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RESEARCH ARTICLE

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Climate vulnerability and fertilizer use – panel evidence from Tanzanian maize farmers

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ABSTRACT

Chemical fertilizers can significantly improve agricultural productivity but their environmental sustainability is much debated. This paper contributes to a growing body of research on the drivers of chemical fertilizer use under climate vulnerability. We study the impact of climate risk (measured as rainfall abundance, rainfall variability, temperature and temperature shock) on fertilizer use by Tanzanian maize farmers using Probit regression analysis on spatially disaggregated agronomic panel survey data for the years 2016 and 2017. Our results show that fertilizer use is extremely sensitive to climate risks, even when accounting for actually observed input prices, the main contribution of this study. Our findings suggest that as the climate crisis escalates with erratic rainfalls and warmer climate, chemical fertilizers will become increasingly less reliable to ensure food security for a growing population as farmers' fertilizer adoption decision is highly responsive to climate variability. This lends support to arguments that perfunctory promotion of chemical fertilizers is at odds with sustainable intensification agricultural policies.

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Technology adoption; Tanzania; maize farmers; sustainable intensification; climate change; fertilizers

1. Introduction

Maize is Tanzania's main staple crop and is already characterized 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 fertilizers (Morris et al., 2007). Anthropogenic climate change poses an additional growing threat to smallholder Tanzanian maize farmers, most of whom practice traditional rain-fed agriculture (Luhunga, 2017). Indeed, the global climatic suitability for maize production is expected to shift away from tropical regions as climate change causes increased rainfall variability, extreme heat and more frequent draughts (Ramirez-Cabral et al., 2017).

In light of a growing population, these multiple stressors have led to increasing calls for sustainable intensification approaches. However, critics argue that sustainable intensification lacks a clear definition and that some use it as a smokescreen to justify environmentally harmful agricultural management practices with the escalating climate crisis (Mdee et al., 2019). The role of chemical fertilizers is key to that debate as improved nitrogen management is at the core of sustainable intensification (Mdee et al., 2019; Zhang et al., 2015).[1] Mineral fertilizers provide plants with Nitrogen (N) at crucial stages in the cropping cycle, significantly boosting agricultural productivity growth especially where soils are depleted (Morris et al., 2007; Smil, 1991). However, while scholars agree that chemical fertilizers are a necessary ingredient for successful sustainable intensification in Sub-Saharan Africa, it is not yet clear what their role should be, and what the best policy is to promote their use (Holden, 2018).

This is in large part due to the significant negative externalities resulting from fertilizer production, distribution and consumption. The production of chemical fertilizers relies on natural gas and large amounts of energy, moreover they are a bulky input requiring long-distance transport. East African countries are heavily dependent on imports for most nitrogenous chemical fertilizers. A recent study found that the East African bloc, of which Tanzania is part, leaves an annual carbon footprint of 4.9 megatons CO_2-equivalent from the import of N fertilizers alone, not including emissions from local distribution (Kabiri, 2020). Local externalities are environmental degradation through denitrification (raising N2O greenhouse gas emissions), nitrate (NO3) leakage or phosphate buildup, all of which can significantly harm local and regional ecosystems (Hutton et al., 2017; Smil, 1991). Interestingly, these externalities do not occur universally but vary with land use practices, soil type and type of fertilizer that is applied (Hutton et al., 2017; Palm et al., 2017; Tully et al., 2016).

As droughts reduce the income of rural populations, their ability to purchase fertilizers is expected to decrease (Alem et al., 2010; Dercon & Christiaensen, 2011). At the same time, if fertilizers are applied but rainfall is insufficient, the excess Nitrogen (N) can 'burn' the seed and therefore reduce the yield compared to if no fertilizer had been applied (Nyssen et al., 2017; Waithaka et al., 2007). The other important climatic shock that is forecasted to be increasingly frequent under climate change is higher temperature during the

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growing season. In light of this background we study the impact of climatic variability (i.e. rainfall and temperature risks) on fertilizer use by applying newly available spatially disaggregated agronomic survey data on Tanzanian maize producers. We define rainfall risk to include both the total amount of rainfall received in the year prior to a growing season, and the current year's rainfall variability, measured as its coefficient of variation. This reflects the fact that precipitation levels differ with a changing climate as established weather patterns become more erratic (through floods, droughts or shifts in seasonal rainfall). Furthermore, temperature risk includes both the previous year's cropping season average maximum temperature (in Celsius degrees), and a dummy variable that indicates whether the previous year's cropping season's average maximum temperature exceeded 28 degrees (i.e. extremely high temperature that can adversely affect crop production according to Arslan et al., 2017). Our analysis expands on existing studies by also including actual fertilizer prices. Our results show that fertilizer use is highly sensitive to rainfall and temperature risks. These findings are robust across different model specifications. This suggests that costly inputs like chemical fertilizers will become increasingly less reliable as climate change worsens, due to the impact that climate risks have on the decision to adopt fertilizers.

The rest of the paper is organized as follows: Section 2 summarizes existing research relevant to our study. Section 3 describes our case study, followed by data and methodology in Section 4. Section 5 presents the results of our study. Section 6 discusses the results, followed by policy implications in Section 7.

2. Existing research

Decades of soil-degrading agricultural practices like reducing fallow periods, and deforestation to access new farmlands have led to widespread soil-mining, which happens when nitrogen (N), phosphorus (P) and potassium (K) are removed by crops as they grow, and not replenished through fertilization (organic or inorganic) and fallow (Morris et al., 2007).[2] Soil mining decreases ecosystem resilience to pests and diseases, reduces soil productivity, and can drive further extensification. The predominant narrative is that low rates of technology adaptation are making this problem worse: World Bank economist Morris et al. (2007, p. 18) states that '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'. This section presents existing literature on why fertilizer use remains low in SSA. Broadly, the adoption of production technologies depends on availability, accessibility and affordability of the technology. Our review of the literature shows that for mineral fertilizers in SSA, the main underlying drivers are income and profitability (financial), human and social capital, and environmental factors.

2.1. The drivers of fertilizer use

2.1.1. Financial drivers

Compared to other inputs to smallholder farming such as rain or unpaid household labour, chemical fertilizers 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 fertilizers and improved seeds, which need to be purchased every year, and that farmers are more likely to apply fertilizer where credit access is better (Kaliba et al., 2000, 1998). Research from Kenya confirms this, finding that fertilizer usage among Kenyan smallholders increases with scale economies for farmers owning a larger farm and having higher income (Nambiro & Okoth, 2013; Waithaka et al., 2007). Mineral fertilizers 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 & Okoth, 2013; Stahley et al., 2012; Waithaka et al., 2007). However, studying income or assets alone is not sufficient. As Liverpool-Tasie et al. (2017) point out, the profitability of fertilizer use from a farmers perspective depends on both agronomics and economics, that is, the yield response of fertilizer application as well as the relative prices of inputs, outputs and transport infrastructure. Their analysis shows that although fertilizer is widely applied in maize production in Nigeria, its profitability of fertilizer 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, as well as accounting for the geographical location of the farm.

2.1.2. Geography and social capital

Poor road infrastructure and remote geographical location can result in low fertilizer use, or diminished profitability from fertilizer application (Kaliba et al., 2000; Liverpool-Tasie et al., 2017; Waithaka et al., 2007). This is in part financial, as fertilizer 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 fertilizer used, although this can be partially offset by owning a means of transport (Waithaka et al., 2007).

Mineral fertilizer 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 their head possessing higher formal education apply more fertilizer (Waithaka et al., 2007), while others control for schooling but find no significant effect (Alem et al., 2010). Similarly, some studies show that access to extension services has a positive significant relationship to fertilizer use (Kaliba et al., 2000; Nambiro & Okoth, 2013; Stahley et al., 2012), while others argue that extension services are less important for well-known productivity enhancing technologies like mineral fertilizers (Alem et al., 2010). These contradictory findings could imply that there is no clear role for education in fertilizer 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 fertilizers. He finds that both ethnic ties and participating in formal social activities seem to influence the adoption decision. Furthermore, surveys 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).

2.1.3. Environmental drivers

This paper adds to a growing area of research around the impacts of the climate crisis on agronomic decision making for smallholder farmers. Environmental conditions pose an inherent risk to agriculture, and environmental conditions determine, in part, the type and amount of inputs chosen for production. For Tanzanian maize farmers, there are two key environmental drivers – rainfall and soil quality. Moreover, another prominent driver highlighted in the existing empirical literature, such as Arslan et al. (2017), is temperature.

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; Arslan et al., 2017; Dercon & Christiaensen, 2011; Kaliba et al., 2000; Wossen, 2018). The second driver is the risk of low fertilizer-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 fertilizers. They assume that fertilizer use is a function of whether or not improved seed varieties were used. It is true that the potential of improved seed can be realized through heavy fertilization and they are complements in the 'Green Revolution'-type package of agricultural practices (Nambiro & Okoth, 2013). However, research shows that mineral fertilizers also complement other, more traditional practices like organic fertilization (Waithaka et al., 2007). This suggests that mineral fertilizers may not be uniquely associated with any single farm practice and that modelling it as an outcome of using improved seeds might have biased Kaliba et al.'s (2000) research.

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 fertilizer use decision negatively (Dercon & Christiaensen, 2011). Alem et al. (2010) develop on these findings by including both rainfall abundance and rainfall variability as regressors, also analysing Panel data from Ethiopia. They match lagged village-level rainfall data with current application of inorganic fertilizer. Finding a positive relationship between last year's rainfall abundance and current fertilizer use, they suggest that abundant rainfall leads to increased liquidity, hence enabling households to buy fertilizer in the following year. On the other hand, they find that a higher rainfall variability decreases the probability that fertilizer is applied to maize crops in any given year.[3] This is likely because farmers are risk-averse and have imperfect information (the future weather not being known), and therefore might decide not to apply fertilizer in a year in which rainfall seems erratic (In line with findings from Dercon & Christiaensen, 2011).

Arslan et al. (2017) use multivariate panel regression to show that maize yields in Tanzania are just as vulnerable to rainfall and temperature shocks. Interestingly, they find that although significant complementarities exist between different agricultural practices, most of them are not exploited by households on their panel analysis. Their findings imply a strong causal chain whereby rainfall risk reduces fertilizer use, hence keeping soil productivity low, and, in the long term, undermining food security and agricultural productivity growth. However, their analysis does not include actual input prices for fertilizers, which this paper does. Asfaw et al. (2016) have also analysed the probability of applying chemical fertilizer, which is significantly and negatively correlated with variability in both rainfall and temperature.

Furthermore, 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) finds that in Ethiopia, female headed households tend to be poorer and therefore less likely to apply costly fertilizers as a climate adaptation strategy. This corroborates findings and supports the idea that women in SSA face discrimination in accessing complementary productive inputs (Alem et al., 2010; Dey, 1981; Doss, 2018). 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 fertilizer use because of the concomitant variation in yield-response to applied N (Morris et al., 2007).[4] Where soils are less responsive, have a steeper slope, or the weather is very dry, adding N from mineral fertilizers 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 fertilizers – so much that in Ethiopia, government-subsidized fertilizer is sold at half the market price in areas with poor soils (Nyssen et al., 2017). Interestingly, their regression analysis shows that monthly rainfall at sowing time has a strong positive correlation with the black-market price for fertilizers and that areas with spate irrigation have the comparatively lower demand for fertilizer (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 emphasizes the importance of accounting for soil characteristics and rainfall as a combination of risk factors when analysing fertilizer decisions.

3. Case study description – Tanzania

Tanzania's economy is agriculture-based with 30% of GDP and half of employed labour attributed to the sector in 2018 (National Bureau of Statistics, 2019). Agriculture sustains the livelihoods of 70% of Tanzanians living in rural areas and is vital for national food security. Maize is by far the most important food crop with a production of over 6 million tonnes in 2016. It is grown predominantly in the South and not normally produced as a cash crop (National Bureau of Statistics, 2017).

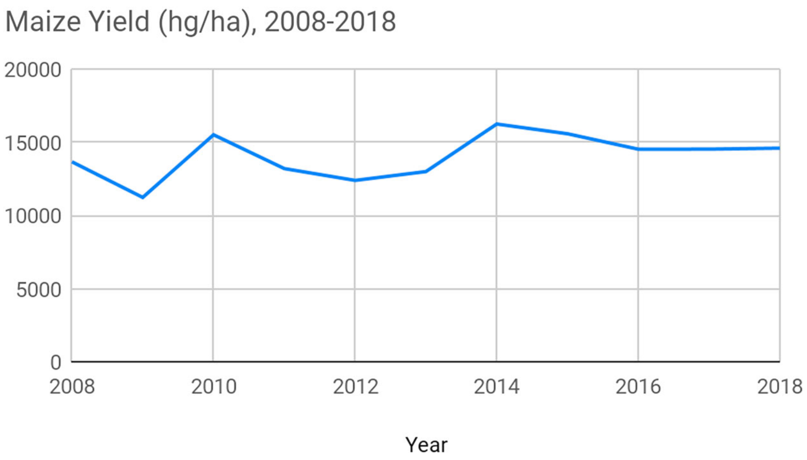


Figure 1. Maize yield in tonnes, 2008–2018 (Food and Agriculture Organization of the United Nations, 2020).

Figure 1 shows that the annual maize yield (measured as hg/ha) has been stagnant in recent years. Table 1 confirms this, reporting slow overall growth of only 0.98% in the 2010–2018 period, despite larger growth in both area harvested and total production. This is in line with overall low agricultural productivity growth in food crops in SSA, one of the main arguments used by those calling for sustainable intensification (Morris et al., 2007).

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 fertilizer application rates dropped to a historical low following the structural adjustment programmes in 1986–1993, which through a combination of market and exchange rate liberalization led to a doubling of the fertilizer-crop price ratio (Kherallah et al., 2000). In the mid-2000s, the Tanzanian government has reversed its fertilizer policy as concerns about food security and stagnant levels of food production were growing. In line with the 2006 Abuja declaration, fertilizer subsidies were restored within the wider strategic aim of generating a Green Revolution for Africa (Funk et al., 2015). The National Agricultural Input Voucher Scheme (NAIVS) was operational from 2009 to 2012. The voucher scheme pursued a dual objective of (1) increasing the use of improved seed and mineral fertilizers among smallholder farmers who have not previously used these inputs and (2) strengthening fertilizer supply by improving the network of agro-dealers (Ministry of Agriculture, 2014). NAIVS was discontinued in 2012 with mixed results. Although it enabled maize farmers to increase their yield by an average of 433 kg per hectare over three years, the scheme failed to target the poorest and women farmers, and experienced ongoing delivery problems along the inputs' supply chains (Malhotra, 2013; Ministry of Agriculture, 2014). At the time of writing, it has not been replaced by a follow-up policy.

Table 1. Compound annual growth rates for the area harvested (ha), maize production (tonnes) and maize yield (hg/ha) from 2008 to 2018 (Food and Agriculture Organization of the United Nations, 2020).

Area harvested	2.22%
Production	2.75%
Yield	0.98%

4. Methodology and data

4.1. Methodology

We use regression analysis on time series survey data in order to study how rainfall risks and temperature shocks impact fertilizer adoption decisions in Tanzania. Choosing the 'correct' estimation strategy depends on both the data structure and the underlying theory of change, i.e. the conceptual framework (Lipper et al., 2014). Our dataset has a binary outcome variable which conveys qualitative information about fertilizer adoption. Linear regression therefore is not an option, as it is biased when dealing with binary outcome variables.[5] Probit regression is a discrete choice model that avoids 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. Probit models are commonly used in empirical studies that investigate farmer's adoption strategies of different agricultural practices (Jones-Garcia & Krishna, 2021). For example, in addition to the aforementioned Arslan et al. (2017) and Asfaw et al. (2016), Kassie et al. (2013) have analysed the factors influencing Tanzanian farmers decisions to adopt sustainable agricultural practices, while Teklewold et al. (2013) have examined the adoption decisions by farm households facing multiple sustainable agricultural practices in Ethiopia. We have also run a logit regression that assumes a logistic distribution of errors, unlike probit regression that assumes normally distributed errors. Our logit regression results were almost identical to our probit regression results, hence we did not report the findings in this paper. Following up on the previous studies, we therefore use a probit estimator:

$$(1)\quad Pr(y_i \neq 0) = \Phi(x_{it}\beta)$$
$$(2)\quad Pr(fertiliser\ use) = Y' = \Phi(\beta_0 + \Sigma Z_{it}\beta_i + u)$$

whereby $Pr(y_{i\neq 0})$ is the probability that the dependent variable, fertilizer use is non-zero, $Z_i\beta_i$ is a vector of control variables with their coefficients and Φ denotes the cumulative normal distribution.

Probit regression coefficients indicate the direction of the relationship between the outcome and control variables, i.e.

whether a change in the control variable increases or decreases the possibility that the outcome is either 0 or 1. To analyse the magnitude of that effect, we run a post estimation command to derive the marginal effects of the coefficients and report those instead of the coefficients themselves. The marginal effect expresses in percent the effect that a one unit change in the explanatory variable x has on the probability that $Pr(y_i \neq 0)$. Because probit assumes a non-linear distribution, the predicted marginal effects are not constant across the distribution. Following standard practice we therefore report average marginal effects.

4.2. Data

We study the determinants of fertilizer 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). Temperature data was collected from historical monthly weather data available at the WorldClim database (WorldClim, 2022). 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 the Appendix.

The APS measures 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., 2018a). They are distributed across 25 districts in Tanzania's Northern zone and Southern Highlands region, as seen in Figure 2. These observations are complemented by community level data from 365 villages, with an average size of 547 households per village.

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). 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. 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 just over 1100 household-year observations. Summary statistics for all variables are presented in Table 2. Household heads have a mean age of 49 and 7.2 years of education, and 13% of household heads are female. The households have an average of 2.6 children. The plots are, on average, 18 min' walk away from the home and 28 km away from the nearest district headquarters. Less than 30% of participants report applying 'alternative' management practices like intercropping

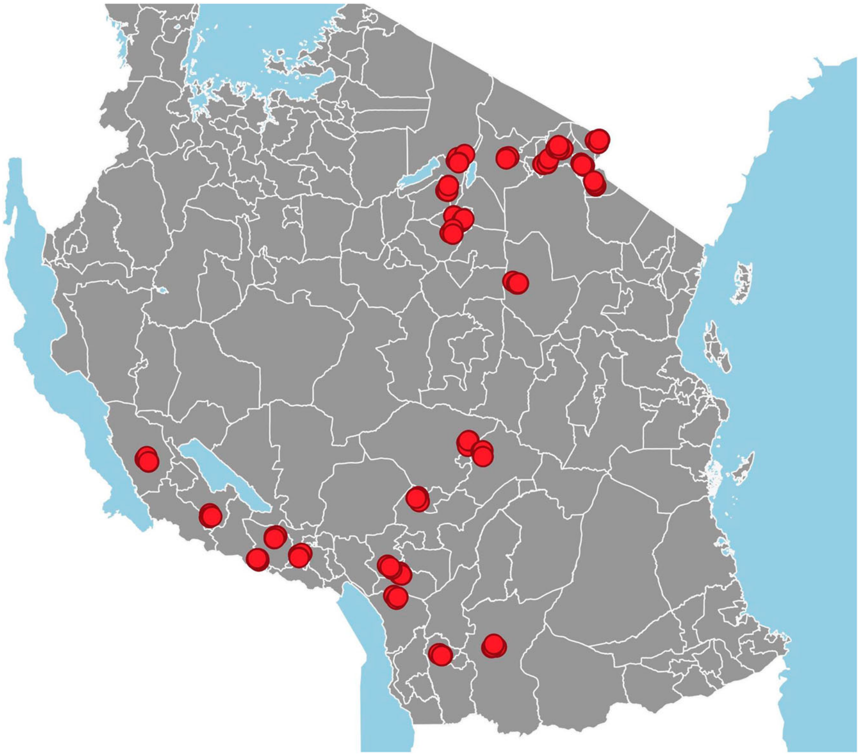


Figure 2. Distribution of APS sample (Chamberlin et al., 2018a).

Table 2. Summary statistics.

	Count	Mean	Std. Dev.	Min	Max
Outcome variable					
Fertilizer use	1106	0.39	0.49	0	1
Climate variables					
Rainfall (10 mm)	1690	13.11	4.15	5.53	23.17
Rainfall^2	1690	189.16	116.34	30.58	536.87
Rainfall variability	1690	6.4	4.04	0.86	22.43
Rainfall variability^2	1690	57.28	79.28	0.75	503.14
Avg. max. temperature	1690	26.02	2.26	20.51	31.02
Avg. max. temperature > 28	1690	0.15	0.35	0	1
Demographic and socio-economics					
Female head	1106	0.13	0.34	0	1
Head age	1103	49	14.07	19	95
Head education (years)	1106	7.23	3.63	0	22
Number of adult males	1106	1.51	0.97	0	8
Number of adult females	1106	1.58	0.93	0	8
Number of children	1106	2.6	2.19	0	16
Farm assets (1000 TSh)	1089	310	1072	5	21,070
Plot characteristics					
Distance to plot on foot (15 min)	1106	1.23	2	0	20
Perceived soil fertility	1106	2.12	0.58	1	4
Slope of plot	1106	1.91	0.84	1	5
Location and input price					
Region dummy North	1113	0.47	0.5	0	1
Fertilizer price (1000 TSh)	674	58.53	10.02	30	70
Distance to district HQ in km	1035	28.38	23.44	3	97.5
Social Capital					
Social capital	1113	0.31	0.46	0	1
Alternative practices					
Intercropping	1113	0.28	0.45	0	1
Manure	1106	0.19	0.39	0	1
Conservation	1106	0.21	0.41	0	1

or conservation agriculture. Note that fertilizer price and distance to the district headquarters have fewer observations because they are reported on the community (village) level, and thus apply to all households in a community.

4.2.1. Dependent variable

The dependent variable is fertilizer use, a binary variable that indicates whether or not any chemical fertilizer 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'. Approximately, 36.4% of households report having used fertilizer 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 fertilizer but were unable to obtain any. Figure 3 shows that the reasons for fertilizer unavailability varies between years. High prices were the main reason in 2016, perhaps because households were financially relatively more constrained from a bad harvest in the previous year. In 2017 in comparison, the majority of those reporting fertilizer unavailability explain this was due to low stocks.

The outcome variable renders qualitative information about fertilizer use for the maximum number of observations.[6] Unfortunately, it is limited in that it does not discriminate by type of chemical applied or register the amount.[7] Our work therefore focuses on fertilizer adoption, and future research could investigate the effects relating to the intensity of fertilizer application.

4.2.2. Explanatory and control variables

4.2.2.1. Climate variables. The explanatory variables were chosen in line with the key themes identified in the literature review. Following Alem et al. (2010), the main regressors are lagged rainfall abundance and current rainfall variability. Taken together, they test for what we refer to as rainfall risk – the climate risk coming from changing rainfall patterns – and the effect this has on the decision to use fertilizer. 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°. We constructed two variables to describe the average monthly rainfall during the main growing season as defined by the APS survey for 2015–2017 (January to May). The household data has been merged with historical climate data (rainfall and temperature) at a household level through coordinates (latitude and longitude).

First, **rain** averages the absolute average monthly rainfall of 1000 mm. Second, **rain variability** is the coefficient of variation and is calculated as the variance of seasonal rainfall

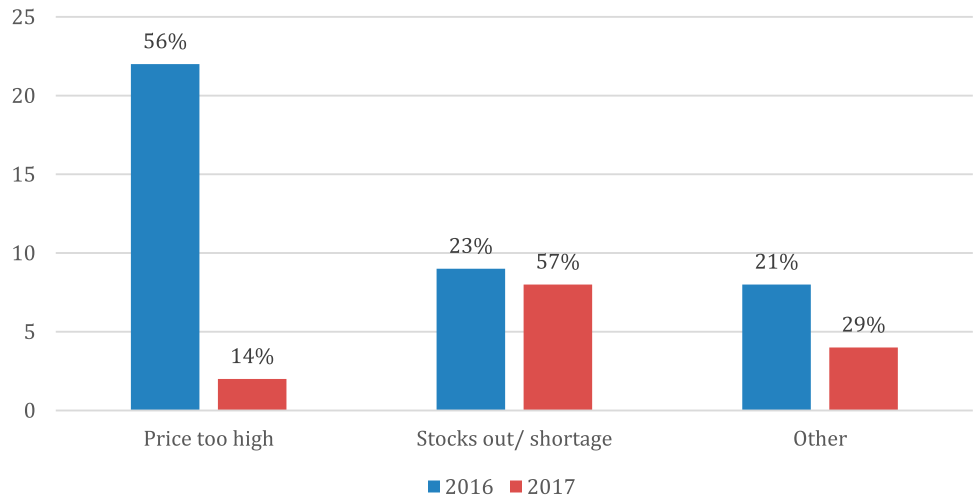


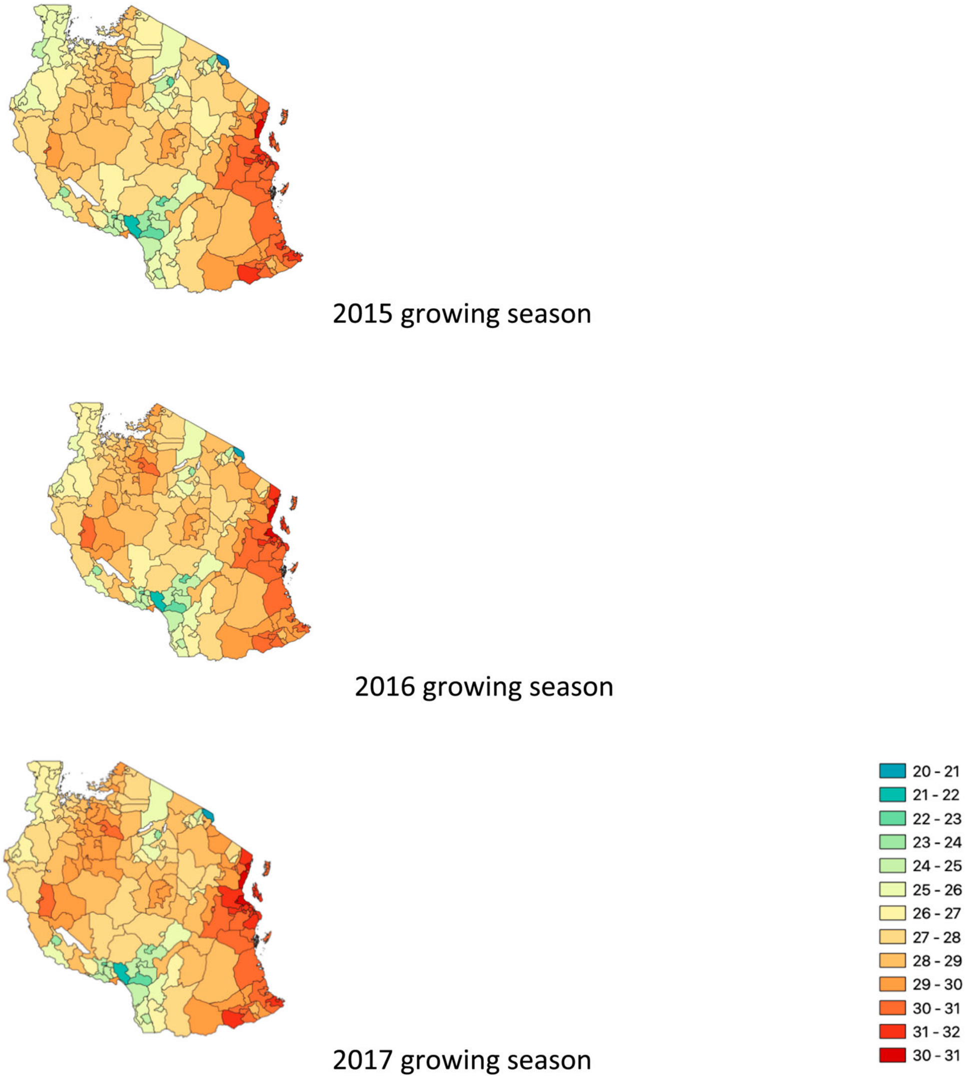
Figure 3. Reasons for fertilizer unavailability. Source: Author's calculations based on Cimmyt data.

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 relatively 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.

In addition to measuring precipitation, we also constructed two variables that control for the impact that temperature has on the adoption decision. The first measures the average maximum temperature during the growing season of the previous year. The second is a dummy variable indicating if the average maximum temperature was above 28 degrees celsius in that season (following Arslan et al., 2017). While the former controls for the impact of actual temperature on a continuous scale of degrees Celsius, the latter tests for heatwaves. Both variables were created based on the WorldClim database (WorldClim, 2022). WorldClim presents historical monthly weather data downscaled from the University of East Anglia's CRU-TS-4.03 database (Fick & Hijmans, 2017; Harris et al., 2014). Figure 4 shows the average maximum growing season temperature, mapped onto the districts of Tanzania, indicating a noticeable, if small, warming trend between years. For the regression analysis, the temperature variables are more disaggregated; we matched them to each household's location at a 2.5 (ca. 21 km) resolution.

4.2.2.2. Fertilizer. Mineral fertilizer is a cash-intensive agricultural input, making affordability an important determinant of technology adoption. We therefore include data on household assets and the price of fertilizer.[8] **Farm assets** measures the total value of farm-related assets held by the household in the year before the growing season in 1000 Tanzanian Shillings (Tsh). It was derived by adding all farm assets at their reported value and dividing it by 1000. **Fertilizer price** is the price for a 50 kg bag of fertilizer (averaged between top and basal fertilizer). Price data are from the APS community questionnaire at the village level, also measured in 1000 Tsh.

4.2.2.3. Demographic controls. Household size varies from 1 to 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


2015 growing season

2016 growing season

2017 growing season

Figure 4. Average maximum temperature during the growing season. Source: WorldClim database.

younger and often 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. Most often this member is also the household head (59% of the time) or their spouse (38% of the time). The activities range from farming-related groups like collective labour, marketing or learning groups to non-farm-related activities such as credit unions or Women's groups. Combining them into one variable follows the logic that there might be a network effect of technology diffusion when people meet regularly, and that social activities can economically empower smallholder farmers, for example through improved credit access in a farming cooperative (Isham, 2002). Indeed, out of 345 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 HQ)** and the walking time to focal plots in minutes (**plot distance**). Remote locations may have fertilizer less readily available and being further away from the farm may lead to less time spent attending to the crops. 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.

Organic fertilizers can be used as substitutes to chemical fertilizers, although field trials show that the two are in fact complementary to each other (Mugwe et al., 2009). This complementarity is also the premise of many approaches to sustainable intensification, such as Integrated-Soil-Management or Climate-Smart Agriculture (Holden, 2018). 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 in the dummy **intercropping** 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-fertilise' the soil with animal or compost manures, measured by **manure**. Of those respondents for whom data are available 44% leave farmyard manure in the field, and 11% use compost manure. 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).

5. Results

Results from the Probit regression are reported in Table 3. We estimated five models. Model I is the most similar to the previous study conducted for Ethiopia, Alem et al.'s (2010) estimation, to see if their findings hold in Tanzania. Model II adds input prices (the cost of fertilizer), 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 control variables.

6. Discussion

Our main finding is that the more abundant rainfall is in a growing season, the more likely farmers are to use chemical fertilizers on their maize plots in the following year. For each additional 10 mm of rain that a plot receives monthly, the probability that fertilizer is used increases by approximately 17–20%. This confirms key findings from the previous studies (Alem et al., 2010; Arslan et al., 2017; Dercon & Christiaensen, 2011; Kaliba et al., 2000). It shows that they are robustly significant even when accounting for actual fertilizer prices, the key contribution of this study.

Surprisingly, rainfall variability is positive and significant, while it is negative and significant for Alem et al. (2010). We chose to use only rainfall data during the main season, following the logic that erratic rainfall during the growing season makes fertilizer use more dangerous as it can burn the plant (drought) or result in N runoff (flood). The highly positive and significant marginal effect of around 4% suggests that this does not hold in our sample: perhaps farmers instead aim to counteract unreliable weather by applying more fertilizers. Alem et al. (2010), on the other hand, have used average rainfall over the whole year and not just the maize growing season. It might be due to the fact that their negative and significant effect thus captures other effects that are unrelated to agronomy (such as income effects of rain variability). 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. Both rainfall and rainfall variability change their signs when squared, which indicates that the relationship between precipitation and fertilizer is not linear.

The result also shows that lagged average maximum temperature during the growing season has a negative and significant impacts on farmers' chemical fertilize adoption decisions. According to our finding, a rise of 1 degree Celcius in the growing season's average maximum temperature is expected to reduce the fertilize use by 3.4–4%. The reason behind lower fertilizer use might potentially be due to income effect (i.e. reduced harvest/crop failure as a result of high temperature), but further investigation on smallholder technology adoption behaviour would be useful. However, the temperature shock dummy (i.e. lagged average maximum temperature during growing season exceeding 28°C) did not appear to share the same significant impacts. This supports the findings of Arslan et al. (2017) and Asfaw et al. (2016), which also show insiginicant impact of previous year's extreme heat on chemical fertilizers use.

We find no statistically significant effect of whether or not the household is female-headed, and tabulating 'female head' with 'fertiliser use' reveals that fertilizer 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

Table 3. PROBIT regression results.

	I	II	III	IV	V
Rain (10 mm), lagged	0.198***	0.187***	0.184***	0.178***	0.177***
	(0.028)	(0.042)	(0.041)	(0.042)	(0.041)
Rain^{2,} lagged	−0.006***	−0.005***	−0.005***	−0.005***	−0.005***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Rain variability	0.048***	0.049**	0.048**	0.048**	0.047**
	(0.014)	(0.020)	(0.021)	(0.021)	(0.022)
Rain variability^2	−0.002*	−0.001	−0.001	−0.001	−0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Avg. max.temperature, lagged	−0.010	−0.040***	−0.038***	−0.035***	−0.034***
	(0.008)	(0.010)	(0.010)	(0.011)	(0.011)
Avg. max. temperature > 28, lagged	0.035	0.062	0.058	0.050	0.046
	(0.049)	(0.062)	(0.061)	(0.062)	(0.062)
Female head	0.017	−0.001	−0.012	−0.003	−0.012
	(0.042)	(0.054)	(0.055)	(0.054)	(0.054)
Head age	−0.002*	−0.002	−0.002	−0.002	−0.002
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Head education (years)	0.011***	0.013**	0.011**	0.012**	0.011**
	(0.004)	(0.005)	(0.005)	(0.005)	(0.005)
Number of adult males	0.008	−0.013	−0.012	−0.010	−0.010
	(0.016)	(0.024)	(0.024)	(0.024)	(0.024)
Number of adult females	−0.005	−0.031	−0.030	−0.031	−0.031
	(0.015)	(0.020)	(0.020)	(0.020)	(0.020)
Number of children	−0.010	0.011	0.012	0.011	0.012
	(0.006)	(0.008)	(0.008)	(0.008)	(0.008)
Farm assets (1000 TSh)	−0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Plot distance on foot (15 min)	−0.011	−0.012	−0.011	−0.009	−0.009
	(0.008)	(0.012)	(0.011)	(0.011)	(0.011)
Perceived soil fertility	−0.043*	−0.079***	−0.075***	−0.078***	−0.075***
	(0.023)	(0.029)	(0.028)	(0.029)	(0.028)
Slope of plot	−0.021	−0.014	−0.013	−0.016	−0.015
	(0.017)	(0.020)	(0.020)	(0.021)	(0.020)
Region dummy North	−0.142***	−0.156***	−0.162***	−0.129**	−0.135**
	(0.035)	(0.059)	(0.059)	(0.060)	(0.060)
Fertilizer price (1000 TSh)		0.002	0.001	0.002	0.002
		(0.002)	(0.002)	(0.002)	(0.002)
Distance HQ (km)		−0.005***	−0.005***	−0.005***	−0.005***
		(0.001)	(0.001)	(0.001)	(0.001)
Intercropping				−0.053	−0.049
				(0.045)	(0.045)
Manure				0.042	0.036
				(0.047)	(0.047)
Conservation				0.065	0.062
				(0.041)	(0.041)
Social capital			0.062*		0.056
			(0.036)		(0.036)
Observations	1073	629	629	629	629

Notes: Marginal effects with Standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

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. This exemplifies a wider-reaching problem of agent-based modelling with the household as a unit of analysis in agronomic research.

The coefficients for farm assets are not statistically significant in any model, even though previous evidence suggests that fertilizer use depends strongly on purchasing power (Kaliba et al., 2000; Nambiro & Okoth, 2013). One reason could be that because weather affects the whole region, assets cannot easily be monetized to purchase fertilizers when e.g. everyone in the area is affected by drought. Alternatively, it might be that income effects are 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 fertilizer: being in a higher category of perceived soil fertility (self-reported from 1 to 5) decreases the likelihood of fertilizer use by 4.3% in model I. The effect almost doubles to 7.5–7.9% in models 2–5 when also accounting for the remoteness and the price of fertilizers. This makes sense as one might expect farmers to forgo pricey inputs when the soil is already more productive.

Each additional year of education of the household head significantly increases the probability of plot fertilization by about 1%. This confirms existing research and points at the importance of human capital for the successful diffusion or more sophisticated crop management practices (Waithaka et al., 2007). The marginal effect of social capital is also robustly significant, as expected from the literature (Isham, 2002). If the household head or their spouse regularly attend social networks such as extension groups, savings circles or women's groups, the probability of fertilizer use increases by approximately 6%.

We also show that location matters. Farmers in the North region are on average approximately 12–18% less likely to use chemical fertilizers than those in the South region, showing that these relationships are heterogeneous across space and that there may be location-specific characteristics that influence if fertilizers are used (political, environmental, economic and historical). For each additional 15 min on foot that a farmer lives away from their plot, they are up to 1% less likely to use fertilizers. This is to be expected, as fertilizers are a bulky input which could incur extra transport costs. The distance to the district headquarters, is also robust across estimations and confirms this point. Each additional km distance to the headquarters makes it 0.5% less likely that farmers apply fertilizers – that is 5 percentage points for each 10 km increase. This confirms existing research on the importance of road infrastructure and location in determining fertilizer use (Kaliba et al., 2000; Waithaka et al., 2007).

Interestingly, the price of fertilizers – a control not included by previous studies – returns non-significant results throughout. Most likely, the effect of higher fertilizer prices is already captured in the distance to district headquarters, as more remote locations would incur higher transport costs. As discussed above, 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 a longer time horizon.

7. Policy implications

The main finding from our empirical analysis is twofold: more rain in the previous year leads to higher fertilizer use this year, and when rainfall is more erratic (making fertilizer use risky in the absence of irrigation), farmers are *more* likely to apply it. As climate change is expected to make tropical rainfall patterns *less* reliant and increase the frequency of droughts and heatwaves, this suggests that costly technologies like fertilizer use will become increasingly unreliable as farmers' technology adoption pattern seems to be highly sensitive to climatic variability. Our study thus supports the growing base of evidence that traditional inputs like chemical fertilizers are an increasingly less reliable tool for food security as the climate crisis escalates because their adoption behaviour is strongly dependent on the climate itself (Alem et al., 2010; Arslan et al., 2017; Asfaw et al., 2016; Dercon & Christiaensen, 2011).

Agricultural policies for sustainable intensification, like Climate Smart Agriculture, aim to increase climate resilience of farmers and ensure food security for a growing population, but the term remains poorly defined. Recent research by Clay and Zimmerer (2020) found that in Rwanda, Climate Smart Agriculture serves to legitimize traditional agricultural practices from the Green Revolution but in practice disenfranchise the poorest farmers rather than meaningfully increasing their resilience. Similarly, Mdee et al. (2020, 2019) find no evidence that existing policies for sustainable intensification in Sub-Saharan Africa promote a narrative of sustainability and inclusivity but are in fact disconnected from the realities of those poor rural farmers most hardest hit by climate impacts. Our findings show that farmers are more likely to use fertilizers only when rainfall was abundant and maximum temperature was not very high in the previous growing season, and that they are more likely to apply fertilizers during periods of erratic weather, which can be dangerous in the absence of irrigation. This lends support to arguments questioning if traditional Green Revolution type inputs like fertilizer are a useful focus for sustainable intensification policies.

Chemical fertilizers can be extremely harmful to the environment, through nitrogen run-off into the soil waterways, and through nitrous oxide emissions that contribute to global warming (Hutton et al., 2017; Smil, 1991). Such externalities vary with land use practices, soil type and the type of fertilizer that is applied (Hutton et al., 2017; Palm et al., 2017; Tully et al., 2016). Low domestic production of fertilizers in lower-income countries means that they have a high footprint and that promoting their increased use can make such economies more dependent on global markets for their food security. At over 90%, SSA has the highest dependence on imported fertilizers among the developing world (Torero, 2015). This is problematic because it makes the fertilizer market vulnerable to currency fluctuation and the volatility of international fuel prices (on which fertilizer production and transport relies) (Timmer, 1975; Torero, 2015). Reducing chemical fertilizer dependence and applying environmentally sustainable agricultural practices are increasingly promoted (MacLaren et al., 2022).

On the one hand, our results confirm that as rainfall and temperature patterns become less reliable, chemical fertilizers are becoming an increasingly unreliable tool for policy makers who want to boost agricultural productivity for food security, because the extent to which smallholder farmers adopt fertilizers depends on is impacted strongly by both rainfall and temperature patterns. On the other hand, resource scarcity and poor quality soils can make it impossible to rely exclusively on organic methods, especially in the short term. Moreover, even if all Tanzanian maize farmers stopped using mineral fertilizers, rainfall variability and climate change would still affect them. Climate change is a global externality, and the poorest suffer its worst consequences as they often lack the means to adapt and become more climate resilient. Our results point to the importance of taking an integrated approach to agricultural policy such as Climate Smart Agriculture, which mainstreams agricultural development issues into other areas of development planning (FAO, 2021). For example, some use of mineral fertilizers is indispensable and better roads in remote rural areas could make them more accesible and affordable when they have to be used. At the same time, our results show that policies are needed to support the more ecological agricultural practices which sustainable intensification policies entail.

Research shows that policies which encourage combining mineral and organic fertilizers can reach equally as productive results at a lower cost for experimental evidence from Malawi (see Ngwira et al., 2013). These traditional methods can be a good complement to applying mineral fertilizers and may reduce the overall amount needed below the 200 N-1 ha aimed for by governments in SSA (Nyssen et al., 2017). However, although intercropping maize with legumes is common in Tanzania (Waithaka et al., 2007), our 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 most of the time. 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. There is a clear role here for policies that support farmers in adopting sustainable practices. Financial mechanisms for rural smallholder farmers, such as payments for ecosystem services, could be used as a policy tool to enable farmers to fallow their land who would otherwise be unable to afford doing so.

8. Conclusion

We study the relationship between rainfall as well as temperature risk and fertilizer use among Tanzanian maize farmers using data from the newly available 2016 and 2017 Agronomy Panel Survey (Chamberlin et al., 2018b). Our analysis fits into the growing literature on the impact that climate risks have on the adoption of agricultural inputs in SSA (Alem et al., 2010; Arslan et al., 2017; Asfaw et al., 2016; Dercon & Christiaensen, 2011). We add to this literature by also including observed input prices for fertilizers at the village level in addition to the level and variability of rainfall as well as temperature. Our results confirm existing research by showing that as rainfall becomes less reliable and global warming intensifies, costly agricultural inputs like chemical fertilizers are becoming increasingly less reliable as farmers' fertilizer use is sensitive to climatic variability. We show that this holds when fertilizer prices are taken into account. First because they are costly and therefore farmers are less likely to afford fertilizers following a 'bad year' due to weather shocks associated with climate risks. Second because mineral fertilizers are inherently unsustainable as they are produced from fossil fuels, a finite resource.[9] Policies are clearly needed to both improve the affordability of chemical fertilizers where they are still needed and to support the adoption of more sustainable agricultural practices, including financial mechanisms.

Our data covers maize in Tanzania, which is the East African country's main food crop. Estimates suggest that the maize growing area in SSA has increased by almost 60% since 2007 and it is well-reported that tropical areas are disproportionately hit by the adverse effects of climate change (Santpoort, 2020). Therefore, the issue at hand is extremely relevant to other countries where large parts of the rural population for their own subsistence and to feed a growing urban population.

Notes

1. Sustainable intensification management practices, like Climate Smart Agriculture (CSA) or Integrated Soil Fertility Management (ISFM) typically combine industrial inputs like chemical fertilisers and improved seeds with non-industrial practices like organic manure and intercropping (FAO, 2021; Vanlauwe et al., 2010).
2. There is a debate about why this has happened. Development economists identified population pressures as the main reason, while others attribute it to local and global political processes within which individual choice takes place (see Koning & Smaling, 2005).
3. Measured as the coefficient of variation (variance/mean).
4. 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.
5. There are three problems with applying OLS to discrete models. 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 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).
6. That is, qualitative information in a binary quantitative format (0–1)
7. Those data are only available for a very small subsample of the APS.
8. The preliminary analysis also included off-farm income and fertiliser transport costs, but we decided not to include those in the final model as they were not significant.
9. There is a potential third reason, although this it is not part of our empirical estimation. Relying on chemical fertilisers to replenish depleted soils might become less viable under extreme heat and risk of draught, as fertilisers can 'burn' the crop seed under these circumstances.

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Appendix. Variable overview

Variable	Unit	Type	Reason for including	Source
Fertilizer use	[0,1]	Dummy	Dependent variable	TZAPS
Rain, Rain^2	10 mm	Continuous	More rain relaxes liquidity constraints	CHIRPS
Rain variability, Rain variability^2	$\frac{\sigma}{\mu}$ (10 mm)	Continuous	Erratic rainfall makes fertilizer use risky	CHIRPS
Avg. max. temperature	Degrees celcius	Continuous	Higher temperatures negatively affect yield, thus increasing liquidity constraint	WorldClim
Avg. max. Temperature > 28	[0,1]	Dummy	Control for extreme temperature shocks	WorldClim
Female head	[0,1]	Dummy	Disadvantage in accessing technology	TZAPS
Head age	Years	Continuous	Older farmers have more experience, but perhaps less physical ability	TZAPS
Head education	Years	Continuous	Higher education more likely to adopt sophisticated technology	TZAPS
Male adults	Number	Continuous	Gender effects	TZAPS
Female adults	Number	Continuous	Gender effects	TZAPS
Children	Number	Continuous	Financial strain from having children age < 15	TZAPS
Farm assets	1000 TSh	Continuous	Asset wealth	TZAPS
Distance to plot on foot	15 min	Continuous	Less likely to attend to plot if further away	TZAPS
Perceived soil fertility	[1,2,3,4]	Ordinal	Less likely to fertilize fertile plots	TZAPS
Slope of plot	[1,2,3,4,5]	Ordinal	Production risk of high slope plots	TZAPS
Region dummy North	[0,1]	Dummy	Regional effects	TZAPS
Distance to district HQ	km	Continuous	Affordability / accessibility to inputs changes with location	TZAPS
Social Capital	[0,1]	Dummy	Network effects from attending regular group activity	TZAPS
Intercropping	[0,1]	Dummy	Organic N fixation from intercropping	TZAPS
Manure	[0,1]	Dummy	Organic N fixation from applying manure	TZAPS
Conservation	[0,1]	Dummy	Soil & water conservation practices	TZAPS