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Food security and adaptation impacts of potential climate smart agricultural practices in Zambia

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Abstract

This paper analyzes how a set of widely promoted agricultural practices, including reduced tillage, crop rotations, legume intercropping as well as the use of modern inputs, affect crop yields and their resilience (i.e. probability of disastrously low yields) in Zambia using panel data from the Rural Incomes and Livelihoods Surveys (RILS). The RILS data are merged with a novel set of climatic variables based on geo-referenced historical rainfall and temperature data to understand whether and how the effects of the practices analyzed here change with climatic conditions. We estimate the impacts on the level of maize yields and the probability of very low yields controlling for time-invariant unobservable household characteristics. We find no significant impact of minimum soil disturbance, positive impact of legume intercropping and a negative impact of crop rotation on maize yields, which is off-set by a significantly positive impact under highly variable rainfall conditions. We also find that the average positive impacts of modern input use are conditioned by climatic variables, whereas that of legume intercropping is robust to shocks. Timely access to fertilizer is the most robust determinant of yields and resilience. This paper provides important insights into the interplay between food security outcomes and climatic variables, and provides policy implications for targeted interventions to improve the productivity and the resilience of smallholder agriculture in Zambia in the face of climate change.[1]

JEL classification: O13,Q01, Q12, Q16, Q18

Key words: Maize productivity, food security, climate smart agriculture, climate change, panel data

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Contents

1. Introduction

The impacts of climate change on food security have been (and continue to be) discussed in many international policy and academic circles. It is widely accepted that our ability to contain the pace of climate change within the 2°C threshold in the long run is now limited and we will have to deal with the consequences of this at various levels (IPCC 2014; Rogelj *et al*. 2011; 2013). Based on global climate models we know that Sub-Saharan Africa (SSA) will be one of the most affected regions, with expected agricultural productivity decreases of up to 20% (for major food crops), and stubbornly high levels of poverty and food insecurity – especially in rural areas (Cline 2008). In spite of having relatively good rainfall compared to other parts of SSA, Zambia is highly exposed to climate change which exacerbates the changes in rainfall patterns and extreme weather events further increasing the high sensitivity of the agricultural sector (NCCRS 2010).

In the past 30 years, frequent rainfall anomalies and droughts have been observed in Zambia – especially in the southern and central regions – with resulting decreases in maize yields associated with these anomalies (Jain 2007). Although urban poverty has decreased in the last 20 years, rural poverty has stayed around 80% and the proportion of the population which is malnourished has increased by 23% since 1990 (Chapoto *et al*. 2011; Garrity *et al*. 2010). Most of the rural poor (75% of total farming population) are subsistence farmers that rely on rainfall for production (Jain 2007). This makes it imperative to have a thorough understanding of how farmers' practices and climate change affect productivity if food security is to be improved. Climate smart agriculture (CSA) seeks to achieve this by sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change and reducing and/or removing greenhouse gases emissions relative to conventional practices (FAO, 2013). Site specific and rigorous analyses are needed to identify potential practices that may be part of a successful CSA strategy under various climatic conditions.

Most of the studies on climate change and productivity in Zambia so far have been based on simulations lacking detail at the household level or cross sectional data lacking detail on climate variables. Large scale panel studies with detailed geo-referenced data on climate and agro-ecological characteristics have been absent from the literature. This paper fills this gap by using large scale household panel data from RILS together with a novel set of climatic variables based on geo-referenced data on historical rainfall and temperature as well as soil characteristics to assess the impacts of potential CSA practices on maize productivity in

Zambia. The CSA practices we consider are: minimum soil disturbance, crop rotation, and legume intercropping. We also consider the impact of the use of inorganic fertilizers and improved maize seeds on productivity. Any of these practices are considered potentially CSA, based on their potential to contribute to increased productivity and incomes, adaptation and/or reduced GHG emissions. The main task in assessing CSA potential of particular practices is to identify their potential contribution to any one of these three objectives and potential tradeoffs between them. In this paper we focus solely on the productivity/adaptation outcomes.

The effects of most CSA practices usually go beyond the impacts on the levels of production by decreasing the variability of production over time through improvements in the capacity to deal with extreme weather events (e.g. droughts or late onset of rains). Empirical research on the effects of various practices on the probability of disastrously low productivity is mostly absent from the literature to date. We also address this gap in this paper in order to identify potential synergies between food security and adaptation to extreme weather events.

We provide an overview of climate change, agriculture and food security in Zambia in the next section, before looking at the literature to date on the practices we focus on in section 3. In section 4, we introduce our data sources and descriptive statistics. We briefly explain our empirical methodology and independent variables in section 5; discuss results in section 6 and conclude with policy recommendations in section 7.

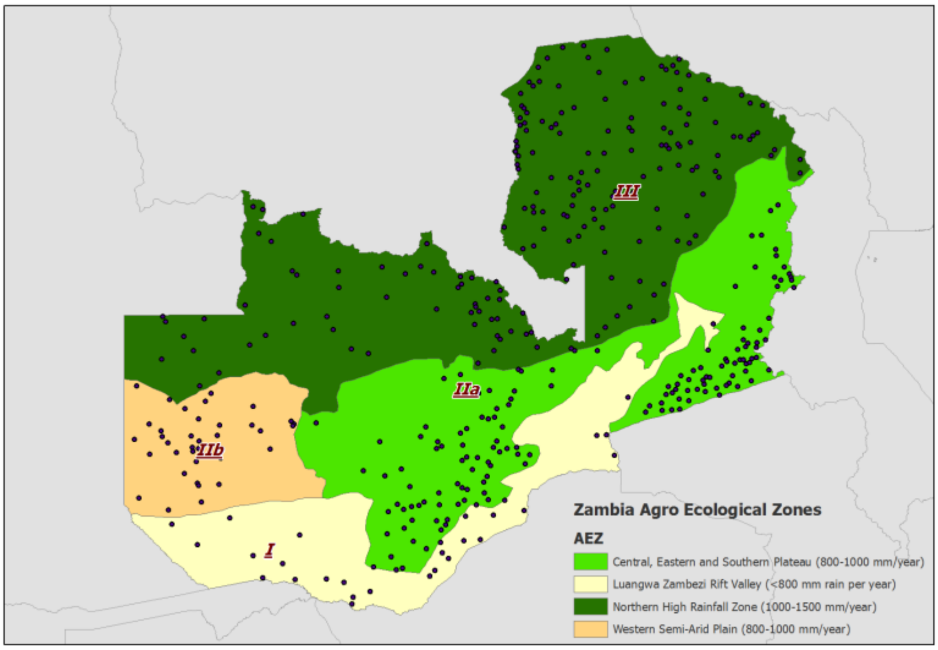
2. Agriculture, food security and climate change in Zambia

The agricultural sector in Zambia accounts for approximately 20% of GDP (ZDA, 2011; World Bank 2013). 64 % of Zambians live in rural areas where rain-fed subsistence agriculture is the dominant economic activity (Govereh *et al.* 2009). Maize is the most important staple crop; over half the calories consumed in Zambia are from maize, although this proportion is decreasing (Dorosh *et al.* 2009).

Despite rapid economic growth over the last decade, driven primarily by an expansion of mining, poverty levels are very high especially in the rural areas (around 80%; Chapoto *et al.* 2011). 75% of Zambians earned equal to or less than USD 1.25 per day (World Bank, 2013). Agricultural commercialization and surplus production are concentrated in the hands of a small proportion of farmers, while over half of Zambian farmers sell little or no crops, creating a strong link between productivity and food security (Hichaambwa and Jayne, 2012).

Predicted impacts of climate change in Zambia differ between the country’s three agro-ecological regions (AER), defined mainly by rainfall (Figure 1). In the western and southern parts of the country, rainfall has been low, unpredictable and poorly distributed for the past 20 years, despite historically being considered a good cereal cropping area (Jain 2007). The central part of the country is the most populous and has the highest agricultural potential, with well distributed rainfall and fertile soil. The northern part of the country receives the highest rainfall but has poorer soils. About 65% of this region is underutilized (Jain, 2007). Despite considerable agricultural potential, Zambia’s maize harvest fails to meet national market demand on average one year in three (Dorosh *et al.* 2009).

Figure 1. Agro-ecological regions of Zambia and RILS survey sites



The dominance of rainfed agriculture in Zambia means that climate change poses a considerable challenge. Droughts in 1991/1992, 1993/1994, 1994/1995, 2001/2002 and 2004/2005 seasons had significantly large negative impacts on yields and consequently on food security (FAOSTAT, 2012). Global climate models (GCM) predict that temperatures will increase in Southern Africa by 0.6-1.4°C by 2030 (based on median projections of average temperature change from 1980–2000 to 2020–2040 of 20 GCMs). Rainfall predictions are more ambiguous, with some models suggesting increased precipitation, and some suggesting reduced precipitation (Lobell *et al.* 2008). Compared to long term changes in levels, variability in rainfall affects agriculture more significantly (Thurlow *et al*. 2011). Crop yields in the region are predicted to suffer, with maize yields projected to fall by around 30% in the absence of adaptation measures (Lobell *et al.* 2008; Müller and Robertson, 2014). Zambia-specific models predict decreased rainfall in AER I, IIa and IIb and increased rainfall AER III, as well as significant warming in AER I. Projected maize yield losses in Zambia are concentrated in regions where most of the maize production takes place (Southern and Eastern provinces), underlining the importance of understanding how climate change affects yields and conditions the impacts of CSA practices (Kanyanga *et al*. 2013).

The impact of climate change on crop production is not limited to total rainfall and average temperature effects: intra-seasonal variation is also important. A 'false start' to the rainy season due to erratic rainfall can be disastrous for crop establishment. Similarly, intra-seasonal dry spells may be more damaging to growth than low total rainfall (Taddross *et al*. 2009; FAO, 2011). Very high maximum temperatures during the growing season are also significantly detrimental to yields (Thornton and Cramer, 2012). Such temporal variation is predicted to increase in many parts of Africa under climate change scenarios (Boko *et al.* 2007).

The Government of Zambia has been promoting various agricultural practices to improve food security. The most important (and controversial) of these policies is the fertilizer subsidies, which take around 60% of the Ministry of Agriculture's budget and are subject to various inefficiencies (Mason and Jayne, 2013; Xu *et al.* 2009). Conservation farming (including minimum soil disturbance, crop rotation and legume intercropping) is another practice that has been promoted as an official priority of the Ministry of Agriculture and Livestock (MAL) since 1990s with extensive support from international agencies (Baudron *et al.*, 2007; Mazvimavi, 2011).[2] Most conservation farming (CF) promotion included subsidized fertilizer and seed packages as well. Adoption of the full CF package consisting of the three practices outlined above has been very low and unstable in most parts of the country, as the existing technologies being promoted within this package are more suitable to the low-

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[2] Conservation Farming package as promoted in Zambia consists of following practices: (1) reduced tillage on no more than 15% of the field area without soil inversion, (2) precise digging of permanent planting basins or ripping of soil with a *Magoye ripper* (the latter where draft animals are available), (3) leaving of crop residues on the field (no burning), (4) rotation of cereals with legumes and (5) dry season land preparation (CFU 2007). Conservation Farming Unit is recently promoting the incorporation of nitrogen fixing crops into the CF package, however the 5 main principals remain essential. Note the differences between this and the more general Conservation Agriculture (CA) package that consist of three principles: minimum mechanical soil disturbance; permanent organic soil cover; and crop rotation (FAO 2012). While these principles were treated as inseparable in the past, recent thought on CA is more flexible in acknowledging that one or more of the components may provide needed food security and adaptation benefits in many smallholder systems in Southern Africa.

rainfall regions with high rainfall variability (Haggblade and Tembo, 2003). High levels of non-adoption of CF practices call for a better understanding of the effects of these practices on yields and the variability thereof under different climatic conditions using large scale data (Arslan *et al.* 2014). Most literature on the impacts of CF is based on either experimental plots or data from small samples of farmers who have participated in related promotion activities, providing only suggestive evidence. This paper addresses this gap in the literature reviewed in more detail in the next section.

3. Productivity implications in the literature

Productivity implications of inorganic fertilizers and improved seeds are well known from the large body of literature on the impacts of green revolution technologies (Byerlee *et al.* 1994, Desai 1990, Smale and Jayne 2003, Evenson 2003), therefore they are not reviewed here in detail. Other practices analyzed in this paper (minimum tillage, legume intercropping and crop rotation) are associated with Conservation Agriculture (CA, the origin of CF as promoted in Zambia). We therefore review the literature assessing the productivity potential of CA practices in particular, as well as the literature on sustainable land management in general in what follows.

3.1. Productivity implications in general

There are a number of meta-studies which attempt to quantify the average benefits (environmental and yield) of practices associated with CA. Lal (2009) reviewed the literature on soil conservation globally and concluded that mulching and no-till clearly improved soil health, sometimes improved yields (depending on conditions) and usually improved profits (due to lower inputs). Farooq *et al.* (2011) reviewed 25 long term CA trials (mainly from North America, Australia and Europe) and found that crop yields showed a slight increase (that increases over time) compared to conventional tillage. The CA advantage is most pronounced in dry conditions. Pretty *et al.* (2006) gathered evidence on the effect of a wide range of resource conserving agricultural interventions (including zero/reduced tillage) from 286 developing country case studies, where ‘best practice’ sustainable agriculture interventions had occurred. For interventions related to maize systems, average yield improvement was over 100%, although most of these case studies were in large scale systems in Latin America and none were strictly CA combining various other resource conserving interventions with zero/reduced tillage.[3] The methodologies of the case studies reviewed are also less than robust relying on with/without comparisons without thorough impact analyses.

Branca *et al.* (2011) undertook a comprehensive, empirical meta-analysis of 217 individual studies on CA globally. Their empirical analysis showed that improved agronomic practices such as cover crops, crop rotations (especially with legumes) and improved varieties have increased cereal productivity by 116% on average across the studies consulted. Similarly, reduced tillage and crop residue management is associated with a 106% increase, and agroforestry techniques with a 69% increase. Tillage management and agroforestry were found to be particularly beneficial in dry agricultural areas.

It should be noted, however, that Pretty *et al.* (2006) purposely selected ‘best practice’ examples, and both Pretty *et al.* (2006) and Branca *et al.* (2011) mainly consider those studies examining CA practices actively promoted by various CA projects, as opposed to “spontaneous” adoption.[4] Hence, although there is general agreement that some of the CA practices can improve yields under at least some circumstances, a debate continues over how extensive these circumstances are in practice.

There are a number of reasons why CA may not be suitable in particular contexts (McCarthy *et al.* 2011; Nkala *et al.* 2011; Giller *et al.* 2009; Gowing and Palmer, 2008; Knowler and Bradshaw, 2007; Lal *et al.* 2004). For instance, crop residues are often used as animal feed: the benefits of mulching with crop residues may not be worth the trade-off of reduced livestock numbers. Similarly, there may be a trade-off between labor saved on tillage and labor spent on increased weeding, in the absence of herbicides. These authors also raise questions about which specific element(s) of CA drives yield improvements as many published studies do not vary only one factor, but instead examine the effects of CA overall (Giller *et al,* 2009; Gowling and Palmer, 2008). This often includes confounding changes to herbicide and fertilizer regimes. While proponents of CA argue that the method is ‘holistic’, and thus cannot be reduced to a single element, such information would allow for ongoing refinement of the CA approach.

3.2. Productivity implications in Zambia

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[3] These packages included contour ploughing, grass barriers, legume rotations/intercropping, farmer-to-farmer learning as well as other incentives (Supporting Material for Pretty *et al.* 2006).

[4] Publication bias is another caveat to be kept in mind for meta-analyses, where results with positive impacts are expected to be published more than those with no/negative impacts.

There is a small literature that assesses the benefits of CF as practiced in Zambia. Langmead (undated) analyzed pooled data from 5 trials in AERs IIa and III during the 2002/2003 season. He finds that timely planting and weeding is the most important determinant of yields and yield variability. Timely conventional farming increased yields by 50%, and CF (planting basins plus lime application) increased yields by 68%. The authors conclude that facilitating timeliness is the most important contribution of CF.

Rockström *et al.* (2009) presented results from a 2 year on-farm trial of different farming systems in Zambia, amongst other SSA countries.[5] They compared the yields of farmer managed CF plots with conventional tillage plots (both with fertilizer inputs) and found that maize yields on the CF plots (> 6tons ha^{-1}) were double those on the conventional plots, with no significant difference between the use of planting basins and rip lines. The authors also noted that CA appeared to improve yields most directly by improving soil moisture, especially for the lowest productivity systems. They concluded that for smallholder farmers in savannah agro-ecosystems, CA is primarily a water harvesting strategy, valuable even when crop residue retention is not practiced. They also noted that the soil moisture effect works in conjunction with fertilizer application, hence, at least some fertilizer input was required for crops to take advantage of the additional soil moisture (based on data from Kenya and Ethiopia).

Similar findings with regard to soil moisture benefits were presented in two related papers by Thierfelder and Wall (2009; 2010). The authors undertook a multiyear, researcher-managed cropping trial at Monze (in Southern Zambia with annual rainfall of 748 mm) to evaluate the impact of tillage practices on water infiltration, runoff erosion and soil water content. Infiltration rates were 57-87% higher on CA plots. Resulting higher soil moisture levels were found to improve yields in poor seasons, demonstrating that CA has the potential to reduce the risk of crop failure due to low or poorly distributed rainfall.

A third paper by Thierfelder and Wall (2010a) used data from the same experiments to assess the impact of crop rotations. Mono-cropped maize was compared to maize-cotton-sunhemp rotations under different tillage and CA regimes.[6] Soil quality as measured by aggregate stability, total carbon and earthworm populations was significantly improved on CA plots. Maize yields were 74-136% higher under the 3-species CA rotation regime, and even in a

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[5] The Zambian trial site was in Chipata (Eastern Province), a moderate rainfall location (approximately 1,000 mm annually).

[6] Sunhemp, i.e. *Crotalaria juncea*, is a leguminous manure crop.

simple maize-cotton rotation were 38-47% higher. Yield-increasing benefits of rotation were recorded even in the absence of pests and diseases, indicating that crop rotation has benefits beyond pest and disease control.

FAO (2011b) reported that CA (defined by the use of planting basins or rip lines) yielded an average of 3tons ha^{-1}, 42% more than conventional draft tillage, in Chongwe (in south-central Zambia with rainfall between 600 and 1,000 mm). It is not clear, however, how many farmers participated in the focus group discussions, or how they were selected for the study. Due to the unfortunate lack of background information in this report, these results can be considered indicative only.

In addition to the trial-based analyses, there are also some publications based on socio-economic surveys of farmers. Haggblade and Tembo (2003) conducted a comprehensive CF assessment in central and southern provinces during the 2001/2002 cropping season. The authors assess the yield and profit impacts of CF, controlling for other variables (such as fertilizer use) that could otherwise confound findings.[7] 125 randomly selected farmers, with both CF and conventional tillage plots, were surveyed. Average maize yields were 3.1 tons ha^{-1} under basin planting CF and 1.3 tons ha^{-1} under conventional tillage. Of this large difference, the authors found that the CF technique itself was responsible for 700 kg of yield improvement, and increased fertilizer and hybrid seed use was responsible for 300-400 kg. A large positive impact was found due to earlier planting, which is facilitated by CF as mentioned above. Haggblade *et al.* (2011) also confirm this using a simulation model calibrated with Post Harvest Survey data from 2004 in order to assess the productivity impact of CF for smallholder cotton farmers in AER IIa. They show that CF has the potential to increase yields (of both maize and cotton) by around 40% due to early planting and improved soil quality.

Umar *et al.* (2011) interviewed 129 randomly selected farmers from a CF adopters list provided by the Conservation Farming Unit in the Central and Southern provinces of Zambia. Simple univariate analysis of yields showed significantly higher yields under planting basins than under conventional tillage, whereas ripping showed no significant yield benefits. This study, however, is mainly descriptive as it cannot separate the confounding impacts of other inputs and resource base from those of tillage practices.

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[7] This is particularly important given that many CF programs in Zambia have been promoted through the provision of ‘input packs’ from sponsors, which contain hybrid seeds, fertilizer, lime and other productivity enhancing materials.

A different approach is taken by FAO (2011c) in their assessment of CA and climatic risk in Southern Africa. The authors used the agricultural production systems simulator models (APSIM) and concluded that in semi-arid environments, CA can improve yields in drier seasons and thus improve climate change resilience. In sub-humid environments, they found that CA offered little yield benefit at least in the short term. A key reason for this is the danger of water logging which can occur in wet seasons, as also mentioned by Thierfelder and Wall (2009; 2010).

Based on the literature reviewed above, the evidence for improved yields indicates potential for significant improvement but is based on less than robust research methods, as some of the studies are potentially subject to endogeneity or selection bias, some conduct only simple comparisons confounding impacts of CF with other variables, some lack adequate background information to assess the quality of the research, and others rely on simulations rather than observed data. While it is clear that CA and CF practices have the technical potential to increase yields, particularly in drier parts of Zambia, how large this effect is, how much of that can be attributed to the practice itself (rather than changes in inputs and timing of cropping operations) and how it interacts with climatic variables requires further research.

This paper contributes to this literature by using a novel data set that combines large scale panel data from households with geo-referenced data on historical rainfall and temperature as well as soil characteristics at the standard enumeration area (SEA) level to estimate the impacts of various potential CSA practices on maize yields controlling for unobserved household heterogeneity that may confound the analyses based on cross sectional data. Given the fact that most studies confound the impacts of fertilizers and improved seeds with those of other practices, we explicitly analyze these two modern practices to identify their impacts on productivity and resilience, as well as to determine how these impacts change in response to climatic stress.

4. Data & Descriptive Statistics

Our main data sources are two rounds of Rural Incomes and Livelihoods Surveys (RILS) conducted in 2004 and 2008. These surveys are the second and third supplemental surveys to the nationally representative 1999/2000 Post-Harvest Survey (PHS). The supplemental surveys, carried out by the Central Statistical Office in conjunction with the Ministry of Agriculture, Food, and Fisheries (MAFF) and commissioned by the Food Security Research Project (FSRP) of Michigan State University, were designed to study options to improve crop production, marketing, and food consumption among small scale farmers.[8] The first panel captured data from 5,358 households for the 2002/2003cropping season; 4,286 of these households were re-interviewed in the second panel (gathering data on the 2006/2007 season) that extended the total sample size to around 8,000 households.[9] We use plot-level data from households that are interviewed in both surveys, covering 4,808 and 4,966 maize plots in the first and second panels, respectively.

We merge RILS data with historical rainfall and temperature data at the SEA level to control for the effects of the levels and variations in rainfall and temperature on productivity. Rainfall data come from the Africa Rainfall Climatology version 2 (ARC2) of the National Oceanic and Atmospheric Administration's Climate Prediction Center (NOAA-CPC) for the period of 1983-2012. ARC2 data are based on the latest estimation techniques on a daily basis and have a spatial resolution of 0.1 degrees (~10km).[10] Our temperature data are surface temperature measurements at 10 day intervals (i.e. dekad) for the period of 1989-2010 obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). We also use data from the Harmonized World Soil Database (HWSD) to control for the effects of soil nutrient availability and soil pH levels on productivity. The HWSD has a resolution of 30 arc-seconds and combines existing regional and national updates of soil information worldwide.[11]

Using the ARC2 data, we create the following variables relevant for productivity: total rainfall, average and maximum daily temperatures, an indicator variable for false onset of the rains[12] - all for the growing seasons covered by the RILS (i.e. 2002/2003 and 2006/2007), and the coefficient of variation of rainfall in the growing season since 1983. Maize productivity is shown to decrease significantly when the growing season maximum temperatures exceed 28°C, as well as with false onsets and dry spells (Thornton and Cramer, 2012; Tadross *et al.*, 2009). Using the HWSD we define two categories of soil nutrient availability constraints: moderate and severe/very severe.

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[8] MAFF was called Ministry of Agriculture and Cooperatives (MACO) during the 2008 surveys, and is now called Ministry of Agriculture and Livestock (MAL). FSRP has recently been transformed into a local institute called Indaba Agricultural Policy Research Institute (IAPRI).

[9] For more details about the surveys and other published work based on RILS see CSO (2004, 2008); Megill (2005) and Mason & Jayne (2013).

[10] See http://www.cpc.ncep.noaa.gov/products/fews/AFR_CLIM/AMS_ARC2a.pdf for more information on ARC2 algorithms.

[11] See http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/ for more information.

[12] False onset is defined as an onset (2 consecutive dekads of at least 50 mm rain starting in October), followed by a dry dekad (less than 20mm rainfall) within 20 days of the onset (Tadross *et al.*, 2009).

Table 1 reports the total rainfall, average and maximum temperatures and the percentage of SEAs with a false rainy season onset by AER. We can see that the growing season rainfall in our data conforms with the agro-ecological region standards presented in Figure 1, with rainfall increasing from southern to northern regions. Growing season rainfall between the two seasons slightly decreased in all but one AER, whereas both the average and the maximum temperatures have slightly increased. AER I is the region with the highest share of SEAs with a false onset, and this share has decreased in all AERs except in IIb (where it increased from 6% to 14%).

Table 1. Growing season rainfall (mm), temperature (°C) and false onset (% of SEAs) by AER and year

	Rainfall		**Avg. Temp.**		**Max. Temp.**		**False onset**	
AER	**02/03**	**06/07**	**02/03**	**06/07**	**02/03**	**06/07**	**02/03**	**06/07**
I	614.8	658.9	23.8	24.1	28.7	28.8	71	51
IIa	813.2	766.2	22.1	22.4	26.8	27.1	71	24
IIb	893.0	854.8	22.9	23.0	28.0	28.3	6	14
III	1008.3	985.4	21.1	21.3	25.9	26.3	67	2
Average	**893.8**	**869.7**	**21.9**	**22.1**	**26.6**	**26.9**	**63**	**17**

Table 2 reports non time-varying geo-referenced variables by agro-ecological region: soil nutrient constraints, soil pH levels, and the coefficient of variation in the growing season rainfall since 1983. Thirty six per cent of the SEAs in the whole country face severe/very severe soil nutrient availability constraint. AER I has the lowest share of severe soil nutrient constraints with 6%, whereas this proportion is around 40% in the rest of the country, as well as the best soil pH levels for maize cultivation (maize grows best in soils with pH levels between 5.8 and 6.5).[13] AER I, however, has the highest rainfall variability. Both pH levels and rainfall variability decrease from south to north, with expected opposing effects on productivity.

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[13] Note that, taking into account all other plant nutrients (Nitrogen, Phosphorus and Potassium), AER I is classified only marginally suitable for maize and many other crops by Zambia's Ministry of Agriculture and Cooperatives (MACO 2003).

Table 2. Time-invariant geo-referenced variables by AER

AER	Moderate Nutrient Const. (%)	Severe/Very severe Nutr. Const. (%)	Avg. pH level	CoV of Rainfall
I	30	6	6.10	0.24
IIa	21	40	5.66	0.21
IIb	42	37	5.75	0.20
III	49	37	5.29	0.18
Average	**36**	**36**	**5.53**	**0.20**

Table 3 summarizes the shares of maize plots cultivated with the 5 practices analyzed in this paper and key combinations among them (all indicators equal to one if a household used the practice on that maize plot). Minimum soil disturbance (MSD) indicates plots that have been treated with planting basins or zero tillage, crop rotation (CR) indicates plots that have been planted with different crops during the 3 years around each survey,[14] legume intercropping (LEGINT) indicates plots intercropped with legumes, and inorganic fertilizer (INOF) and improved seed (IMPS) indicate plots that have been cultivated using these modern inputs.

Table 3. Population shares of adoption of agricultural practices and key combinations

Year	2004	2008	Signif.
MSD	0.030	0.043	***
CR	0.239	0.361	***
LEGINT	0.047	0.029	***
INOF	0.374	0.391	
IMPS	0.436	0.476	***
MSD+CR	0.009	0.021	***
MSD+LEGINT	0.001	0.001	
MSD+INOF	0.010	0.008	
MSD+IMPS	0.010	0.010	
CR+LEGINT	0.007	0.007	
CR+INOF	0.087	0.143	***
CR+IMPS	0.079	0.146	***
LEGINT+INOF	0.011	0.007	**
LEGINT+IMPS	0.014	0.006	***
INOF+IMPS	0.217	0.259	***
CR+INOF	0.052	0.098	***
LEGINT+INOF+IMPS	0.007	0.003	***

Note: *, ** and *** indicate that the mean differences over time are significant at 10%,5% and 1% levels, respectively.

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[14] Most common maize rotations in our data include groundnuts, cotton and cassava. In total 58% of maize plots are rotated with non-leguminous crops. The results remain the same when we restrict the rotation indicator to legume rotations only.

MSD was practiced on 4% of all maize plots in 2008 (up from 3%), CR was practiced on 36% of plots (up from 24%) and LEGINT was practiced on 3% of plots (down from 5%). The most common practice is IMPS, which is used on around 48% of plots in the 2006/2007 season with a significant increase over time. This is followed by INOF, which is used on 39% of plots in both years. The most common combinations include CR, INOF and IMPS, where 26% of plots were cultivated with INOF and IMPS at the same time. Around 15% and 10% were cultivated with CR in combination with IMPS and INOF, respectively, in 2008. All other combinations are practiced on very small numbers of plots preventing econometric analyses of the effects of combinations of practices on productivity.

Given the very low numbers of observations on combinations of practices, we analyze the impacts of each of these 5 practices holding constant the use of other practices at their sample average levels in what follows. Table 4 shows maize yields by practice and year. Average maize yields are consistently (and statistically significantly) higher for households that use CR, INOF and IMPS in both years. Yields were (statistically significantly) lower for those who practiced MSD in 2008, but this was not true in 2004.

Table 4. Maize yields (kg./ha) by practice and year

	2004		**2008**	
Practice	**No**	**Yes**	**No**	**Yes**
MSD	1,580	1,495	*1,551*	*1,317*
CR	*1,538*	*1,703*	*1,513*	*1,589*
LEGINT	1,576	1,619	1,538	1,629
INOF	*1,320*	*2,011*	*1,206*	*2,060*
IMPS	*1,417*	*1,786*	*1,229*	*1,884*

Note: Differences between the two groups within a year are significant if *italic*

In addition to maize yields, we also analyze the impacts of these practices on the probability of very low yield and yield shortfall. Low yield variable equals to one if the yield on that plot is more than one standard deviation below the provincial average yield, and the yield shortfall variable equals to the difference between provincial average yield and the yield for plots that have a yield shortfall (this variable equals to zero for plots that have yields equal or greater than provincial average).

Table 5 summarizes all dependent variables by AER to investigate the spatial variation in these variables.

Table 5: Dependent variables by AER and year

	Maize Yield (kg./ha.)		Share with low yield		Yield shortfall (kg.)	
AER	**2004**	**2008**	**2004**	**2008**	**2004**	**2008**
I	1,082.7	1,219.2	0.05	0.07	558.6	495.8
IIa	1,732.8	1,565.0	0.10	0.11	768.5	726.4
IIb	740.1	901.1	0.14	0.14	395.8	427.5
III	1,710.5	1,776.0	0.13	0.14	717.4	805.2
Average	**1,577.9**	**1,540.6**	**0.11**	**0.12**	**694.6**	**707.7**

Overall average maize yields were around 1.5 tons per ha in both years. Although AER III has the highest average yields, it also has the highest share of plots with low productivity and the highest average yield shortfall. Lowest average yields as well as the lowest average yield shortfall are found in AER IIb.

Our dependent variables seem to show significant variation by AER and year according to descriptive statistics. There are many other dimensions along which we expect these variables to vary, which are taken into account in the econometric analyses in the next section. We pay special attention to exploit the panel structure of the data in our empirical models as explained in the next section.

5. Empirical Models

5.1. Maize Productivity

Modeling the effects of agricultural practices on agricultural production is inherently subject to various endogeneity problems, as adoption behavior is not random and farmers that adopt a given technology are likely to have unobserved characteristics that are correlated with their productivity (Mundlak, 2001). This constitutes the standard self selection problem causing bias in estimated parameters of the production function. The instrumental variables approach is usually used to address this problem, where an instrumental variable (IV) that is correlated with the endogenous variable in question (e.g. adoption of MSD) and not correlated with the error term in the outcome equation (yield) is necessary to establish causality. Finding variables to satisfy these requirements is usually a challenge faced by empirical econometric models. This challenge is multiplied when there are multiple endogenous variables and panel data methods are used, as in this paper.

Panel data (fixed effects) models control for time-invarying household variables that are unobserved and can address this endogeneity inasmuch as the selection into adoption is caused by time-invarying household characteristics. Most common forms of selection arise due to our inability to observe farmer "ability" or "openness to innovation," which can be expected to change little over short periods of time. Given that our data cover two seasons that are only 4 years apart from each other, we use the fixed effects model to control for the unobserved household characteristics in order to identify the impacts of these practices on productivity. To the extent that endogeneity of adoption of these practices is caused by time-invariant characteristics, our approach also controls for potential endogeneity.

We model the maize yield by using the following reduced form equation:

$$Y_{pt} = \alpha X_{pt} + \beta MSD_{pt} + \chi CR_{pt} + \delta LEGINT_{pt} + \gamma INOF_{pt} + \theta\, IMPS_{pt} + e_{pt} \qquad (1)$$

where Y_{pt} is the maize yield on plot *p* at time *t*; *X* is a vector of variables including household and plot characteristics including climatic and agro-ecological variables, as well as provincial controls; *MSD, CR, LEGINT, INOF* and *IMPS* are dummy variables indicating maize plots that have been cultivated with the corresponding practice in year *t;* and *e* is a normally distributed error term. Two econometric challenges arise because, *(i)* all adoption variables are potentially endogenous causing the error term to be correlated with the right hand side variables; and *(ii)* the error term is not *iid* as it includes time-invariant unobservables that are correlated with yields (i.e. $e_{pt} = u_{pt} + v_p$ where u_{pt} is a normally distributed error term independent of the *rhs*, and v_p are time invariant unobserved effects (Wooldridge, 2002, Ch. 15)).

The first challenge is usually addressed by an IV strategy, where one has to find at least 5 instruments correlated with the adoption of each practice in equation (1) but not correlated with maize yields except through their impact on adoption. Moreover, these IVs have to be time-varying in a fixed effects framework, which adds another challenge to the standard nonlinear IV approach (i.e. the incidental parameters problem).

The second challenge can be addressed by modeling the unobserved time-invariant heterogeneity using fixed (FE) or random (RE) effects methods. Fixed effects models treat the unobservables as parameters to be estimated that can be correlated with the *rhs*, whereas the random effects models treat them as a random variable uncorrelated with the *rhs*, whose probability distribution can be estimated from data (Wooldridge, 2002). We test the unrelatedness assumption of RE using the Hausman test and strongly reject it using various specifications, therefore we use the FE model in our analysis. It is important to note that the FE approach also addresses the first challenge mentioned above inasmuch as the endogeneity of adoption is caused by time-invariant unobserved heterogeneity. Given the challenges of finding 5 reasonably strong IVs that are time-variant and the dimensionality problem of estimating binary models with FE and IV, our approach is the best option to identify the determinants of yields using a two-period panel data spanning 4 years.

5.2. Low Production Probability and Yield Shortfall

In addition to the productivity analyses as explained above, we also conduct analyses to understand the impacts of the practices analyzed here on the probability that a household has disastrously low production and on the yield shortfall. The probability of very low production can be modeled within the latent variable framework, where we observe the indicator variable equal to one if the maize yield was more than one standard deviation below the provincial average yield during the survey year:

$$D_{pt} = 1 \ \ if \ Y_{pt} < \left(\bar{Y}_{jt} - SD_{jt}\right), \ \text{0 otherwise.} \qquad (2)$$

$D_{pt}$is the disaster probability on plot p at time t, $Y_{pt}$is the yield on plot p at time t, $\bar{Y}_{jt}$ is the average maize yield in province j (where the plot p is) in time t and $SD_{jt}$is the standard deviation of yield in province j at time t. Assuming a normal distribution for this probability, we estimate its determinants using a probit model with population average framework to model the unobservable effects.

The probability model does not tell us how far below the provincial yield the maize production is on that plot (i.e. yield shortfall), which can provide valuable information as some practices may decrease the yield shortfall more than others under certain circumstances. Yield shortfall S_{pt} on plot p at time t is by definition censored at zero for observations that do not have a shortfall.

$$S_{pt} = \left(\bar{Y}_{jt} - Y_{pt}\right) if \ \ Y_{pt} < \bar{Y}_{jt}, \ \text{0 otherwise} \qquad (3)$$

We use a Poisson distribution to account for censoring at zero and estimate the determinants of shortfall using FE. The Poisson model controls for censoring that occurs as a part of the optimization process, where everyone participates in the underlying distribution of the outcome variable (while it does not handle censoring that occurs due to non-participation of censored observations) (Wooldridge 2002, Ch. 18).

5.3. Independent Variables

Table 6 summarizes the variables that are hypothesized to affect maize productivity. In addition to the standard variables of household human capital (age and education), productive capital (number of adults, share of chronically ill adults, wealth index,[15] oxen holdings and land size) and gender, we also use controls for production-specific variables on each plot. These include: organic fertilizer application, number of complete weedings applied, and whether it was tilled before the rains started. We merge the plot level data with a number of policy related variables as well as a novel set of geo-referenced climatic and soil quality variables at the SEA level. Policy variables include an Agricultural Support Programme (ASP) dummy and a household level variable to capture timely access to fertilizers. The indicator variable for ASP equals one for the 20 districts where this programme, which facilitated participatory agricultural development (including land, seed, crops and livestock development), was implemented between 2003 and 2008.[16] The timing of fertilizer access is an indicator for households that reported having had timely access to fertilizers. Timely access to fertilizer is an important determinant of whether farmers can realize full yield benefits from fertilizer use as well as from other practices, and has been found to increase yields significantly (Rockström *et al.* 2009; Xu *et al.* 2009).

Table 6. Mean values of independent variables used in empirical models

Variables	**2004**	**2008**	**Signif.**
Age of household head	49.50	52.48	***
Education (average)	5.23	5.47	***
# of adults (age>=15)	4.58	3.91	***
Share of ill adults	0.07	0.02	***
Female headed	0.21	0.21	***
Total maize area (ha)	1.09	1.52	***
Wealth index	0.21	0.18	
# of oxen owned	0.78	1.18	***
Organic fertilizer applied	0.12	0.12	

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[15] The wealth index is created using PCA based on the number of bikes, motorcycles, cars, lorries, trucks, televisions and wells owned by the household.

[16] The ASP dummy is a time-invariant variable, hence drops out from the FE regressions.

# of weedings applied	1.72	1.70	
Tilled before rainy season	0.37	0.33	***
Policy Variables			
ASP Dummy	0.50	0.53	**
Had fertilizer on time	0.29	0.34	***
Geo-referenced Variables			
Growing season rainfall (100mm.)	8.62	8.19	***
CoV of growing season rainfall (1983-2012)	0.20	0.21	***
False onset of rainy season	0.63	0.19	***
Growing season avg. temperature (°C)	21.96	22.27	***
Growing season max. temperature≥28°C	0.14	0.18	***
Moderate nutrient constraint	0.35	0.34	
Severe/very severe nutrient constraint	0.35	0.34	
Average soil pH	5.59	5.61	
Observations (# maize plots)	4,138	4,354	

Our geo-referenced variables include SEA level data on total seasonal rainfall, average and maximum temperatures during the growing season, an indicator variable to capture false rainfall onsets, and the coefficient of variation in the growing season rainfall to capture the long term (1983-2013) variability in rainfall. Significant maize yield losses are reported in locations where growing season average temperature is 23°C or more and maximum temperatures are 28°C or more based on 20,000 field trials in Africa (Thornton and Cramer, 2012). The false onset of the rainy season is defined as a rainfall onset that is followed by a dry spell (one dekad with less than 20mm rainfall), and is expected to affect yields negatively (Taddross *et al*. 2009). The coefficient of variation of rainfall during the growing season captures the (scale invariant) variation in rainfall that is expected to affect yields through adoption of practices that help farmers deal with climate stress (Arslan *et al*. 2014). This variable is time-invariant and drops out of FE models, however, its effects are captured by a set of interaction terms as will be explained later.

Variables on soil nutrient availability and pH levels are expected to impact yields in opposing ways: whereas higher nutrient constraints would decrease yields, higher pH levels (less acidity) would increase them. These variables are also time-invariant, therefore are used only in descriptive analysis, and in the OLS and RE models presented below for robustness checks and comparison.

6. Results

6.1. Yield Models

Table 7 presents the results of yield models with a simple OLS model, an RE model and an FE model, in order to check for the robustness of FE coefficients under different specifications. The estimated coefficients are robust to various specifications, and given the Hausman test results mentioned above rejecting the consistency of RE coefficients, we continue with the FE specification in what follows.

We find no significant effect of MSD and a negative effect of CR on maize yields controlling for the use of all other practices and the large set of control variables. The use of LEGINT, INOF and IMPS all have highly significant positive effects on yields. Having access to timely fertilizer is significant in all specifications. As expected the growing season rainfall has a significant and positive coefficient, however the average temperature has no significant coefficient. The negative and significant coefficient of the indicator variable for maximum temperatures higher than 28°C loses its significance once we control for FE. Education, chronic illness and wealth indicators all have significant coefficients of expected signs.

Table 7. Determinants of maize yields (OLS, RE and FE models)

	OLS	**RE**	**FE**
MSD	-0.065	-0.062	-0.044
CR	-0.012	-0.028	-0.109***
LEGINT	0.217**	0.247***	0.385***
INOF	0.289***	0.294***	0.308***
IMPS	0.180***	0.175***	0.114**
Fertilizer on time	0.167***	0.165***	0.148***
Growing season rain (100mm)	0.051**	0.058**	0.102***
False onset	0.117*	0.103	0.016
Growing season temp.	0.039	0.038	-0.068
Max temp≥28°C	-0.387***	-0.378**	-0.164
CoV of growing season rain	1.837	1.747	
Log(total maize area)	-0.117***	-0.129***	-0.270***
Moderate soil constraint	0.087	0.074	
Severe/very severe soil constraint	0.039	0.038	
Soil pH (SEA avg.)	-0.049	-0.040	
# of adults (age≥15)	0.022***	0.022***	0.007
Age (head)	-0.002*	-0.002*	-0.003
Education (avg.)	0.026***	0.025***	0.023*
Share of ill adults	-0.237**	-0.239**	-0.272*
Female head	-0.034	-0.044	-0.003

Wealth index	0.024***	0.026***	0.026***
# of oxen owned	0.029***	0.032***	0.025***
Organic fertilizer applied	-0.039	-0.023	-0.013
# of complete weedings	0.011	0.013	0.020
Tilled before rains	-0.028	-0.022	0.034
ASP district	0.007	0.015	
2008 Dummy	0.067	0.059	0.054
Constant	4.780***	4.735***	7.348
Number of observations	8,434	8,434	8,434

Among the standard socio-economic variables, some lose significance after controlling fixed effects whereas others remain highly significant. The coefficient of the total maize area cultivated remains strongly significant, providing support for the inverse farm-size-productivity (IR) hypothesis.[17] Gender, number of adults and age are not significant, while education and share of chronically ill adults remain significant with expected signs. Education positively affects productivity, whereas chronic illness has a negative effect. Indicators of wealth (wealth index and oxen ownership) remain significant as well, indicating wealthier households are more productive.

The CSA practices analyzed here are hypothesized to increase yields especially under rainfall or temperature stress (Rockström *et al.* 2009, Thierfelder and Wall 2009 and 2010, FAO 2011c). These types of effects can be captured using interaction terms between the indicator variables for each practice and variables that represent climate stress. We use three sets of interaction terms between the practice indicators and: (*i*) the false rainy season onset indicator, (*ii*) the indicator for greater than 28°C growing season maximum temperature, and (*iii*) the coefficient of variation of rainfall, in order to tease out whether the effect of a practice differs between areas that are subject to these climatic conditions and those that are not (Table 8).[18]

False onset interactions show that the impacts of MSD, CR and LEGINT do not depend on this variable. The interaction terms with INOF and IMPS are significant with opposing signs. The combined impact of INOF following a false onset is less than its impact under normal

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[17] The main reasons for IR in the literature are market failures, omitted variables and measurement errors. Carletto *et al.* (2013) recently showed that accounting for measurement error strengthens, rather than weakens, the IR relationship. See Binswanger *et al.* (1995) and Eastwood *et al.* (2010) for a comprehensive review of the IR debate.

[18] We only present the coefficients of practices we focus on, their interactions with climate shock variables and geo-referenced variables in the rest of the paper for the sake of brevity. The coefficients of other variables remain virtually unchanged compared to those presented in Table 7. Full results can be obtained from the authors upon request.

onset. On the other hand, IMPS affects yields positively only after a false onset, perhaps reflecting the impact of re-planting farmers do using IMPS after the first crops fail to germinate due to a false onset. The fact that the coefficients of both LEGINT and INOF are larger than those in the simple model (Table 7) indicates that the effects of these practices are higher when there is no false onset.[19]

Interactions with the indicator of very hot growing season show that the positive effect of IMPS is reversed if the growing season maximum temperatures are 28°C or more, underlining the vulnerability of the positive impact of this modern input. Impacts of other practices do not vary depending on the maximum temperature during the growing season. The finding that the positive impacts of modern inputs are muted or reversed in the wake of climatic shocks supports the argument that modern inputs are risk-increasing (Just and Pope 1979). Given that these shocks are predicted to increase with climate change, the risk-increasing nature of modern inputs can be expected to intensify affecting adoption behavior and yield outcomes.

Table 8. Determinants of maize yield with interaction terms

	False Onset interactions	**Tmax28 interactions**	**CoV Rain interactions**
MSD	-0.062	-0.024	-0.011
CR	-0.122**	-0.098***	-0.107***
LEGINT	0.457***	0.355***	0.382***
INOF	0.444***	0.285***	0.309***
IMPS	0.018	0.201***	0.110**
False onset*MSD	0.071		
False onset*CR	0.045		
False onset*LEGINT	-0.163		
False onset*INOF	-0.267***		
False onset*IMPS	0.202**		
Tmax 28D*MSD		-0.169	
Tmax 28D*CR		-0.094	
Tmax 28D*LEGINT		0.214	
Tmax 28D*INOF		0.124	
Tmax 28D*IMPS		-0.469***	
CoV of rain*MSD			4.173
CoV of rain*CR			2.509*
CoV of rain*LEGINT			-1.444
CoV of rain*INOF			-1.449
CoV of rain*IMPS			-0.021
Fertilizer on time	0.141***	0.144***	0.147***
Growing season rain (100mm)	0.107***	0.101***	0.100***

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[19] The coefficients of practice indicators in models with interaction terms reflect the effect of each practice when the interaction term is zero (i.e. no false onset in this example). The coefficients in the simple model, on the other hand, reflect their impacts holding all other variables at their sample means.

False onset	0.013	0.015	0.017
Growing season temp.	-0.017	-0.023	-0.116
Max temp≥28°C	-0.150	-0.011	-0.164
Number of observations	8,434	8,434	8,434
AIC	19,159.14	19,150.77	19,176.43
BIC	19,349.22	19,340.85	19,366.51

Note: *** p<0.01, ** p<0.05, * p<0.1. AIC and BIC are Akaike and Bayesian Information Criteria, respectively, to compare the model fit across specifications.

The average impacts of all practices remain practically the same after including interactions with the coefficient of variation of rainfall, with the exception of CR. The interaction of CR with the CoV of rainfall is positive and significant, indicating that CR has a significantly positive impact on yields in areas of higher than average rainfall variability. CR seems to offer long term benefits building up soil structure and making it more resilient to rainfall variability.

Having had timely access to fertilizer is still one of the most consistent determinants of productivity in these specifications. Maize yields on average are 15% higher for those that have timely access to fertilizers, *ceteris paribus*, underlining the importance of fertilizer timing and distribution as effective policy entry points.

6.2. Probability of Low Yield and Yield Shortfall Models

Table 9 reports the results of low yield probability models controlling for time-invariant unobserved heterogeneity using population average models with and without interaction terms.

Table 9. Determinants of low maize yield probability (population average models)

	No interactions	**False Onset interactions**	**Tmax28 interactions**	**CoV Rain interactions**
MSD	0.074	0.089	0.076	0.036
CR	-0.055	-0.073	-0.073	-0.057
LEGINT	-0.121	-0.115	-0.138	-0.115
INOF	-0.263***	-0.381***	-0.255***	-0.256***
IMPS	-0.140***	-0.063	-0.224***	-0.136**
False onset*MSD		-0.073		
False onset*CR		0.044		
False onset*LEGINT		-0.016		
False onset*INOF		0.238**		
False onset*IMPS		-0.152		
Tmax 28D*MSD			-0.092	

Tmax 28D*CR			0.171	
Tmax 28D*LEGINT			0.065	
Tmax 28D*INOF			0.157	
Tmax 28D*IMPS			0.393***	
CoV of rain*MSD				-3.537
CoV of rain*CR				0.159
CoV of rain*LEGINT				1.126
CoV of rain*INOF				3.176*
CoV of rain*IMPS				0.625
Fertilizer on time	-0.307***	-0.302***	-0.302***	-0.305***
Growing season rain (100mm)	0.006	0.004	0.005	0.009
False onset	-0.013	-0.023	-0.004	-0.012
Growing season temp.	-0.016	-0.019	-0.020	-0.013
Max temp≥28°C	0.204**	0.213**	0.009	0.218**
Number of observations	8,434	8,434	8,434	8,434

Note: *** p<0.01, ** p<0.05, * p<0.1.

While MSD, CR and LEGINT do not have a significant impact on the probability of obtaining low yields, both INOF and IMPS decrease this probability significantly when no climate shock occurs. However, a false onset to the rainy season on a plot treated with INOF increases the low yield probability such that the combined impact of INOF is much smaller under a false onset (i.e. INOF decreases the yield loss probability by a much smaller amount). Similarly, plots cultivated with IMPS have a significantly higher probability of low yields if the growing season maximum temperatures exceed 28°C, overriding the average impact of IMPS that decreases the probability of low yields. Plots treated with INOF have also higher probabilities of producing low yields in areas of high rainfall variability (i.e. the probability increasing effect of the interaction term overrides the probability decreasing effect of INOF alone). Timely fertilizer access significantly decreases the probability of obtaining low yields as expected, while growing season maximum temperatures that exceed 28°C increase this negative outcome in all specifications.

Table 10 presents the results of yield shortfall models using the same specifications.

Table 10. Determinants of yield shortfall

	No interactions	**False Onset interactions**	**Tmax28 interactions**	**CoV Rain interactions**
MSD	-0.074	-0.084	-0.062	-0.104
CR	0.069*	0.081	0.065	0.064
LEGINT	-0.417***	-0.451***	-0.407***	-0.401***
INOF	-0.298***	-0.421***	-0.293***	-0.314***
IMPS	-0.150***	-0.046	-0.182***	-0.150***
False onset*MSD		0.031		
False onset*CR		-0.037		
False onset*LEGINT		0.073		
False onset*INOF		0.221**		
False onset*IMPS		-0.201***		
Tmax 28D*MSD			-0.151	
Tmax 28D*CR			0.039	
Tmax 28D*LEGINT			-0.123	
Tmax 28D*INOF			-0.004	
Tmax 28D*IMPS			0.187*	
CoV of rain*MSD				-4.307
CoV of rain*CR				-0.847
CoV of rain*LEGINT				3.509
CoV of rain*INOF				3.422**
CoV of rain*IMPS				0.523
Fertilizer on time	-0.226***	-0.213***	-0.226***	-0.221***
Growing season rain	-0.079***	-0.083***	-0.080***	-0.078***
False onset	-0.070	-0.044	-0.070	-0.064
Growing season temp.	-0.100	-0.140	-0.112	-0.072
Max temp≥28°C	-0.224*	-0.232*	-0.275**	-0.224*
Number of observations	6,744	6,744	6,744	6,744

Note: These models are estimated using FE Poisson models as explained above. The FE Poisson model requires a balanced panel, therefore the number of observations is smaller in these models.

The yield shortfall results closely mirror low yield probability results with two exceptions. Plots treated with IMPS have smaller yield shortfall after a false rainy season onset in these models, whereas this interaction terms was not significant above. Growing season rainfall significantly decreases yield shortfall, but this variable was not significant in affecting the low yield probability.

Consistent with the findings from the yield models, having had access to timely fertilizer is one of the most robust determinants of low yield probabilities and shortfalls: timely fertilizer significantly decreases both of these outcomes in all specifications. Timely access to fertilizer has been identified as an important determinant of yields in Zambia by Xu *et al.* (2009) as well, who used a smaller and older data set to analyze impacts of fertilizers on yields. These authors also report that most smallholders in Zambia do not have access to fertilizer when they need it through public or private channels due to the inefficiencies in the system and the uncertainty created by public policy.

Given that timely access to fertilizer emerges as an important policy entry point to improve yields and hence food security, we look at the distribution of this variable along other variables. Tables 11 and 12 show the share of maize farming households that had timely access to fertilizer by province and total land size, respectively.

Table 11. Timely fertilizer by province

Province	2004	2008
Central	0.43	0.54
Copperbelt	0.45	0.49
Eastern	0.28	0.30
Luapula	0.33	0.16
Lusaka	0.45	0.54
Northern	0.31	0.35
Northwestern	0.11	0.20
Southern	0.29	0.31
Western	0.05	0.03
Average	**0.29**	**0.32**

Table 12. Timely fertilizer by land size

Land size	2004	2008
<=1.5ha	0.22	0.25
1.5-2.5ha	0.28	0.30
2.5-5ha	0.34	0.36
5-20ha	0.46	0.46
>20ha	0.55	0.53
Average	**0.29**	**0.32**

The share of households with timely access to fertilizer increased between 2004 and 2008 in all provinces except in the Western province. Central, Copperbelt and Lusaka are the provinces with highest shares (50% or more) of households with timely access to fertilizers, whereas Luapula, Northwestern and Western provinces have lowest shares (20% or less). The distribution by land size clearly demonstrates that timely access is strongly correlated with land size: around 50% of households with landholdings greater than 5 ha have timely access, whereas this share is only 25% for those that have less than 1.5 ha of land. An exploratory analysis of yields using interaction terms between the practice indicators and timely fertilizer access indicator reveals that the impact of MSD on yields is positive and significant if the household had timely access to fertilizers.[20]

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[20] Other interaction results remain largely unchanged by the inclusion of this interaction variable in FE maize yield regressions, and therefore are not presented here for the sake of brevity. The results can be obtained from the authors upon request.

One caveat in interpreting our results is that the models estimated here cannot control for potential endogeneity of adoption of these practices that may be caused by unobservable variables that are not constant over time. Panel data spanning longer time periods to ensure enough climate variability is observed, a valid set of instruments to capture time-varying unobserved heterogeneity and a system of equations including adoption and yield models with high computing power requirements would be needed to control for this potential remnant of endogeneity. Future research should try to address this if data and computing power permit.

7. Conclusions

Our analysis indicates there is a variety of agricultural practices with the potential to increase yields and help farmers adapt to climate change in Zambia and these vary by the types of climate impacts and AER. Most of the practices analyzed here form part of the CA package, whose impacts on production have been extensively researched in the literature (FAO 2011b; Haggblade and Tembo 2003; Haggblade *et al.* 2011; Umar *et al.* 2011 among others). Most of this literature, however, is subject to (*i*) data from experimental plots, (*ii*) small data sets from a non-representative group of farmers, or (*iii*) selection or other endogeneity problems. Studies that control for rainfall, temperature and soil quality variables in a panel setting are also rare. We contribute to this literature with an in-depth econometric analysis of the impacts of a set of potentially CSA practices on maize yield and its probability of falling below a low threshold using nationally representative panel data of rural households merged with geo-referenced climate and soil quality data from Zambia. We also control for the impacts of modern inputs (that usually confound the impacts of other practices in the literature).

Controlling for a large set of variables that affect production, we find no significant impact of minimum soil disturbance, a positive impact of legume intercropping and a negative impact of crop rotation on maize yields over the 2004-2008 time period. The positive impact of legume intercropping is robust to climatic shocks – i.e. legume intercropping has positive benefits even under climate shocks. Crop rotation is found to have a positive yield effect under highly variable rainfall conditions, in contrast to the negative yield effect found in areas of more stable rainfall patterns. We also find that the average positive impacts of modern input use are conditioned by climatic variables: inorganic fertilizers have a much smaller impact under false rainfall onsets, and improved seeds have a yield decreasing impact under very high growing season temperatures.

One of the most robust findings shows that having timely access to fertilizers increases maize yields, and decreases low yield probability and yield shortfall significantly in all specifications, similar to Xu *et al.* (2009), who report a similar finding from AER IIa using an older data set. Delays in fertilizer delivery through government programs are well known in Zambia, causing further delays due to the uncertainty created for private distributors (Xu *et al.* 2009). Most smallholders in Zambia do not have access to fertilizers at all, and those that do have disproportionately late access compared to larger landholders (Mason *et al.* 2013). Given the fact that some fertilizer application is required to realize the benefits of most CSA practices and improved seed use, and that timeliness adds to these benefits, this finding indicates a relatively easy policy entry point to improve food security in the country. Efficiency improvements in this policy would also decrease its heavy burden for limited government resources further facilitating food security.

This paper also demonstrates that an analysis based on combining agricultural household and geo-referenced climate data can provide new insights on the relevant climatic variables when thinking about adaptation. For example, from our analysis it appears that variations in rainfall in Zambia mostly impacts maize farmers through its interaction with inorganic fertilizer, but not in other respects. On the other hand, the amount of rain in the growing season is an important determinant in the average yield, and in determining the yield shortfall. Apparently the amount of rain does not affect the probability of a yield shortfall, which depends on timely access to fertilizer, management practices, and interactions between practices and select climatic variables.

It should be noted that the interactions of different climatic variables with management practices can alter the outcome at the farm level quite substantially. So the oft-mentioned positive impacts of modern inputs on yield decrease and/or disappear once their interactions with various climate shock variables are taken into account. For example, applying inorganic fertilizer and using improved seeds increases yields and reduces the probability of a shortfall; however, both these positive effects are contingent on not having a false onset of the rains (for fertilizer) and not having high temperatures (for improved seeds). More traditional practices, such as crop rotations are found to significantly increase yields under rainfall variability, whereas the positive impacts of legume intercropping are robust to various shocks considered here.

Given the challenge of addressing food security under the projected impacts of climate change that is expected to increase the frequency of climate shocks, this paper highlights the importance of understanding which economic and climatic variables are constraining productivity and affecting household resilience so as to better target any intervention. Our results indicate that climate change impacts are heterogeneous across AERs and effective adaptation strategies are also varied. This implies the need for identifying different "adaptation zones" based on the variation in exposure and sensitivity to climate shocks, with adaptation strategies developed for each.

In the case of Zambia, we find that timely access to fertilizer is a consistently important element in determining yields and targeting smallholders, who are universally found to have less timely access, is an important policy measure needed to increased productivity amongst the highly food-insecure agricultural population of Zambia. We also find that other interventions that are robust to climate shocks could be adopted, such as increasing legume intercropping to increase yields and limit the extent of yield shortfalls. The sensitivity of the effectiveness of improved seeds and inorganic fertilizer application to false onsets of the rainy season and maximum temperature indicates that better information to farmers on how to deal with these climatic shocks could help in retaining the positive effects of these practices on yields, which otherwise risk being lost.

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