the plant does not take place in an environmental void. Environmental conditions pose an inherent risk to agriculture, and thus there is reason to believe that they, at least in part, determine the type and amount of inputs chosen for production. Regarding Maize in Tanzania, two aspects are of interest. The first is exacerbated rainfall risk from climate change: while there are few studies that centre on rainfall as a deciding factor in fertilizer adoption for maize farming, they all find a positive significant effect (Alem et al., 2010; Dercon and Christiaensen, 2011; Kaliba et al., 2000; Wossen, 2018); The second is the risk of low fertiliser-yield response posed by poor-quality soils (Morris et al., 2007; Nyssen et al., 2017).

Kaliba et al. (2000) find a positive effect of rainfall on the use of mineral fertilisers. Problematically however, they assume that fertiliser use is a function of whether or not improved seed varieties were used. It is true that the potential of improved seed can be realised through heavy fertilisation and they are complements in the 'Green Revolution'-type package of agricultural practices (Nambiro and Okoth, 2013).[4] However, research shows that mineral fertilisers also complement other, more traditional practices like organic fertilisation (Waithaka et al., 2007). This suggests that mineral fertilisers may not be uniquely associated with any single other farm practices and therefore that modelling it as an outcome of using improved seeds could be a source of bias for Kaliba et al.'s research (2000).

Analysis of panel data from Ethiopia shows that irrespective of seed variety, the prospect of low rainfall is a consumption risk in the absence of insurance markets and therefore impacts the fertiliser use decision negatively (Dercon and Christiaensen, 2011). Alem et al. (2010) develop on these findings by including both rainfall abundance and rainfall variability as regressors, also working with Panel data from Ethiopia. They match lagged village-level rainfall data with current application of inorganic fertiliser. Finding a positive relationship between last year's rainfall abundance and current fertiliser use, they suggest that abundant rainfall leads to increased liquidity, hence enabling households to buy fertiliser in the following year. On the other hand, they find that a higher rainfall variability decreases the probability that fertiliser is applied to maize crops in any given year.[5] This is likely because farmers are risk-adverse and have imperfect information (the future weather not being known), and therefore might decide not to apply fertiliser in a year in which rainfall seems erratic (in line with findings from Dercon and Christiaensen, 2011). However, their data do not include input prices, and therefore cannot show the relative impact of profitability concerns from 'rainfall risk'. Nonetheless, it implies a strong causal chain whereby rainfall risk reduces fertiliser use, hence keeping soil productivity low, and, in the long term, undermining of food security and agricultural productivity growth.

The impact of climate variability on agricultural practices and productivity has a gender dimension (Alem et al., 2010; Wossen, 2018). Male and female-headed households often differ in initial endowments and therefore in vulnerability, access to information and adaptation strategies (Wossen, 2018). Wossen (2018) finds that Ethiopia, female headed households tend to be poorer and therefore less likely to apply costly fertilisers for as a climate adaptation strategy. This corroborates findings by Alem et al (2010) and supports the idea that women in SSA face discrimination in accessing complementary productive inputs (e.g., Dey, 1981; Doss and Morris, 2000). This could be different for Tanzania, given that the overall female labour share in crop-production is estimated to be more than 50% in Tanzania, but only 29% in Ethiopia (Palacios-Lopez et al., 2017).

Low-quality or unknown soil quality also pose a risk to fertiliser use because of the concomitant variation in yield-response to applied N (Morris et al., 2007).[6] Where soils are

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[4] The term GR refers to "the breeding of improved varieties combined with the expanded use of fertilisers, other chemical inputs and irrigation, leading to dramatic yield increases for [rice and wheat] in Asia and Latin America in the late 1960s." (Hazell (2009, p. 1). It was a success for food security in these regions but is now associated with a number of severe environmental problems.

[5] Measured as the coefficient of variation (variance/mean).

[6] Note that this risk can be reduced by determining soil quality from soil sample analysis in a laboratory. However, most smallholder Maize farmers in Tanzania do not have access to this technology and are thus unable to predict how N will interact with their soils. This is exacerbated by the fact that soil quality changes over time due to agricultural practices and unrelated environmental factors.

less responsive, have a steeper slope, or the weather is very dry, adding N from mineral fertilisers at the rate recommended by governments (200 kg ha^{-1}) may not lead to the expected increase in yields or, in the worst case, 'burn' the seed (Alem et al., 2010; Nyssen et al., 2017). Research shows that therefore, low quality soils can reduce the demand for chemical fertilisers. Nyssen et al. (2017) show that in Ethiopia, government-subsidised fertiliser is sold at half the market price in areas with poor soils. Interestingly, their regression analysis shows that monthly rainfall at sowing time has a strong positive correlation with the black market price and that areas with spate irrigation have the comparatively lowest demand for fertiliser (both in the black and official market). This implies that profitability can vary within a country, confirming the need for spatially disaggregated research. It further emphasises the importance of accounting for soil characteristics and rainfall as a combination of risk factors when analysing fertiliser decisions.

In summary of the literature, agronomic studies apply statistical analysis to panel or cross-section data to study decision-making on the household level. Although this is not frequently mentioned, the underlying model of decision-making is that households are populated by economic agents who optimise their resources and may or may not, as a result of the optimisation process, decide to apply fertiliser to their maize crop. It is important to keep this in mind when interpreting the results of this study in context.

Financial constraints are a key factor limiting fertiliser use in SSA maize production, as is distance (because it raises the price). Fertiliser is often applied together with other productivity-enhancing technologies such as improved seed or manure, while evidence on education, government extension services and age is ambiguous. Spatially disaggregated data are important as fertiliser adoption decisions have been found to vary within and between countries. Further, there is recent, yet strong evidence that rainfall risk has a negative impact on fertiliser use (Alem et al., 2010; Dercon and Christiaensen, 2011). However, to our best knowledge, no paper includes both rainfall and input prices. Existing research on rainfall and fertiliser stems from Ethiopia, and it will be interesting to see if those findings can be replicated for Tanzania. Two research questions arise from this literature review, which we study for Tanzanian maize farmers.

RQ1: What is the impact of rainfall risk on fertiliser use?

RQ2: What is the role of fertilisers for sustainable agricultural development as envisioned by the Sustainable Development Goals (SDGs)?

Methodology:

This section outlines the study's data and methodology. We begin by describing Maize in Tanzania as a case study, followed by an explanation of the dataset and econometric models.

Case study description

Tanzania has an agriculture-based economy with 25 percent of GDP and half of employed labour attributed to the sector in 2012 (Smil, 1991)[7] Agriculture sustains the livelihoods of 70 percent of Tanzanians who live in rural areas, and is vital national food security (NBS, 2017). Maize is by far the most abundant food crop with a production of 6.1 million Tonnes on the Tanzanian mainland in 2016, compared to Rice and Cassava which come second and third at only 2.2 million Tonnes. It is grown predominantly in the South and not normally produced as a cash crop (NBS, 2017.

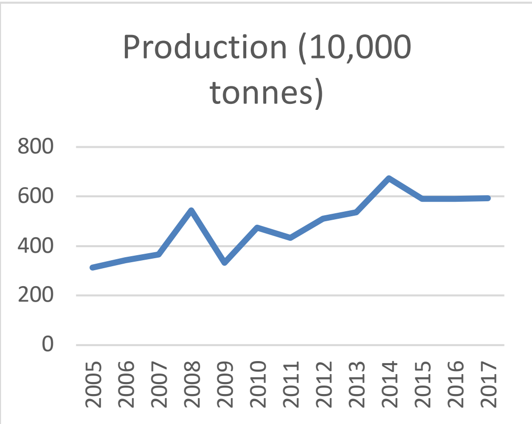


Figure 1Maize production in Tanzania (FAOSTAT, 2018)

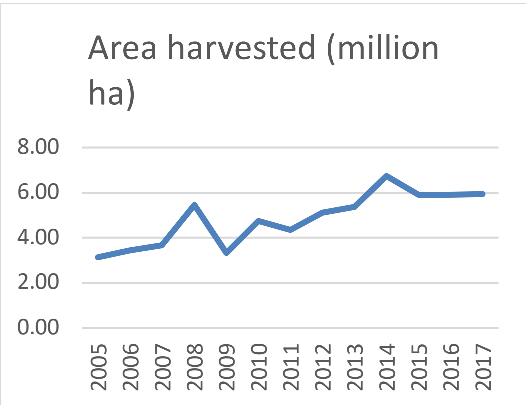


Figure 2 Maize harvest area in Tanzania 2005-2017 (FAOSTAT, 2018)

[7] This is the most recent year for which data are available.

The graphs show that all three indicators have grown from 2005 to 2017, following an upwards linear trend. The compound annual growth rates reported in Table 1, however, show that maize yield (tonnes per hectar) has been growing more slowly than total production It is further representative of overall low agricultural productivity growth in SSA, especially for food crops (Morris et al., 2007).

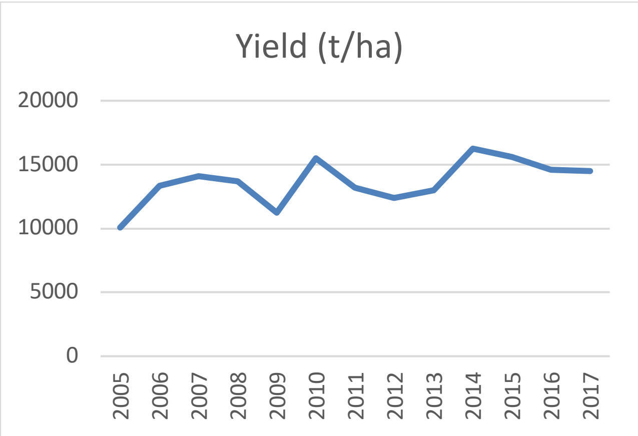


Figure 3 Maize yield in Tanznia, 2005 -2017 (FAOSTAT, 2018)

Table 1: compound annual growth rates (FAOSTAT, 2018)	
Maize area harvested	2.14%
Maize production	5.05%
Maize yield	2.85%

Estimates from the Global Yield Gap Atlas (2018) suggest that rain-fed maize production in Tanzania is currently only at 20% of its capacity. Chemical fertiliser application rates dropped to a historical low following the structural adjustment programmes in 1986-1994, which through a combination of market and exchange rate liberalisation led to a doubling of the fertiliser-crop price ratio (Kherallah and International Food Policy Research Institute, 2000). However, concerns about food security and stagnant levels food production resulted in a policy reversal by the Tanzanian government since the mid-2000s. In line with the 2006 Abuja declaration, fertiliser subsidies were restored in a strategic pursuit to initiate a GR for Africa (Isinika and Msuya, 2011).[8] Increased use of mineral fertilisers remains seen as a necessary condition for boosting agricultural productivity and closing the yield gap (Morris et al., 2007; Waithaka et al., 2007).

Just over 1% of potentially irrigable agricultural land is actually irrigated at present in Tanzania and most farmers rely on seasonal rainfall as a core agricultural input, making them extremely vulnerable to droughts ("Global Yield Gap and Water Productivity Atlas," 2018). It is therefore estimated that changes in rainfall will lead to a decrease in maize yield in Tanzania of 3.15% in the short run and 9.6% by the end century (Luhunga, 2017; see also Munishi et al., 2015).

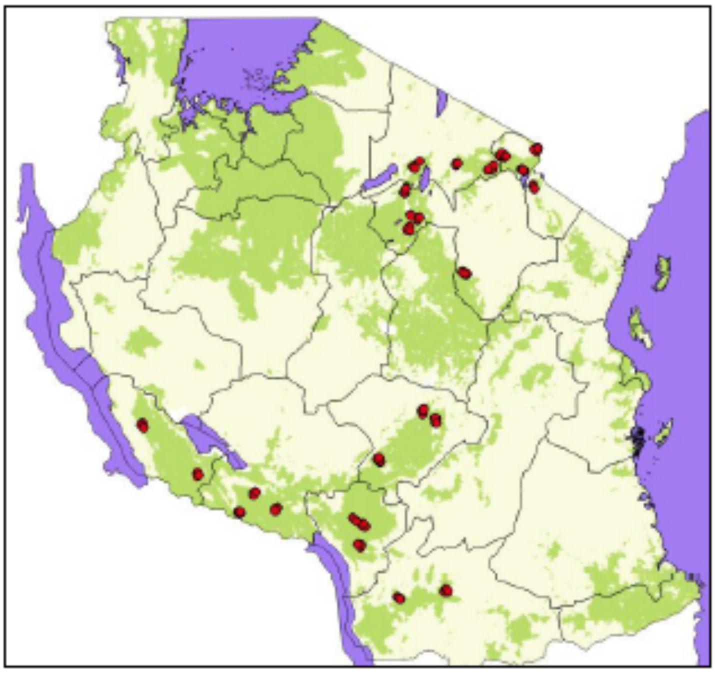
Data description

[8] Recently, the NAIVS Input subsidy scheme for improved seed and fertiliser enabled targeted farmers to increase their maize yield by 433 kg per hectare on average over three years but has since been discontinued (Ministry of Agriculture, 2014).

We study the determinants of fertiliser use under climate change in Tanzania using a panel dataset combined from two primary sources. Household socio-economic characteristics, maize production and farm practices come from the 2016 and 2017 waves of the Agronomy Panel Survey (APS) for Tanzania, which Chamberlin et al. (2018a) conducted for the International Maize and Wheat Improvement Center (CIMMYT) in collaboration with the Sustainable Intensification Innovation Lab. Rainfall data was added from CHIRPS.v20 (Funk et al., 2015). This section describes how the dataset was compiled and explains how key variables were measured. A detailed list of all variables, sources and measurements can be found in Appendix A.

The APS contains multi-level agronomic farm-household panel data for maize producers in Ethiopia, Nigeria and Tanzania. Because all observations are geo-referenced, the APS uniquely lends itself to analysing the economics of maize production technologies as a spatial phenomenon. In Tanzania, 580 survey households were randomly selected in a stratified spatial sampling frame (Chamberlin et al., 2018b). They are distributed across 25 districts in the Tanzania's Northern zone and Southern Highlands region, as seen in Fig. 4. These observations are complemented by community level data from 365 villages, with an average size of 547 households per village.

Fig. 4 Distribution of APS Sample (from Chamberlin et al., 2018a, p. 4 in "TZAPS_desciption_andSOPs.pdf")



The North and Southern highlands are distinct agro ecological zones, where the North is dominated by warm and semi-arid climate and the Southern Highlands have both warm and cool sub-humid areas (Senkoro et al., 2017). Apart from this, the areas share similar characteristics. In accordance with the sampling strategy, all sampled households are located in predominantly maize-producing areas, with moderate or higher population density and good market access.

APS data tables for 2016 and 2017 are publicly available from https://data.cimmyt.org. For 2016 there is a main file information on the household and focal plot, while for 2017 those are kept as separate main files. Further, there are over 15 sub-files containing detailed information from subsections of the questionnaire, for example "demographics of all household members" and "fertiliser unavailability". We computed our variables of interests within the respective dataset, collapsed it onto household level and then merged it into that year's main file with a unique parent-child identifier.[9] Data cleaning involved homogenising variable names that vary between years, inconsistent coding of missing values within and between years and finally, inconsistencies between the survey questionnaires excel file and pdf format in the same year. Great care was taken to minimize error, although human error can never be ruled out entirely when manually cleaning large datasets.

Outliers were removed after merging the 2016 and 2017 waves into a panel file. There were two types of outliers: extreme values that are possible but could distort the results, and impossible extreme values (for example, a person aged 4000, and households with no head). The cleaned dataset is a strongly balanced panel of 1075 household-year observations.[10] Summary statistics for all variables are presented in Table 2.

[9] All do-files and data are available in the online appendix here

[10] The sample size is smaller for some regressions, as not all variables are available for the full sample.

Table 2: Summary Statistics

	count	mean	sd	min	max
Fertiliser use	1075	.39	.49	0	1
Rain variables					
Rain	1623	.132	.042	.055	.231
Rain ²	1623	.019	.012	.003	.054
Rain variability	1623	.063	.039	.009	.224
Rain variability ²	1623	.006	.007	.000	.050
Demographic & socio-economics					
Female head	1075	0.13	0.34	0	1
Head age	1072	48	14.07	19	95
Head education	1075	7.2	3.63	0	22
Adult males	1075	1.5	0.97	0	8
Adult females	1075	1.5	0.93	0	8
Children	1075	2.6	2.19	0	16
Farm assets	1060	11.42	1.49	3.87	16.86
Farm characteristics					
Plot distance	1075	18.48	29.96	0	300
Soil fertility	1075	2.12	0.58	1	4
Slope	1075	1.91	0.84	1	5
North region	1075	.47	.50	0	1
Input price & location					
Fertilizer price	318	10.96	0.18	10.31	11.16
Distance DHQ	355	34.45	26.05	2	109
Social capital					
Social capital	1075	.31	.46	0	1
Alternative practices					
Nitfix	1075	.27	.44	0	1
Manure	1075	0.19	0.39	0	1
Conservation	1075	0.21	0.41	0	1

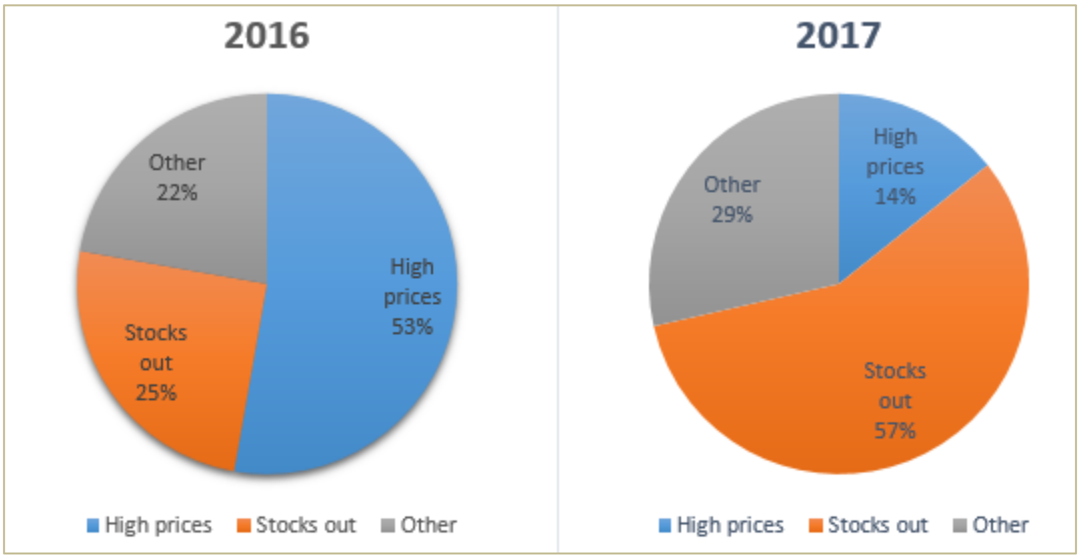
Dependent variable

The dependent variable is $fertilizer_{bin}$, a binary variable that indicates whether or not any chemical fertiliser was used on the focal plot for maize production during the main growing season. Corresponding to the question "Have you applied chemical fertiliser on [the focal plot] in the main growing season of this year?" it takes on 1 if the answer is 'yes' and 0 if the answer was 'no'. 36.4% of households report having used fertiliser for maize production in 2017, down from 40.5% in 2016. This is in addition to 9% (2016) and 3.1% (2017) of households who report having wanted to buy fertiliser but were unable to obtain any.[11] Fig 4 shows that the reasons for fertiliser unavailability varies between years. High prices were the

[11] This excludes ca. 100 missing observations in each year.

main reason in 2016, perhaps because households were financially relatively more constrained from a bad harvest in the previous year. In 2017 in comparison, only 14 households encountered fertiliser unavailability, mostly due to low stocks.

Figure 5 Reason for fertiliser unavailability by year



Interestingly, 151 households in 2017 say that "there is no need to use" fertiliser, compared to 93 in 2016 (not graphed). This points at time-varying reasons for fertiliser use like those pertaining to the weather. Most respondents mention financial constraints as the key reason, citing reasons such as "not enough cash", "no cash when needed" and "too expensive".

We use $fertilizer_{bin}$ because it renders qualitative information about fertiliser use for the maximum number of observations.[12] Unfortunately, it is limited in that it does not discriminate by type of chemical applied or register the amount.[13] Our work therefore focuses on fertiliser adoption, and future research could investigate the effects relating to the intensity of fertiliser application.

Explanatory and control variables

The explanatory variables were chosen in analogy to the key themes identified in the literature review. Following Alem et al. (2010), the main regressors are lagged rainfall abundance and current rainfall variability to test for the effect of climate risk on the decision to use fertiliser..

Rainfall records stem from the CHIRPS v2.0 database published by the Climate Hazards Group at UC Santa Barbara (Funk et al., 2015). CHIRPS v2.0 combines satellite images with station data into a gridded rainfall time series at 0.05° resolution available daily from January 1st 1981. We constructed three variables to describe the average monthly rainfall during the

[12] That is, qualitative information conveyed in a quantitative format, as 0 and 1.
[13] Those data were available in the APS but only for a very small subsample.

main growing season as defined by APS survey for 2015 – 2017 (January to May).[14] . $Rain$ averages the absolute average monthly rainfall in 1000 mm. $Rain\ variability$ is the coefficient of variation and is calculated as the variance of seasonal rainfall divided by its mean.

CHIRPSv2.0 is the best available precipitation data that both minimizes bias and covers a large variety of locations at a relative low resolution. Nonetheless, it should be noted that matching village level data to all surveyed households within a village might obscures variations in the local microclimate.

Mineral fertiliser is a cash-intensive agricultural input, making affordability an important determinant of technology adaption. we therefore include data on assets and the price of fertiliser.[15] $Farm\ assets$ measures the total value of farm-related assets held by the household in log of Tanzanian Shillings (logTsh).[16] It was derived by adding all farm assets at their reported value and taking the log. we include actual input prices from the APS community questionnaire on village level, using the price for a 50kg bag of fertiliser (averaged between top and basal fertiliser) in logTsh.

Household size varies from 1 – 16 adults, with a mean of 3. On average, household heads are 49 years old and have completed 7 years of schooling and 13% of households are female-headed. Given an average adult age of 38 years of age 10 years of education for the most educated household members, it seems that household heads are younger and less educated than other adult members of their household.

We control for $social\ capital$ using a dummy variable which takes the value 1 if at least one household member is reported to be regularly attending a social or group activity, and 0 otherwise. It follows the logic that there might be a network effect of technology diffusion, and that certain social activities can economically empower smallholder farmers, for example through improved credit access in a farming cooperative (Isham, 2002). Indeed, out of 335 observations reporting regular social activity, 58% attend 'savings and credit services' which are by far the most widely reported group activity followed by 'merry go round' and 'women's groups' (12% each).

We control for location of the farm by including the average distance to the district headquarters in km ($Distance\ DHQ$), and the walking time to focal plots in minutes ($Plot\ distance$). Remote locations may have fertiliser less readily available, and being further away from the farm may lead to less time spent attending to the crops (especially when walking). Only 6% of plots in our sample are irrigated, with furrow irrigation (61%) and piped irrigation (15%) being the most popular types for those that have irrigation.

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[14] 2015 data serve as lagged rainfall for 2016 APS results.

[15] Our preliminary analyses also included off-farm income and fertiliser transport cost, but we decided not to include them in our final models as they were not significant.

[16] Asset data were stated both for the survey date and for 'one year back'. we chose the latter to measure asset wealth 'pre-' growing season, as households may wish to sell off assets to buy farm inputs like fertiliser.

Organic fertilisers can be used as substitutes to chemical fertilisers, although field trials show that the two are in fact complementary to each other (Mugwe et al., 2009). We therefore control for three alternative ways of enhancing soil fertility and resilience. Intercropping maize plants with nitrogen-fixing legumes like beans and peas is measured is measured in the dummy $Nitfix$ which takes 1 if at least one type of nitrogen fixing intercrop is used (farmers could report up to 5 intercrops). In addition, some farmers 'top'-fertilizing the soil with animal or compost manures, measured by $Manure$**.** 44% of respondents for which data are available leave farmyard manure in the field, and 11% use compost manure. Low quality manure is a problem in SSA agriculture, but unfortunately, no information on manure quality was available. Finally, $Conservation$ takes 1 if farmers practice at least one soil and water conservation practice (minimum tillage, incorporating crop residues, mulching and ridging). Although the main aim of such practices is not N supply, they can positively impact nitrogen synthesis by improving water retention and soil resilience (Vanlauwe et al., 2014).

Panel analysis

Choosing the 'correct' estimation strategy depends on both the data structure and the underlying theory of change, i.e., the conceptual framework (Besley and Case, 1993). This paper has as outcome variable the binary variable $fertiliser_{bin}$, which conveys qualitative information and is limited to two values (0 and 1). Linear regression is biased when dealing with binary outcome variables.[17] Probit and logit are discrete choice models that avoid problems with nonconforming predicted probabilities by transforming the linear estimation index used in linear probability models into a range of predicted values bound by 0 and 1. We therefore use probit and logit to fit 5 different models (variable combinations):

The probit estimator is:

(1) $\Pr(y_i \neq 0) = \phi(x_{it}\beta)$

(2) $\Pr(fertilizer_{bin}) = Y' = \phi(\beta_o + \sum Z_{it}\beta_i + u)$,

whereby Pr $(y_{i\neq 0})$ is the probability that the dependent variable, $fertilizer_{bin}$ is non-zero, $Z_i\beta_i$ is a vector of control variables with their coefficients and ϕ denotes the cumulative normal distribution. Logit models are similar to probit but assuming a cumulative logistic distribution function instead of a cumulative normal distribution:

(3) $\log(\frac{Y}{1-Y}) = X\beta$

(4) Therefore, $Y' = \frac{e^{X\beta}}{1+e^{X\beta}} = \ln[\phi(\beta_o + \sum Z_{it}\beta_i + u)]$

[17] There are three problems with applying OLS to discrete models (Wooldridge, 2013). First, it is heteroscedastic by construction thus requiring the use of robust standard errors. Second, there is a risk of 'nonconforming predicted probabilities', which exist when the coefficients fall outside of 0 and 1 despite the outcome variable being unable to take values other than 0 and 1. Third, by modelling a linear relationship between the fitted values of the dependent variable and it regressors, the marginal effect of a 1 unit change in β Y is assumed to be the same at each level, which is unlikely to be the case with, for example, rainfall variability (where you would assume more extreme values to be more devastating to crops than smaller variations).

Rather than the change in X that accompanies a change in Y, coefficients of probit and logit estimations are therefore interpreted as a percentage change in the probability that the outcome variable is either 0 or 1. Thus, changes in the marginal impact of a 1 unit change are not constant but vary across the distribution, thereby addressing another key shortcoming of the baseline OLS.

The difference between logit and probit is the underlying distribution based on which they link the regression function to the latent variable Y'. Both render similar results and both are used in the literature, hence we report both.

Results

Results from the Probit and Logit regression are reported in Tables 2 and 3, respectively. We estimated five models. Model I is the most similar to Alem' et al.'s (2010) estimation, to see if their findings hold in Tanzania.[18] Model II is reported in column two and adds input prices (the cost of fertiliser), and the distance to the district headquarters. Model III builds on model II by additionally controlling for social capital. Model IV includes alternative farm practices and model V contains all controls.

The results confirm Alem et al.'s (2010) key finding that higher lagged rainfall squared increased the probability fertiliser use. Rainfall abundance changes its sign when squared, which implies that there is the relationship between precipitation and fertiliser is not linear. However, it loses its significance when additional controls are included in Model II -V. This is interesting because Alem et al. (2010) did not use these additional controls. It shows that input prices and location are important controls when analysing the relationship between rainfall and fertiliser use.

Surprisingly, rainfall variability is positive and significant, while it is negative and significant for Alem et al. (2010). This discrepancy might have to do with the structure of the data. We chose to use only rainfall data during the main season whereas Alem et al. average rainfall over the whole year, which could be another reason for deviating results. Alternatively, it might imply that rainfall variability is not a good proxy for planting risk in the current year, or that Alem et al.'s findings do not hold in Tanzania.

We find no statistically significant effect of whether or not the household is female-headed, and tabulating 'female head' with 'fertiliser use' reveals that fertiliser use between male-headed and female-headed households differs only by 1 percentage point (not reported). This contrasts to previous findings from Ethiopia. It could indicate that women farmers in Tanzania are less discriminated against in input markets or it could be due to sample characteristics. More likely, however, it confirms Doss's (2018) criticism that using the household's head's gender as a variable fails to acknowledge that plot management decisions are generally made by both men and women within a household. As such, it exemplifies a wider-reaching problem of agent-based modelling with the household as unit of analysis in agronomic research.

[18] See probit regression included in the appendix at Alem et al. (2010).

Table 3: PROBIT estimates of fertiliser use

	Model I	Model II	Model III	Model IV	Model V
L. Rain	65.656***	89.845***	89.909***	89.381***	89.453***
	(10.017)	(31.107)	(30.802)	(30.529)	(30.268)
L. Rain ^{2}(L)	-	-	-	-	-
	183.487***	246.513**	246.854***	243.356**	243.768***
	(32.679)	(96.640)	(95.700)	(95.085)	(94.239)
Rain variability	15.899***	8.173	6.653	7.437	6.249
	(4.644)	(11.680)	(11.814)	(12.150)	(12.267)
Rain variability ^{2}	-58.335*	-4.191	7.585	3.592	12.777
	(30.008)	(105.196)	(105.535)	(109.053)	(109.250)
Female head	0.065	-0.134	-0.159	-0.126	-0.146
	(0.143)	(0.291)	(0.298)	(0.296)	(0.300)
Head age	-0.007**	-0.000	-0.000	-0.000	-0.000
	(0.004)	(0.007)	(0.007)	(0.007)	(0.007)
Head education	0.036***	0.038	0.035	0.041	0.038
	(0.013)	(0.026)	(0.027)	(0.027)	(0.028)
Adult males	0.026	-0.059	-0.057	-0.049	-0.048
	(0.056)	(0.148)	(0.148)	(0.145)	(0.145)
Adult females	-0.022	-0.139	-0.133	-0.137	-0.132
	(0.052)	(0.115)	(0.115)	(0.115)	(0.115)
Children	-0.038*	-0.006	-0.002	0.003	0.006
	(0.021)	(0.042)	(0.042)	(0.043)	(0.042)
Farm assets	0.007	0.089	0.081	0.079	0.073
	(0.032)	(0.067)	(0.067)	(0.069)	(0.069)
Plot distance	-0.003*	-0.004	-0.004	-0.002	-0.002
	(0.002)	(0.004)	(0.004)	(0.005)	(0.005)
Soil fertility	-0.140*	-0.158	-0.154	-0.151	-0.148
	(0.077)	(0.130)	(0.130)	(0.133)	(0.133)
Slope	-0.052	-0.017	-0.017	-0.033	-0.032
	(0.054)	(0.089)	(0.090)	(0.092)	(0.092)
North region	-0.523***	-0.829***	-0.829***	-0.793***	-0.796***
	(0.109)	(0.281)	(0.282)	(0.298)	(0.299)
Fertilizer price		-1.176**	-1.190**	-1.047*	-1.067*
		(0.572)	(0.577)	(0.608)	(0.618)
Distance DHQ		-0.017***	-0.017***	-0.017***	-0.017***
		(0.005)	(0.005)	(0.005)	(0.005)
Nitfix				-0.095	-0.094
				(0.250)	(0.250)
Manure				0.203	0.202
				(0.234)	(0.234)
Conservation				0.175	0.161
				(0.236)	(0.242)
Social Capital			0.099		0.081
			(0.176)		(0.180)
N	1,075	313	313	313	313

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4: LOGIT estimates of fertiliser use

	Model I	Model II	Model III	Model IV	Model V
L. Rain	119.827***	170.567***	169.645***	169.831***	168.982***
	(18.594)	(52.801)	(52.544)	(53.589)	(53.471)
L. Rain ^{2}(L)	-337.930***	-472.760***	-470.180***	-468.855***	-466.595***
	(59.763)	(164.167)	(163.263)	(166.428)	(165.860)
Rain variability	25.676***	12.235	9.931	11.349	9.594
	(7.934)	(20.772)	(20.838)	(21.648)	(21.659)
Rain variability ^{2}	-90.201*	14.646	31.921	22.579	35.661
	(51.181)	(186.700)	(186.460)	(194.042)	(193.272)
Female head	0.116	-0.249	-0.292	-0.255	-0.287
	(0.236)	(0.515)	(0.525)	(0.521)	(0.527)
Head age	-0.012*	0.001	0.000	0.001	0.000
	(0.006)	(0.012)	(0.013)	(0.013)	(0.013)
Head education	0.064***	0.070	0.066	0.071	0.068
	(0.023)	(0.046)	(0.047)	(0.047)	(0.048)
Adult males	0.020	-0.196	-0.194	-0.176	-0.175
	(0.099)	(0.297)	(0.297)	(0.303)	(0.303)
Adult females	-0.048	-0.261	-0.252	-0.257	-0.249
	(0.087)	(0.219)	(0.220)	(0.219)	(0.220)
Children	-0.062*	-0.001	0.005	0.009	0.014
	(0.036)	(0.072)	(0.072)	(0.072)	(0.072)
Farm assets	0.019	0.144	0.132	0.130	0.121
	(0.053)	(0.116)	(0.116)	(0.121)	(0.120)
Plot distance	-0.005*	-0.007	-0.007	-0.005	-0.005
	(0.003)	(0.007)	(0.007)	(0.008)	(0.008)
Soil fertility	-0.240*	-0.275	-0.267	-0.267	-0.260
	(0.130)	(0.225)	(0.224)	(0.231)	(0.231)
Slope	-0.077	-0.050	-0.052	-0.069	-0.068
	(0.091)	(0.156)	(0.157)	(0.160)	(0.160)
North region	-0.868***	-1.488***	-1.488***	-1.429***	-1.437***
	(0.184)	(0.498)	(0.500)	(0.539)	(0.543)
Fertilizer price		-2.154*	-2.191*	-1.939	-1.991
		(1.122)	(1.139)	(1.247)	(1.290)
Distance DHQ		-0.030***	-0.030***	-0.030***	-0.030***
		(0.008)	(0.008)	(0.008)	(0.008)
Nitfix				-0.075	-0.074
				(0.455)	(0.456)
Manure				0.191	0.191
				(0.413)	(0.414)
Conservation				0.226	0.195
				(0.430)	(0.449)
Social Capital			0.158		0.131
			(0.296)		(0.311)

N	1,075	313	313	313	313

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The coefficients for farm assets are not statistically significant in any model, even though previous evidence theory suggests that fertiliser use depends strongly on purchasing power (Kaliba et al., 2000; Nambiro and Okoth, 2013). One reason could be that because weather affects the whole region, assets cannot easily be monetised to purchase fertilisers when e.g., everyone in the area is affected by drought. Alternatively, it might be that income effects being already captured in other variables such as rainfall. Other demographic variables (like household composition into female adults, male adults, and children) are also not robustly significant. As expected, more fertile soils are less likely to receive mineral fertiliser in Model I, as are plots with a steeper slope. However, this effect loses statistical significance when also accounting for the price of fertiliser, the distance to the district headquarters and more detailed plot management practices.

Higher education of the household head is positively associated with plot fertilisation, although their significance declines when introducing additional controls. This points at the importance of human capital for the successful diffusion or more sophisticated crop management practices. Interestingly, having more children is associated with a lower probability of fertiliser use, where Alem et al. (2010) have found a positive association. This may be due to the increased financial strain from having an additional child.

In summary of our findings, rainfall abundance is robust across estimations, showing that costly technologies like fertiliser use will become increasingly unstable as climate change gets worse and makes rainfall patterns more erratic. Robustness of the regional dummy shows that these relationships are heterogeneous across space and that there may be location-specific characteristics that influence if fertilisers are used (political, economic and historical). Another location-specific variable, distance to the district headquarters, is also robust across estimations and confirms this point. However, other controls are not robustly significant where one would expect it, especially gender-related aspects, asset wealth and input prices. These discrepancies would be worth investigating in a subsequent study with it a longer time horizon

Discussion

The main finding from our empirical analysis is that lagged rainfall risk (variability) has a robust negative significant impact on fertiliser use among Tanzanian rice farmers. This confirms Alem et al.'s (2010) findings, pointing to the prolonged impact of financial, and resource constraints on technology adaptation.

This is in interesting finding in light of the SDGs, which require agricultural development that is sustainable and inclusive across the economic, social and environmental spheres, to "leave no-one behind" (United Nations, 2015). In this context, evaluating agricultural technology requires considering the efficiency and environmental impact, but also the socioeconomic consequences of technology adoption, at the macro and the micro level. Chemical fertilisers were instrumental to the GR in Asia, leading to high productivity growth and stabilising food security. From this perspective, one could argue that they are needed in SSA, too, to achieve the same. But just how big a role should fertilisers be given in Tanzanian agriculture?

Writing in 'Fertilizers & Agriculture', the quarterly newsletter of the International Fertilizer Industry Association (IFA), IFA chairman Abdulrahman Jawahery claims that 'fertilisers will directly contribute to meeting [Sustainable Development] goals 1 -3, which focus on poverty eradication; the promotion of food security and sustainable agriculture; and healthy lives and wellbeing for all' (2015:1). He further contains that the fertiliser industry can contribute to the remaining development goals, although admitting that "Goal 14 [on marine conservation] is potentially the most sensitive for the fertiliser industry" (Jawahery and Mkandawire, 2015, p. 2). Looking beyond the industry's self-portrayal, however, reveals three areas for concern about the compatibility between chemical fertiliser and sustainable development: its fossil fuel and energy consumption, environmental degradation from N runoff, and distributive consequences of pushing for fertiliser use

Environmental concerns

Chemical fertilisers link inextricably to fossil fuel consumption for two reasons. First, producing mineral fertilisers requires natural gas as an input, and large amounts of energy to heat up the environment enough for nitrogen synthesis to take place in the Haber-Bosch process (Smil, 1991). Second, fertiliser is a bulky input needing transport across long distances from its place of production to consumers in remote rural locations (Morris et al., 2007). The notion of strong sustainability suggests that different types of capital, especially natural and non-natural capitals cannot be substituted to sustain economic growth at infinitum and that economic activity is limited by stocks of resources like fossil fuels (Angelsen, 1997; Daly, 1999).[19] It follows that if adopting a position of strong sustainability; mineral fertiliser is

[19] The mainstream conceptualisation of sustainability among environmental economists remains one of weak sustainability, not strong sustainability. Weak sustainability implies a techno-centric worldview in which the environment is a sub-system of the economy, in which it is not problematic to use natural resources as a means to the end of 'development' (Angelsen, 1997; Daly, 1999).

inherently unsustainable and therefore should not be an adaptation strategy for sustainable development.

Adding nitrogen to the soil creates nitrous oxide (N2O) through denitrification. N2O is a greenhouse gas, which once released remains in the atmosphere at increasing concentrations, and changes the Planet's radiation balance in a way that contributes to global warming and climate change (Smil, 1991). Like carbon emissions from fertiliser production and transport operation discussed in the previous subsection, this operates at the planetary level and therefore is a global externality. This sheds an unfavourable light on policies that promote mineral fertilisers following the 2015 Paris Climate Agreement, and for efforts of climate mainstreaming like the Tanzanian government pursues.

Additionally, the concentration of nitrates (NO3) the soil increases as more mineral fertilisers are applied. NO3 leaking into waterways can fuel excessive growth of aquatic plants (fertilizing algae), which can result in severe pollution of freshwater reserves that kills animals living in the water. Moreover, if combined fertilisers like N P K are applied, less mobile nutrients like phosphate can build up in the soil over time. This is undesirable from an ecological perspective but also for humans relying on ecosystem (Hutton et al., 2017; Smil, 1991). This is a local externality, although it may have regional ramifications, such as for downstream users of aquatic bodies.

Interestingly, these externalities do not occur universally but vary with land use practices, soil type and type of fertiliser that is applied (Hutton et al., 2017; Palm et al., 2017; Tully et al., 2016). A field experiment comparing the build-up of inorganic N in different soil types showed that on sandy soils in Tanzania, the amount of inorganic N in soil samples had increased four-fold after two years of continuous cropping. This is because leaching is more likely to occur in sandy soils as opposed to clay-heavy soils, where N pools stayed constant (Tully et al., 2016). From an ecological standpoint, it is therefore important to know the soil characteristics before deciding on fertiliser application in order to minimise negative externalities. Although soil-sampling is unavailable to many rural households, policy makers can use tools like planning maps to adjust fertiliser policies to different regional characteristics including soil quality, slope and the climate (Palm et al., 2017). Similarly, Nitrogen footprint models can simulate the impact of N on air and water quality arising from different sectors of the macro economy, including from agriculture. Hutton et al. (2017) made a nitrogen footprint model for Tanzania, finding that although just 9% of farms are fertilised, they contribute 17% of the food production N footprint. Tanzania's overall N footprint is much lower than that of developed countries for which models exist, which may indicate that globally, rich countries cause N-related pollution at disproportionate amounts to their population (Hutton et al., 2017).

<u>Distributive consequences</u>

Fertilisers are costly, and not everyone can afford them, ceteris paribus. Evidence from India shows that the GR led to a decrease in poverty but also a steep rise in inter-regional rural income inequalities (Prahladachar, 1983). Poor and marginalised groups like women, the older population, people living in remote communities or ethnic minority groups are at particular risk of being 'left behind'. Policy-makers should consider these aspects when designing policy interventions such as fertiliser subsidy schemes.

Second, and in relation to the first point, there is a risk of increased financial dependency, both on the micro and on a macro level. Because domestic fertiliser production is low and not internationally competitive, countries like Tanzania would be increasingly dependent on imports for their agricultural sector and food security. At over 90%, SSA has the highest dependence on imported fertilisers among the developing world (Torero, 2015). This is problematic because it makes the fertiliser market vulnerable to currency fluctuation and the volatility of international fuel prices (on which fertiliser production and transport relies) (Timmer, 1975; Torero, 2015).

Practicability of large-scale fertiliser adoption

The preceding analysis has shown the negative effects of chemical fertilisers on the sustainable development, especially when adopting a position of strong sustainability. It is further unclear if large-scale fertiliser adoption is realistically achievable in SSA. Morris et al. (2007) explain that establishing functioning fertiliser markets faces problems, both from the demand side and supply side. On the demand side, fertiliser is a specialised input for which the return on investment is best achieved together with other specialised inputs, but many consumers are poor and demand only seasonally and dependent on rainfall. On the supply side, it is a bulky input with a low value to volume ratio, therefore the selling price is driven up by transport prices. It has long value chains with multiple liquidity constraints and generally demands higher working capital to deal with market risks.

Alternatives to mineral fertilisers

Nitrogen fixation is largely anthropogenic in industrial food systems today, but organic sources of nitrogen remain an important complement, if not alternative (Hutton et al., 2017). Organic fertilization take place when organic matter releases nutrients into the soil and includes intercropping, improved fallow, and the use of manures (green manures, and animal manures). Compared to chemical fertilisers, these methods have the added benefit of increasing soil resilience (Hutton et al., 2017). Although organic fertiliser has insufficient N in the short term to maximise yields, they can increase maize at a low risk over the medium-long term by increasing the amounts of soil N (Ngwira et al., 2013).

Experimental evidence from Malawi by Ngwira et al. (2013) confirms that a combination of compost (including liquid manure) and low-dosed inorganic fertiliser is equally as productive as relying on synthetic fertiliser only, including in drought-prone areas. They see this 'combination' practice as a crucial strategy but nor in every environment - "However, maize yields were higher with chemical fertiliser than all other fertility inputs in areas with good rainfall and soils, as well as poor rainfall and soils with low quality compost" (Ngwira et al., 2013, p. 875).

Intercropping maize with legumes is common in Tanzania (Waithaka et al., 2007), but out data show that very few farmers fallow their land regularly or use manures and crop residues. Similarly, animal manures and crop residues have alternative uses (fuel, animal fodder), and low quality manures or compost could in fact damage the soil more than nourishing the plant (Morris et al., 2007). The regression results reflect this, as controls for 'alternative practices' were not significant. According to Waithaka et al. (2007), land scarcity and food insecurity are the main reason why farmers are reluctant to fallow a plot even for one season. Still, returning to these 'traditional' methods can be a good complement to applying mineral fertilisers and may reduce the overall amount needed below the 200 N-1 ha aimed for by governments in SSA (Nyssen et al., 2017).

To fertilise or not to fertilise?

On the one hand, chemical fertilisers can be extremely harmful to the environment, and promoting their increased use faces inherent challenges and risks making the region even more dependent on global markets. On the other hand, resource scarcity and poor quality soils make it impossible to rely exclusively on organic methods, especially in the short term. Moreover, even if all Tanzanian maize farmers stopped using mineral fertilisers, rainfall variability and climate change would still affect them. This is because climate change is a global externality, and reflects the fact that the poor suffer the most from climate change both globally, as they often lack the means to adapt and become more climate-resilient (Goldenberg, 2014)**.** This is a dilemma, but the yield gap, food security and rural poverty will not solve themselves. Continuing on a path of agricultural extensification is also unsustainable, for example when forests are cleared to access new cropland. It is therefore necessary to find a sustainable way of intensifying maize production in SSA (Palm et al., 2017). This will include chemical fertilisers, but should not repeat past mistakes of the Asian green revolution in Africa. It seems that even World Bank economists and staunch defenders of market liberalisation for fertiliser as Morris et al (2007, p. 27) agree, stating that "the strong faith exhibited by some policy makers and development practices in the potential ability of fertiliser to address a wide range of economic and social problems is a bit worrisome". Instead, perhaps the focus should be on climate smart agriculture which works towards a triple bottom line of increasing productivity, increasing resilience and minimize greenhouse gas emissions (FAO, 2018).

Conclusion

Mineral fertilisers are an important tool for boosting agricultural productivity growth. However, they can be environmentally destructive and climate change has become a key consideration for agricultural policy makers. This paper studies fertiliser use under rainfall variability to assess how rainfall risk affects fertiliser use, and what the role of chemical fertilisers is for sustainable agricultural development. Our analysis of Tanzanian rural farm panel data shows that fertiliser use is highly sensitive to rainfall, which suggests that overly relying on fertilisers is not a useful development tool if droughts are expected to become more frequent. In light of these findings, we outlined sustainability concerns in relation to fertilisers and analysed possible more environmentally friendly alternatives. The global fertiliser industry could be a big polluter, but food security and economic development may not be achieved through organic methods alone in Tanzania. We therefore conclude that there may be a role for synthetic fertilisers even in sustainable development, but that chemical fertilisers are not a panacea. In order to shape sustainable policies, there is a need for more nuanced research and to question dominant narratives.

This suggests several avenues for further research. It would be interesting to study the quantitative relationship between rainfall risk and *intensity* of fertiliser application in Tanzania, because the negative externalities from fertiliser may vary depending on the amount supplied. Similarly, a longer panel could give insights into climate vulnerability and fertilisers over time. Our research shows that to understand the complex interactions of fertilisers, climate and food security, it is important to go beyond agronomist econometric analyses of fertiliser use. Therefore, future research could address the research questions from a political economy perspective. This could help shed light on the underlying causes for econometric findings, and the power structures that shape interplay between agrochemicals, environmental degradation and food security.

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