Norwegian University of Life Sciences
School of Economics and Business

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Climate-smart agriculture in Malawi: Uptake and opportunities in the face of climate change

Klima-smart landbruk i Malawi: Teknologivalg og muligheter under varierende nedbørforhold

Samson Pilanazo Katengeza

CLIMATE-SMART AGRICULTURE IN MALAWI: UPTAKE AND OPPORTUNITIES IN THE FACE OF CLIMATE CHANGE

KLIMA-SMART LANDBRUK I MALAWI: TEKNOLOGIVALG OG MULIGHETER UNDER VARIERENDE NEDBØRFORHOLD

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Dedication

O-Dala *(grandpa) and o-Mayi (grandma), may your beautiful souls continue resting in eternal peace. Your legacy lives.*

To my mom – the late Kwanali (Alaida Kankhwani), my wife – Nankhoma, my daughter – Kwanali and my son – Asher, find pleasure in this thesis as a living testimony of your sacrifice.

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Born and growing up in a remote village of Nankumba in Lilongwe, Malawi was fun. Taking care of the goats and cattle every morning, life was so exciting. One morning, **o-Dala**, had something to tell me. "C*haka chino mmudzi uwo! mukuyamba sukulu, ndie ukayambe kuphunzira. Kuchoka kumeneko udzapita ku fomu, kenako ku kozi, kenako udzagwira ntchito ya mu ofesi*" (Government is opening a primary school in that village this year, you need to start going to school. After primary school, you will go to secondary school, then to college, and then you will work in an office). I did not know what **o-Dala** meant, but I had to obey. Losing him when I was only in standard 7, almost killed my destiny. I dropped out of school. Few months later, **o-Dala**'s words kept reminding me of what I was supposed to achieve, i.e. finish primary school, go to secondary school, go to college and work in the office. Going back to school was not an option but an obligation to fulfil the destiny **o-Dala** prophesied. I am so grateful grandpa! Continue resting! Till we meet again!

Leaving home in 2014 for Norway to start the PhD journey when Nankhoma my wife, was a month away from being a mother to our 1st child – Kwanali – was a big sacrifice. In 2016, God blessed us with another child, a son – Asher. Huge responsibility to the lone Nankhoma. I am so grateful she took the challenge with pride and excellence. I will forever love you Nankhoma. I am happy that finally I am in a position to answer Kwanali's daily question, "*a dadi mubwera liti ndakusungirani freezes mu fridge*" (Dad when are you coming, I have kept freezes for you in the fridge). To my siblings and families: Machitidwe, Daniel, Mwalisi, Anderson and Chifundo and the Kapoteza family, am so thankful for being part of us. Special mention to Pious & Jessy Chavula, Robert & Lonny Chirambo, and Eliam & Dora Kasambara for continuously checking on my family and offering all the support they needed.

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Samson Pilanazo Katengeza
Ås, 2018

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Summary

Is agriculture becoming climate-smart? Can recurrent weather events such as droughts explain increased use and adoption of agricultural technologies that are perceived climate-smart? I have merged a four-wave household panel data of nine years (2006-2015) with daily rainfall data (2003-2015) in this thesis to examine farmer uptake and opportunities of climate-smart agriculture (CSA) technologies in Malawi. Specifically, I have tested how exposure to dry spells influences use of CSA technologies and how adoption affects maize productivity in the face of weather shocks.

CSA holds potential to minimize negative effects of weather shocks, particularly among smallholder farmers in sub-Saharan Africa (SSA). Smallholder farmers in SSA have limited adaptation options against weather shocks such as floods, hailstorms, droughts and prolonged mid-season dry spells. CSA technologies provide such farmers with options to hedge against weather-related crop production losses. An empirical question however is whether farmers respond to exposure to weather risks by adopting CSA technologies and how adoption protects them against weather-related yield losses. I have addressed this empirical question in my thesis through four related specific questions. One, what are the impacts of exposure to recent dry spells on use of integrated soil fertility management (ISFM) technologies? Two, how do recent dry spells and farm input subsidies affect adoption of drought tolerant (DT) maize varieties? Three, what is the impact of DT maize varieties on maize productivity under rainfall stress? Four, what are the farm-level impacts of farm input subsidies vis-à-vis climate-smart technologies?

In paper one I examined the impact of early-season and late-season dry spells on use of ISFM technologies focusing on organic manure and maize-legume intercropping. Results showed an increase in use of organic manure and maize-legume intercropping over time. There was also an increase in adoption of DT maize varieties from 2006 to 2015 as reported in paper two. Previous exposure to one-year lag of both early- and late-season dry spells was associated with high likelihood of using maize-legume intercropping and organic manure. Similarly, the likelihood of adopting DT maize varieties was positively influenced by exposure to recent dry spells and access to seed subsidy. There was, however, inconsistent impact of two-year and three-year lags of both early- and late-season dry spells on use of maize-legume intercropping and organic manure.

The results in papers one and two imply that farmers build weather expectations from previous weather conditions and respond to weather risks by investing in CSA technologies. Farmers' response is influenced by perceived benefits of the technologies under changing weather. The results also indicate that immediate dry spells are more influential in building such weather expectations than long-term weather conditions and hence more significant in enhancing use of CSA practices. In addition, the results reveal that agricultural extension services and farm input subsidies play important roles in promoting use of CSA technologies. Farm input subsidies for example, directly influences adoption of DT maize varieties through provision of cheap seed and indirectly by providing farmers with experience of DT maize varieties under weather risks.

In papers three and four, I have argued that CSA technologies have potential to protect farmers from drought-related yield losses. Evidence from paper three showed that average maize yields of adopters of DT maize varieties were significantly higher than that of non-adopters in the sample areas. The literature review in paper four provides further evidence that adoption of CSA technologies such as organic and inorganic fertilizer and conservation agriculture provides stable and long-term maize productivity effects. These results suggest that consistent and appropriate use of CSA technologies in SSA countries can help reduce the risk of low crop production under weather shocks.

In paper four I have also argued that integrating farm input subsidies and CSA technologies is potentially a magic bullet. Many countries in SSA are implementing large-scale farm input subsidies but the impact on maize productivity is modest mainly because of declining soil fertility and frequent dry spells. In addition, poor timing of input delivery, beneficiaries receiving less than the required amount of inorganic fertilizer and targeting errors have contributed to modest impact of input subsidies. While recent reforms in Malawi FISP are working towards improving on timing of input delivery and targeting errors, soil fertility concerns remain unaddressed in FISP implementation strategies. Addressing soil conditions by integrating subsidized inorganic fertilizer with organic fertilizer and CA has potential to enhance the impact of FISP. This approach is potentially drought-resilient, soil fertility enhancing, and increases the efficiency with which subsidised inputs are used. Consequently, the impact of FISP on maize production is likely to be higher, more consistent and enduring and provide the government with an exit strategy.

Sammendrag

Blir landbruket mer klimasmart? Kan gjentatte klimasjokk som tørke forklare økt bruk og opptak av landbruksteknologier som oppfattes som klimasmarte? Jeg har kombinert fire runder av bondehushold panel data som går over ni år (2006-2015) med daglige nedbørsdata (2003-2015) i denne oppgaven for å undersøke opptak og muligheter for klima-smarte landbruksteknologier (CSA) i Malawi. Nærmere bestemt har jeg testet hvordan eksponering for tørkeperioder påvirker bruk av CSA-teknologier og hvordan adopsjon påvirker maisproduktivitet i møte med klimasjokk og -variasjoner.

CSA har potensial til å redusere negative effekter av klimaendringer, særlig blant småbønder i Afrika sør for Sahara (SSA). Småbønder i SSA har begrensede tilpasningsalternativer ved klimavariasjoner som oversvømmelser, haglstormer, og tørkeperioder. CSA-teknologier gir slike bønder muligheter til å bli mindre sårbare for klimabaserte avlingsskader. Et empirisk spørsmål er imidlertid om bønder reagerer på eksponering mot værrisiko ved å ta i bruk CSA-teknologier og hvordan adopsjon beskytter dem mot værrelaterte avkastningstap. Jeg har studert dette empiriske spørsmålet i avhandlingen min gjennom fire relaterte konkrete forskningsspørsmål: En, hva er virkningen av eksponering for nylige tørkeperioder ved bruk av integrerte teknologier for bevaring av jordas fruktbarhet (Integrated Soil Fertility Management - ISFM)? To, hvordan påvirker eksponering for tørkeperioder og tilgang på subsidiert gjødsel og såkorn adopsjon av tørketolerante (drought tolerant – DT) maissorter? Tre, hva er virkningen av adopsjon av tørketolerante (DT)-maissorter på maisproduktivitet under varierende nedbørforhold? Fire, hvordan påvirker subsidiering av kunstgjødsel og såfrø opptak av klimasmarte landbruksteknologier?

I artikkel 1 undersøkte jeg effekten av tørkeperioder tidlig og midt i regntiden på bruken av samplanting av mais og belgvekster og organisk gjødsel (ISFM teknologier). Resultatene viste en økning i bruk av organisk gjødsel og mais-belgvekst samdyrking over tid. Det var også en betydelig økning i adopsjon av DT mais sorter fra 2006 til 2015 som rapportert i artikkel 2. Eksponering for tørkeperioder tidlig og midt i regntiden i tidligere år var knyttet til høyere sannsynlighet for bruk av mais-belgvekst samdyrking og organisk gjødsel. På samme måte var sannsynligheten for adopsjon av DT maissorter positivt påvirket av eksponering for nylige (ett år tilbake i tid) tørkeperioder i regntiden og tilgang på subsidiert kunstgjødsel og såfrø. Eksponering

mot slike tørkeperioder lengre tilbake i tid hadde mer varierende virkninger på opptak av disse teknologiene.

Resultatene i artikkel 1 og 2 innebærer at bønder danner seg forventninger om framtidige værforhold på basis av erfaringer med været i nær fortid og som følge av dette kan komme til å investere mer i CSA-teknologier. Småbøndene responderer derfor rasjonelt gjennom opptak av teknologier som de oppfatter som fordelaktige under endrede klimaforhold. Værforhold i nær fortid har sterkere påvirkning på teknologibruk og adopsjon av nye teknologier enn værforholdene litt lengre tilbake i tid. Tilgang på subsidier og råd fra veiledningstjenesten bidrar også til større opptak av disse teknologiene.

I papir fire har jeg også hevdet at integrering av subsidierte innsatsvarer og CSA-teknologier har potensiale for positive effekter. Mange land i SSA implementerer store landbruskssubsidieprogrammer, men virkningen på produktivitet har ikkje vært så god som ønskelig, blant annet på grunn av lav og synkende jordfruktbarhet og varierende nedbørforhold. Forsinkelser i distribusjonen og fordelingsproblemer har bidratt til begrensede virkninger av subsidiene. I Malawi forsøkes det nå på å bedre timingen av leveransene av subsidierte innsatsvarer, men lite har vært gjort for å ta tak i problemene med synkende fruktbarhet av jorda. Her burde politikken fokusere på å kombinere subsidierte innsatsvarer mot meir klimasmart konserveringslandbruk for å øke de meir langsiktige virkningene av subsidiene. Dette har potensiale til å gi et meir berekraftig og klimasmart landbruk som vil kunne redusere behovet for subsidier på sikt.

INTRODUCTION

Climate-Smart Agriculture in Malawi: Uptake and Opportunities in the Face of Climate Change

Samson P. Katengeza

1 Introduction

1.1 Motivation

Climate change threatens food security of a growing global population because of increased incidences of extreme weather events such as droughts and floods (FAO, 2013). Such weather shocks often interrupts consistency and stability in food production (Wheeler & Von Braun, 2013). In fact, food crisis and economic hardships worsen especially in developing countries due to disruptions and decline in crop production (Thornton *et al.*, 2008). Countries in sub-Saharan Africa (SSA) who largely depend on rain-fed agriculture (IPCC, 2014) are particularly at risk because of limited adaptation options to weather shocks (Brown & Funk, 2008). The problem is exacerbated in SSA by declining soil fertility, soil degradation (Mafongoya *et al.*, 2006) and rapid population growth (Waldman *et al.*, 2017). Agricultural production therefore needs urgent climate-smart systems to support food production under increasing weather changes.

Climate-smart agriculture (CSA) is an alternative approach with potential to solve interlinked global challenges of food security and climate change (Neufeldt *et al.*, 2011; FAO, 2013; Neufeldt *et al.*, 2013). CSA is defined as "*agriculture that sustainably increases productivity, resilience (adaptation), reduces/removes greenhouse gases (mitigation), and enhances achievement of national food security and development goals*" (FAO, 2010). This definition depicts three fundamental pillars of CSA. One, achieve sustainable increase in agricultural production, productivity and incomes by efficiently utilising resources such as land, water, energy and nutrients. Two, enhance adaptation and build resilience to the negative effects of climate change. CSA increases the capacity of agriculture to prevent, mitigate or cope with and recover from climate risks. CSA builds resilience by reducing sensitivity to climate shocks and increasing adaptive capacity. Three, reduce and/or remove greenhouse gasses emissions. CSA through efficient use of resources e.g. using less land to produce more output reduces deforestation thereby reducing CO_2 emissions. Similarly, efficient use of inorganic fertilizer for crop production reduces nitrous oxide emissions in the field (FAO, 2013).

CSA is however not a single specific universal agricultural technology but a set of practices that are site-specific and varies according to spatial and temporal climatic variations. Its uniqueness is the capacity to bring under one brand the goals of agriculture, climate change and development. It brings simultaneous solutions to the interconnected challenges of food security, climate change adaptation and mitigation of climate change effects. CSA aims to provide opportunities for improved farm management practices and offers a framework to facilitate adoption. Proper integration of these into farming systems enhances efficiency of agricultural production and reduces vulnerability to weather shocks thereby providing farm households with greater opportunity for increased food security (Neufeldt *et al.*, 2011; FAO, 2013).

In Malawi, efforts to integrate CSA practices in maize-based farming systems are underway. The government, non-governmental organisations (NGOs), bilateral donors and research institutions are all actively involved in promoting CSA technologies (Murray *et al.*, 2016). The government through the National Agriculture Policy (NAP) has set investment in CSA and sustainable land and water management as one of strategic policy tools to achieve sustainable agricultural production and productivity (Government of Malawi, 2016). Common CSA practices include, but not limited to agro-forestry systems, conservation agriculture (CA), drought tolerant crop varieties, integrated soil fertility management (ISFM) and rainwater harvesting.

Several of these CSA technologies are not new among smallholder farmers in Malawi and the entire SSA region. However, the simultaneous approach with which these technologies address multiple challenges in agriculture under the new realities of weather shocks is a new concept emphasized in CSA framework. It is therefore imperative to understand farm-level uptake and opportunities of these technologies in the face of increasing weather shocks.

Recent weather shocks such as droughts of 2005, 2012 and combined early-season floods and late-season droughts of 2015 (Murray *et al.*, 2016) make Malawi an interesting case to study. The country also faces frequent mid-season dry spells with devastating effects on crop production (Chabvungma *et al.*, 2015). The occurrence of such hazardous events and losses, create fear and worry amongst people, and may affect risk preferences (Van Den Berg *et al.*, 2009). Farmers are expected to increase risk averse choices to minimize negative impacts of such weather shocks.

However, whether farmers respond to previous exposure to weather shocks by using CSA technologies remains an interesting empirical question. Interestingly, the government has been implementing a large-scale Farm Input Subsidy Program (FISP) since 2006 with the objective of increasing access to improved inputs such as inorganic fertilizer and improved seed (Dorward *et al.*, 2008), which are also CSA technologies. FISP may therefore have both direct and indirect impacts on use of CSA technologies and on crop yield amidst increasing weather shocks. Taking into account the impact of FISP, this thesis makes a novel contribution by addressing the impacts of weather shocks on use of CSA technologies and how use affects maize production.

1.2 Objectives and research questions

The purpose of this thesis is twofold. One, to understand farmer uptake of CSA technologies and how exposure to weather shocks affects use. Two, to assess and review maize productivity impacts of CSA technologies under weather risks. I have addressed these objectives through four related specific questions. One, what are the impacts of exposure to recent dry spells on use of integrated soil fertility management technologies in Malawi? Two, how do recent dry spells and farm input subsidies affect adoption of drought tolerant maize varieties in Malawi? Three, what is the impact of drought tolerant maize varieties on maize productivity under rainfall stress in Malawi? Four, what are the farm-level impacts of farm input subsidies vis-à-vis climate-smart technologies? Question four focuses on comparing the impacts of farm input subsidies and CSA technologies on maize productivity. These questions are respectively addressed in papers one to four.

2 Background

2.1 Agriculture and climate in Malawi

Malawi is located in the south-eastern part of Africa, between latitudes 9° and 18°S and longitudes 33° and 36°E. The country is bordered by Zambia (northwest), Tanzania (northeast) and Mozambique (east, south and west). It is politically divided into three major regions: Southern, Central and Northern Region. The Southern Region has 13 districts, Central has nine while the Northern Region has six districts (Government of Malawi, 2006). The country's population was in 2015 estimated at 17.2 million with annual growth rate of 3.1% (UNDP, 2016). The Southern Region is overall, highly populated followed by the Central Region (NSO, 2008). Approximately 85% of the population is rural and predominantly involved in subsistence farming. About 50.7%

of Malawians live below the national poverty line, 70.9% below international poverty line of $1.90 (in purchasing power parity terms, i.e. PPP) a day, and per capita income in Malawi is estimated at US$1,113 (at PPP) per year (UNDP, 2016).

Malawi occupies a total territorial area of approximately 118,324 square kilometres, of which 20% (approximately 23,600) is covered by water. Of the remaining land area (about 94,700), 53,070 is considered suitable for cultivation (Government of Malawi, 2002). With a population of about 17.2 million, the population density is approximately 185 people per square kilometre, an increase from 139 reported in 2008 (NSO, 2008). Estimates on land availability indicate that the country has a total of 11.8 million hectares of which 9.8 million is land. 1.2 million hectares is occupied by agricultural estates, 1.7 million is protected areas (e.g. national parks, forest and game reserves) while 4.5 million is potentially available for smallholder agriculture after adjusting for wetlands, steep slopes and traditional protected areas (Government of Malawi, 2002).

Malawi's economy is agriculture-based and highly climate-sensitive. Approximately 30% of the country's GDP comes from agriculture. The sector generates over 80% of national export earnings and employs close to 65% of the country's labour force. The agriculture sector is broadly dualistic involving the estate and smallholder subsectors. The smallholder subsector contributes over 70% of agriculture GDP and production is dominated by maize, rice, cassava, sweet and Irish potatoes, and legumes for both subsistence needs and commercial sales. Smallholder farmers are also involved in production of tea, tobacco, sugarcane and coffee. Recent efforts are promoting smallholder engagements in other commercial crops such as paprika, cotton, horticulture, and fruit trees (e.g. mango, banana and citrus). Smallholder agriculture is also characterised by small and fragmented farm holdings of less than one hectare per household. On the other hand, the estate subsector is primarily for commercial production of high-value cash crops, namely, tobacco, tea, sugarcane, and macadamia. These are major export commodities for Malawi. In addition, the estate subsector provides contract farming opportunities for smallholders. A third group of farmers is also emerging and these are categorised as medium-scale farmers cultivating between 5-25 hectares of land (Government of Malawi, 2016).

Maize is the most important food crop in Malawi (Smale, 1993). It is grown by over 97% of smallholder farmers and takes over 90% of land under cereals production (Denning *et al.*, 2009). Annual consumption per capita is estimated at 129 kilograms and approximately 90% of per capita cereals intake and 54% of caloric per capita intake is maize (Derlagen, 2012). On the other hand, tobacco is the key export commodity. The high dependence on maize for food and tobacco for export earnings has limited Malawi's diversification potential as agriculture policy instruments tend to be focused on these two crops (Government of Malawi, 2016). Production of both maize and tobacco is heavily dependent on rain-fed conditions and highly vulnerable to the country's frequent and prolonged mid-season dry spells.

Climate in Malawi is sub-tropical, relatively dry and strongly seasonal with three major seasons. First is the warm-wet season between November and April during which about 95% of the annual rainfall takes place. On average, the country receives 725 mm to 2,500 mm of rainfall. Second is a cool, dry winter between May and August. During this period the mean temperatures range between 17 and 27 degrees Celsius and falling to as low as 4 degrees Celsius. Third is the hot, dry season from September to October. The temperature during this period varies between 25 and 37 degrees Celsius. Humidity in Malawi ranges from 50% during drier months of September and October to 87% for the wetter months of January/February (DCCMS, 2006).

The country is broadly grouped into four major agro-ecological zones, namely: lower Shire valley; lakeshore, middle and upper Shire valley; mid-altitude areas; and high altitude plateaux and hilly areas. Each of these zones is characterized by unique features in terms of rainfall, temperature, altitude and agricultural operations. The lower Shire valley for example lies below 500 metres above sea level (MASL), receives less than 600 mm of rainfall annually and is generally not suitable for rain-fed farming for most crops grown in Malawi. It is characterised by continuous flooding during the rainy season. The narrow range of crops grown include sorghum, millet, maize, Irish potato and cassava. The area is however highly fertile and suitable for irrigation farming (Bunda College, 2008; Benson *et al.*, 2016).

The lakeshore, middle and upper Shire valley lies between 400 and 1000 MASL with high average temperatures. Rainfall distribution ranges from 600 to 800 mm and have very fertile alluvial soils. Key food crops include maize, cassava, rice, sorghum and millet. The medium altitude zone enjoys high annual average rainfall ranging from 800 – 1,200 mm with an altitude of 1,000 to 1,500 MASL. The zone is associated with high production of maize and comprises the Lilongwe – Kasungu plain which is Malawi's bread basket. Other major crops include tobacco, cassava, rice and pulses. Finally, the high plateaux and hilly areas receive over 1,200 mm of annual rainfall and lie in an altitude over 1,500 MASL. The average temperatures are low and the major crops grown include maize, pigeon pea, tea, coffee, bananas, pineapples, cassava and potatoes (ibid).

2.2 Extreme weather events and impacts on agricultural production in Malawi

Agriculture production in Malawi is heavily dependent on climate-sensitive rain-fed subsistence which is highly vulnerable to recurrent weather extremes such as droughts, mid-season dry spells and floods (Government of Malawi, 2006; 2011; 2015). The extreme weather events are so regular in the country because of climate variability which has negative effects on amounts, timing and frequency of rainfall (Chabvungma *et al.*, 2015). The severity has increased in recent times because of climate change, population growth, urbanisation and environmental degradation (FAO, 2012).

Estimates using the EM-DAT data (Table 1) for the past three decades show that Malawi experiences frequent weather shocks with devastating livelihood effects. In 2002 for example, the country experienced droughts that affected over 2.8 million people claiming approximately 500 lives. Maize production was 30% lower than normal (Chabvunguma & Munthali, 2008). Another severe drought was reported in 2005 described by local meteorologists as one of the worst in 60 years (ibid). Approximately 30% of the country's population (over 4 million people) were affected by a hunger crisis and needed emergency food aid (Denning *et al.*, 2009). There were also reported extensive droughts in 1990, 1992, 2007 and 2012 that affected many people. In 2015, the country reported early-season floods and late-season droughts. The early-season floods affected 15 of the country's 28 districts. Approximately 1.1 million people were affected, 230,000 displaced while 176 and 172 people were reportedly killed and missing respectively (Government of Malawi, 2015). The late-season droughts were responsible for the poor maize harvests that were estimated at 25-30% less than the previous five-year average (FEWS NET, 2015).

Figures in Table 1 also suggest that droughts than floods have more severe impacts in Malawi. While floods are localised, droughts tend to be country wide (Pauw *et al.*, 2010). Droughts became so common from 1980s (Government of Malawi, 2006) and usually occur when seasonal rainfall is below 75% of annual average (Chabvungma *et al.*, 2015). Although the whole country is vulnerable to droughts, the following districts are particularly drought prone: Chikhwawa, Karonga, Salima, Nsanje and Zomba (World Bank, 2010).

Table 1: Extreme weather events in Malawi (1988–2018)

Year	Disaster type	No. of occurrence	No. of people affected	Total deaths
1987	Drought	1	1,429,267	0
1990	Drought	1	2,800,000	0
1992	Drought	1	7,000,000	0
2002	Drought	1	2,829,435	500
2005	Drought	1	5,100,000	0
2007	Drought	1	520,000	0
2012	Drought	1	1,900,000	0
2015	Drought	1	6,700,000	0
1989	Flood	1	100,000	13
1991	Flood	1	150,000	472
1997	Flood	1	400,000	0
2000	Flood	1	20,000	0
2001	Flood	2	508,750	59
2002	Flood	2	396,340	9
2003	Flood	2	19,500	12
2005	Flood	1	44,500	1
2007	Flood	4	201,965	2
2008	Flood	1	16,380	0
2010	Flood	1	21,290	0
2011	Flood	3	83,587	4
2012	Flood	2	90,735	4
2013	Flood	1	33,000	3
2015	Flood	1	638,645	278
2017	Flood	1	55,921	0
2012	Storm	1	6,000	0
2015	Storm	1	350	5

Source: EM-DAT: The Emergency Events Database - Université catholique de Louvain (UCL) - CRED, D. Guha-Sapir, www.emdat.be, Brussels, Belgium.

2.3 Climate-smart agriculture practices in Malawi

Several interventions are underway in Malawi to promote CSA technologies. The Agricultural Sector-Wide Approach (2011–2015) program (ASWAp), for instance, prioritised soil and water conservation technologies in order to build soil fertility, prevent soil erosion and conserve rainwater. Such technologies included contour and box ridges, organic manure, minimum tillage and agroforestry (Government of Malawi, 2011). The ASWAp also emphasized on the Greenbelt Initiative to increase the level of irrigation farming. The initiative was to establish rainwater-harvesting systems in both the field and off field. Kaczan *et al.* (2013) also reported that Malawi has been promoting agroforestry as a CSA technology in four main ways: 1) permanent tree planting, 2) sequential tree fallows, 3) annual relying intercropping and 4) biomass transfer. Furthermore, the Government of Malawi (2015) reported CA, drought tolerant crops, precision agriculture and agro-forestry as CSA technologies being promoted in the country. Recently, the National Agriculture Policy has also emphasized on investments in CA, agroforestry, improved seeds, irrigation, organic and inorganic fertilizer and other integrated soil fertility management (ISFM) technologies (Government of Malawi, 2016).

I briefly discuss CA and agroforestry technologies here but I present a brief background and adoption levels of the technologies I have studied in the thesis in individual papers. These are ISFM in paper one, DT maize varieties in paper two and paper three, and organic and inorganic fertilizer in paper four.

CA is a suite of three basic interlinked principles of minimum soil disturbance, permanent organic soil cover and crop diversification involving crop rotation and/or intercropping (FAO, 2015). Full adoption requires use of all the three key principles with 30% as a minimum requirement for permanent organic soil cover (Giller *et al.*, 2009; Government of Malawi, 2012). Significant investment in CA in Malawi was first seen in late 1990s (Andersson & D'Souza, 2014). It started with the Sasakawa Global 2000 between 1998 and 2003, implemented in partnership with the country’s Agricultural Development Divisions (ADDs). The emphasis was on optimum plant densities and spacing, fertilizer use, weed control and crop protection (Government of Malawi, 2012). As an incentive, the program provided farmers with free starter packs of maize seed and fertilizer worthy 0.1 ha with farmers encouraged to buy herbicides themselves (Andersson &

D'Souza, 2014). Later, reduced tillage was introduced in the system to minimize soil erosion, conserve moisture and reduce labour drudgery. The system also incorporated legumes such as soybean, cowpeas, and pigeon peas to enhance crop diversification. The program resulted in higher maize yield of up to 5.1 tonnes per hectare (t/ha) (Government of Malawi, 2012).

Adoption of CA however remains low in Malawi and many other countries in SSA despite the relevance and many potential benefits on agricultural systems (Andersson & D'Souza, 2014; Ward *et al.*, 2018). One important reason is long waiting period before the benefits start (Baudron *et al.*, 2007). CA often takes 2-5 seasons before farmers start realising benefits in terms of yield increase (Thierfelder *et al.*, 2017). Another reason is that CA as a medium-long term investment requires quality training of smallholder farmers, constant monitoring of the system for several years and economic support to adopters to share the risk of converting the land and the practices (Baudron *et al.*, 2007). Other key reasons are competing uses of crop residues with livestock farming, demand for labour for weeding especially when herbicides are not used and limited access to external inputs (Baudron *et al.*, 2007; Giller *et al.*, 2009).

Agroforestry, on the other hand, is commonly termed “fertilizer tree system”. The system involves sequential or contemporaneous planting of selected tree and shrub species with food crops (Kaczan *et al.*, 2013). The technology helps to maintain soil cover; increase soil organic matter, soil nutrients and water retention capacity; provide additional sources of food, fuel, fodder, fibre and income; and enhance carbon sequestration (Garrity *et al.*, 2010). Evidence by Akinnifesi *et al.* (2008) in Malawi, Tanzania, Zambia and Zimbabwe showed that the system more than doubled maize yield from less than one t/ha to two or more. In another study in Malawi, Sirrine *et al.* (2010) reported maize yield increase of 1.3 – 1.6 t/ha on plots with agroforestry compared to unfertilized mono-cropped plots. The technology has potential to add 60 Kg of nitrogen to the soil per hectare per year and this is equivalent to 75% of nitrogen from inorganic fertilizer (Akinnifesi et al. (2008) in Kaczan *et al.*, 2013). The advantage of this technology over synthetic fertilizer is double benefits in crop productivity and soil health.

Agroforestry interventions in Malawi started in late 1980s where the government identified leguminous agroforestry shrub, *Tephrosia vogelii* and indigenous *Faidherbia albida* locally named *Msangu*. The adoption was however very low and the initiative was abandoned (Carr, 2014). In 2005, the government put agroforestry as a priority in the National Agricultural Agenda. In conjunction with the International Centre for Research in Agroforestry, the government started Agroforestry Food Security Program to provide tree seeds, nursing materials and extension materials in order to enhance adoption (Kaczan *et al.*, 2013). However adoption remains low (Sirrine *et al.*, 2010). Some reasons reviewed by Kaczan *et al.* (2013) include delayed benefits, labour requirements for pruning and biomass transfer, missing or poor functioning markets for fertilizer trees and limited funding on research and agricultural extension services.

3 Methodology

3.1 Theoretical and conceptual framework

This section presents a theoretical and conceptual model used in this thesis. I link the theoretical model and the specific objectives of the thesis in Figure 1. The framework is based on technology adoption decisions under production uncertainty as proposed by Koundouri *et al.* (2006). Farmers in Malawi and many parts in SSA live in an environment where physical and economic systems are complex such that the outcomes of production decisions are uncertain. Such outcomes could be desirable or not. This implies that decision making under uncertainty is risky. Usually, the quantity and quality of output from a given bundle of inputs is not known with certainty at the time of decision making, implying that the production function is stochastic. This is because several uncontrollable elements such as weather are involved in agricultural production characterised by long production lags between the time of decision making and the final product. These long production lags also give rise to price uncertainty as the output price cannot be predicted with certainty at the time of decision making (Moschini & Hennessy, 2001).

Weather shocks – the focus of my thesis – increase production dilemma among farmers and the situation is complicated when soil fertility concerns are also included in production decisions. To enhance crop production farmers will be interested in using a mix of weather-resilient and soil fertility enhancing technologies such as CSA. The decision will be based on the characteristics of the technologies and farmers' expectations of weather conditions during the following season. Use of CSA technologies however, is associated with production uncertainty in two main ways: one, uncertain output after adoption i.e. technological uncertainty and two, production risks associated with farming itself (Koundouri *et al.*, 2006). There is technological uncertainty associated with a given technology, as outputs after adoption are not known with certainty. At the same time farming itself is associated with both production and price uncertainty emanated from weather and long production lags (Moschini & Hennessy, 2001). The farmer's choice is therefore reversible after one or more seasons depending on observable agronomic benefits of the chosen technology compared with others and traditionally practiced technologies (Ding *et al.*, 2009).

Production under uncertainty can thus, be presented as a state-contingent production function (Chambers & Quiggin, 2000; Quiggin & Chambers, 2006). Let X denotes a set of distinct production inputs available to a farmer, X_{csa} represents a set of CSA technologies, S represents a set of all possible states of nature, and let Y be a set of distinct outputs. Input decisions are made before the state of nature is revealed and determine production outcomes that form the basis for consumption decisions within that year and next year's input decisions. Production decisions are made as a first step to maximize weighted probability utility of returns in different states of nature (Holden & Quiggin, 2017). Thus, a farm household allocates input $X \in \Re_+^X$ and chooses state contingent output $Y \in \Re_+^{S*Y}$ before the state of nature is revealed (*ex ante*). Inputs are then fixed and output produced *ex post* (Quiggin & Chambers, 2006). If the household chooses output Y and state of nature S is realized then the observed output is Y_S.

Let P_y represents a vector of output prices and P_x denotes a vector of inputs prices. Farmers face production uncertainty due to weather shocks denoted as ε, which are not known to the farmer at planting time and has a distribution function of G(.) (Koundouri *et al.*, 2006; Ding *et al.*, 2009). As noted, use of CSA technologies has potential to enhance weather-resilience in this setting. Weather-resilience implies that integrating CSA technologies increases the capacity of agricultural systems to prevent, mitigate or cope with and recover from weather shocks (FAO, 2013). The efficiency with which CSA technologies achieve this may depend on farmers' managerial skills, knowledge of the technologies and other characteristics. To capture this in the model, I include the term $\mathrm{h}(\alpha)$. The production function can therefore be specified as:

$$Y = \mathrm{f}[\mathrm{h}(\alpha)\mathrm{X}_{\mathrm{csa}}, \mathrm{X}, \varepsilon] \tag{1}$$

In this setting the farmers' choice of $\mathrm{X}_{\mathrm{csa}}$ will depend on their expectations of the state of nature in the following season. I will here assume that the farmer is rational and will aim at maximizing expected utility E[U(.)] under the expected utility theory (EUT) through farm profits (π) which are subject to input and output prices. There are four main sources of risks and uncertainties in this model: one, production uncertainty due to weather shocks, two, price uncertainty due to production uncertainty and long production lags, three, technological uncertainty and four, policy uncertainty (Moschini & Hennessy, 2001). For simplicity and for the purpose of this thesis I consider in the model only production uncertainty due to weather shocks. The rational and maximizing farmers with full information about possible states of nature will therefore solve the following $E(U[\pi])$ function:

$$\max_{X,X_{csa}} E(U[\pi]) = \max_{X,X_{csa}} \int (U\left[P_y f(h(\alpha)X_{csa}, X, \varepsilon)\right] - P_{csa}X_{csa} - P_x X) dG(\varepsilon) \tag{2}$$

where U(·) is the von Neumann-Morgenstern utility function. Solving this problem yields input demand functions that depend on input and output prices. Taking first order conditions determines the optimal choices of the inputs and is independent of household preferences and characteristics.

$$\frac{\partial \mathrm{U}}{\partial \mathrm{X}_{\mathrm{csa}}} = \mathrm{E}\left[\mathrm{P}_{\mathrm{y}} \frac{\partial \mathrm{f}(\mathrm{h}(\alpha)\mathrm{X}_{\mathrm{csa}},\mathrm{X},\varepsilon)}{\partial \mathrm{X}_{\mathrm{csa}}} \frac{\partial U(\pi)}{\partial \pi}\right] \leftrightarrow \tag{3a}$$

$$\frac{\mathrm{P}_{\mathrm{csa}}}{\mathrm{P}_{\mathrm{y}}} = \mathrm{E}\left[\mathrm{P}_{\mathrm{y}} \frac{\partial \mathrm{f}(\mathrm{h}(\alpha)\mathrm{X}_{\mathrm{csa}},\mathrm{X},\varepsilon)}{\partial \mathrm{X}_{\mathrm{csa}}}\right] + \frac{\mathrm{COV}[\mathrm{U}';\partial \mathrm{f}(\mathrm{h}(\alpha)\mathrm{X}_{\mathrm{csa}},\mathrm{X},\varepsilon)/\partial \mathrm{P}_{\mathrm{csa}}]}{\mathrm{E}[\partial U(\pi)/\partial \pi]} \tag{3b}$$

where $\frac{\partial U(\pi)}{\partial \pi}$ is the change in utility due to change in income. The first term on the right-hand side of equation (3b) represents the expected marginal product from adoption of a CSA technology while the second term (the covariance term) is a measure of deviations from a risk-neutral position. For risk-neutral farmers, the second term is equal to zero such that the adoption decision will be influenced only by the expected marginal product of the technology. In that setting the random variable ε is equal to its mean ($\bar{\varepsilon}$) and risk preferences are irrelevant (Moschini & Hennessy, 2001).

On the other hand, for risk averse farmers, the covariance term is different from zero and is negatively proportional to the marginal risk premium with respect to the CSA input (Koundouri *et al.*, 2006). In this case, adoption will not only be influenced by the cost and benefit of the technology but also production risks and other factors that may influence the cost and performance of the technology (Ogada *et al.*, 2010).

I now include in the model the adoption decision of a CSA technology of a rational farmer. First, the farmer may decide to invest in a technology now based on its perceived benefits. If the technology turns out to be profitable, rationally, the farmer is likely to increase adoption intensity in the following year. The farmer may however dis-adopt the technology or reduce intensity of use if it proves less profitable compared to others or if the technology has delayed benefits – the case of most CSA technologies. Dis-adoption due to delayed benefits could be the case of information asymmetry with respect to long-term benefits of the technologies or farmers' impatient behaviour where immediate gains are given more weight than future benefits. On the other hand, due to technological uncertainty, the risk averse farmer may delay investments in the new technology while observing from a distant. The delay may mean loss in year one profits if the technology is profitable (Moschini & Hennessy, 2001).

For simplicity, I assume the rational farmer decides to use a CSA technology in year one based on perceived benefits under climate change and their expectations of weather conditions. Let $csa = 1$ for adopters and $csa = 0$ for non-adopters. Adoption of CSA technologies increases drought-resilience such that $h^1(\alpha) > h^0(\alpha)\ for\ 0 < \alpha < 1$. This will then reduce production risks during drought conditions. Thus, the rational farmer will adopt a CSA technology if:

$$E(U[\pi^1]) - E(U[\pi^0]) > 0 \qquad (4)$$

where $E(U[\pi^1])$ and $E(U[\pi^0])$ are respectively the expected utility with and without adoption. Ignoring the fixed costs associated with the technologies, I can respectively expand the first and second terms in the left hand side of equation (4) as follows:

$$\max_{X^1, X^1_{csa}} E(U[\pi^1]) = \max_{X^1, X^1_{csa}} \int (U\left[P_y \mathrm{f}(h^1(\alpha)X^1_{csa}, X^1, \varepsilon)\right] - P^1_{csa}X^1_{csa} - P_x X^1) dG(\varepsilon) \tag{5a}$$

$$\max_{X^0, X^0_{csa}} E(U[\pi^0]) = \max_{X^0, X^0_{csa}} \int (U\left[P_y \mathrm{f}(h^0(\alpha)X^0_{csa}, X^0, \varepsilon)\right] - P^0_{csa}X^0_{csa} - P_x X^0) dG(\varepsilon) \tag{5b}$$

The first order conditions for equations (5a) and (5b) can therefore be respectively denoted as:

$$\frac{P^1_{csa}}{P_y} = E\left[P_y \frac{\partial f\left(h(\alpha)X^1_{csa}, X^1, \varepsilon\right)}{\partial X^1_{csa}}\right] + \frac{COV[U'; \partial f\left(h(\alpha)X^1_{csa}, X^1, \varepsilon\right)/\partial P^1_{csa}]}{E[\partial U(\pi)/\partial \pi]} \tag{6a}$$

$$\frac{P^0_{csa}}{P_y} = E\left[P_y \frac{\partial f\left(h(\alpha)X^0_{csa}, X^0, \varepsilon\right)}{\partial X^0_{csa}}\right] + \frac{COV[U'; \partial f\left(h(\alpha)X^0_{csa}, X^0, \varepsilon\right)/\partial P^0_{csa}]}{E[\partial U(\pi)/\partial \pi]} \tag{6b}$$

Given this framework, the rational farmer will adopt a CSA technology if $E(U[\pi^1]) > (U[\pi^0])$. However this framework rests on a strong rationality assumption of the EUT which is often violated by individual farmers' behaviours. Alternative theoretical frameworks to explain behavioural responses to risk and uncertainty that violate EUT are the rank-dependent utility (RDU) (Quiggin, 1991) and Cumulative Prospect Theory (CPT) (Tversky & Kahneman, 1992). These approaches allow probability subjective weighing. In addition, the CPT enables different valuations of gains and losses. The EUT assumes concavity in utility function for risk averse individuals for both losses and gains implying that rational farmers value losses and gains same way. On the other hand, CPT assumes concavity of the utility function for gains but convexity for losses. Further, the utility function is assumed steeper for losses than for gains. Individual farmers tend to value losses more than gains (loss aversion) taking the state-contingent production as a reference point. In this case, there is high probability of farmers adopting a technology that minimises production losses (risk-substituting) under production risks e.g. droughts than a technology that enhances crop yield only under good rains (risk-complementary technologies).

If we assign each prospect π a number $V(\pi)$, π^1 is preferred to or indifferent to π^0 iff $V(\pi^1) \geq V(\pi^0)$. Assuming the outcomes of each prospect can be arranged in an increasing order with respect to a reference point, we can define a cumulative function as:

$$V(\pi) = \sum \gamma(p_i)U(\pi_i) \tag{7}$$

where V is the expected utility, U is a von Neumann–Morgenstern utility function; p is a vector of subjective probabilities for each outcome π while γ is a probability weighting function. γ captures the notion that individuals have a tendency to over- and underreact to small and larger probabilities respectively (Kahneman & Tversky, 1979; Tversky & Kahneman, 1992).

My thesis focuses on both the reduced form and structural form of this framework. First, the reduced form allows prediction of the effect of weather shocks on the choice and use of a given CSA technology ($\mathrm{X_{csa}}$). Second, the structural form of this equation enables assessment of the impact of a CSA technology on production (Y). An increase in weather shocks under climate change can be conceptualized as an increase in downside risk. This can increase or decrease adoption of a given technology depending on farmers' perception on whether the technology is perceived as risk-decreasing or risk-increasing (Arslan *et al.*, 2017). This is tested in the thesis by carefully constructing the long-term weather variable that affects technology choices. I specifically focus on two CSA technologies: ISFM and DT maize varieties. The second stage of this model, the production itself, is directly affected by weather shocks and adoption and use of the CSA technologies and other inputs. I test the effect of a CSA technology by including DT maize varieties in the model while controlling for weather shocks, other inputs use and household and plot characteristics. We can also test whether the CSA technology is risk-increasing or risk-decreasing by including an interaction of the technology and the weather shock. This is however not tested in my thesis but recommended for future studies.

I present a conceptual framework in Figure 1 linking weather shocks, adoption decisions and productivity impact on maize crop. The upper part of the figure shows how weather shocks affect food security. Occurrence of droughts is a natural hazard that farmers have no control over. Such occurrences have devastating effects on both crop and livestock production. CIMMYT (2013) for example, reported that a severe drought can reduce maize yield by as much as half its normal average. FAO (2013) also reported that a drought may affect availability of water and land degradation. The decrease in water availability and land degradation reduces availability of grass in livestock production thereby directly affecting livestock feed. Eventually livestock production is significantly reduced. Similarly both reduced water availability and land degradation affect crop production and productivity. The ultimate impact is on food security. Reduction in crop and livestock production directly and indirectly affect food security through reduced supply and increased prices due to imbalances between demand and supply in the market.

Use of CSA technologies has potential to minimize the negative impacts of drought on crop yields (Kilcher, 2007; Muzari *et al.*, 2012; Makate *et al.*, 2017). However, whether farmers respond to previous exposure to dry spells by using CSA technologies remains an interesting empirical question. I address this question in paper one and paper two focusing on ISFM technologies (organic manure and maize-legume intercropping) and DT maize varieties respectively as shown in the lower part of Figure 1. I hypothesise that farmers who were previously exposed to droughts are more likely to adopt CSA technologies in the following years as an adaptive mechanism. This is in line with the CPT where individual farmers will be stimulated by the loss aversion to adopt a technology that will minimise losses in case of another drought season.

Farmers' decision to use CSA technologies in response to drought shocks can be influenced by both external and internal factors. The farmers' decisions are somehow a function of the available information in line with the bounded rationality. I therefore assume that externally, the government and some NGOs provide information to farmers about CSA technologies through agricultural extension services. A drought may influence extension workers to encourage farmers to adopt CSA technologies in order to avoid resulting drought-related production losses. Farmers would therefore be motivated to use such technologies having experienced devastating impacts of the droughts the previous season. Whether farmers continue using the technology depends on internal factors i.e. how the farmers assess the performance of the technology compared to other technologies under the same growth conditions.

Another external factor by the government is the farm input subsidies. If the government through FISP make CSA technologies available e.g. DT maize seed, legume seed and inorganic fertilizer, there is high likelihood of adoption. Drought occurrence may influence allocation of DT maize seed in FISP packages in areas perceived to be drought prone. FISP may therefore directly influence adoption of CSA technology. Indirectly FISP may influence adoption by giving farmers an opportunity to experiment the technology. If farmers observe higher maize yield on plots with CSA technologies than other plots, there is high likelihood of increased adoption assuming farmers expect another drought season. I control for the impact of agricultural extension services on use of CSA technologies in paper one while FISP is controlled for in paper two. I however leave the investigation on how maize yield affects use of CSA technology for another study.

Finally, I show in the conceptual model that adoption of CSA technologies has potential to increase maize yield. I specifically focus on impact of DT maize variety on maize yield in paper three. While some authors have tested this hypothesis e.g. Idrisa *et al.* (2014), Holden and Fisher (2015), Lunduka *et al.* (2017) and Makate *et al.* (2017), I focus on impact heterogeneity of this CSA technology by using a continuous treatment approach. I control for other production inputs such as organic and inorganic fertilizer in this paper. Finally, in paper four, I review literature on maize productivity impacts of farm input subsidies and CSA technologies and synthesise the findings.

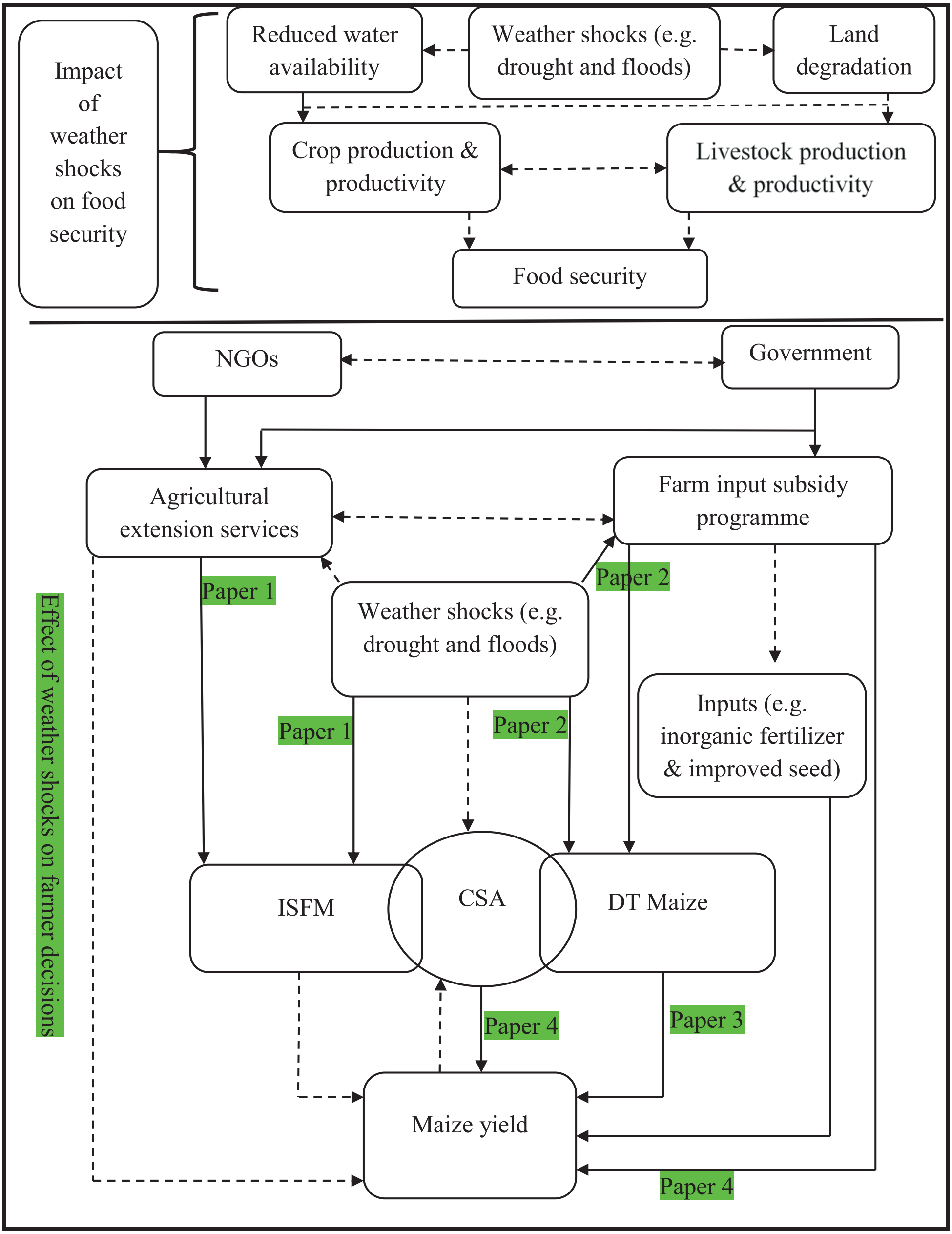

Figure 1: Conceptual framework

Notes: the upper part of the figure shows how weather shocks affect food security. The dotted lines in this figure show causal relationships but are not tested nor controlled for in this thesis.

3.2 Data and study areas

The data in this thesis come from six districts in Malawi namely: Chiradzulu, Machinga, Thyolo and Zomba in Southern Region; Kasungu and Lilongwe in Central Region (Figure 2). These districts capture two important aspects: one, rainfall variations and two, land dynamics. In terms of rainfall variations, Zomba district is drought prone (World Bank, 2010) while Thyolo lies in the high plateau and hilly areas receiving over 1200 mm of annual rainfall. The other four districts receive average annual rainfall ranging from 800-1,200 mm (Bunda College, 2008). With respect to land dynamics, households in Southern Region districts have small land holdings (Matchaya, 2007; Tchale, 2009) compared to households in Central Region districts. The advantage of these spatial dynamics in this study is that both rainfall variations and land sizes are likely to influence use of drought-resilient and land intensification technologies focused in this study.

The data are panel of four waves spanning nine years from 2006 to 2015. The initial sampling of the households in 2006 used a multistage sampling approach following the 2004 Integrated Household Survey Two (IHS2) (Lunduka, 2009). The first stage was purposive sampling of the six districts with the primary goal of capturing land dynamics. Second stage was simple random sampling of enumeration areas (EAs) from the list of EAs used in the IHS2. Two EAs were randomly sampled in Chiradzulu, Machinga and Thyolo districts, while three were randomly sampled in Kasungu, Lilongwe and Zomba districts resulting in 15 EAs (Figure 2). The third and final stage was random sampling of households from the EAs. 30 households were randomly sampled from each EA giving a total of 450 respondents. 378 were resurveyed in 2009, 350 in 2012 and 2015, resulting in four rounds of unbalanced panel data (Table 2).

Table 2: Study areas

District	**2006**		**2009**		**2012**		**2015**		**Total**	
	HHs	Plots	HHs	Plots	HHs	Plots	HHs	Plots	HHs	Plots
Chiradzulu	53	98	35	77	36	70	34	60	158	305
Kasungu	102	122	88	183	83	141	81	135	354	581
Lilongwe	96	128	71	114	61	119	64	113	292	474
Machinga	51	77	49	84	47	85	45	76	192	322
Thyolo	62	94	51	100	47	98	47	92	207	384
Zomba	86	139	84	114	76	167	79	151	325	571
Total	**450**	**658**	**378**	**672**	**350**	**680**	**350**	**627**	**1528**	**2637**

Figure 2: Map of Malawi showing sample districts

Data collection used a detailed semi-structured questionnaire administered to a household and collecting household and plot level information. The plot was defined as a piece of land with a uniform crop stand and receiving homogenous input treatment. The plot sizes were physically measured using a Global Positioning System (GPS) device. The household panel data were merged with daily rainfall data from Malawi's Department of Climate Change and Meteorological Services (DCCMS) from 2003 to 2015. I obtained the rainfall data for all weather stations in the survey districts. These included: Chiradzulu weather station in Chiradzulu district; Kaluluma and Kasungu in Kasungu; Bunda, Chitedze and Kamuzu International Airport in Lilongwe; Chikwewo, Liwonde and Ntaja in Machinga, Bvumbwe and Thyolo in Thyolo and Chancellor College, Chingale and Makoka weather stations in Zomba district. I used data from a weather station close to the enumeration area where the household data was collected in each district. These weather stations were Chiradzulu, Kasungu, Chitedze, Ntaja, Bvumbwe and Chancellor College. I merged the household and rainfall data at enumeration area level.

I used the daily rainfall data to generate dry spell variables, which are key to my study. I defined the dry spells as the consecutive number of days (at least 5 – 15) with a total precipitation below 20 mm after the onset of the rainy season.[1] I respectively generated longest early-season and late-season dry spells to coincide with maize planting and grain filling phases. I generated these variables for all the survey years and for the previous three seasons of each survey year. Dry spells are common during Malawi's rainfall season and local meteorologists consider a dry spell as drought if their duration is three-to-four months or longer (Chabvungma et al., 2015). I have however used the two words interchangeably in this thesis as often times Malawians do not differentiate prolonged dry spells and short duration droughts. I also generated rainfall distribution variables such as average rainfall (mm) lagged three years and monthly averages for critical months of December, January and February.

The data set has some advantages over large sample surveys. One, the data are of four rounds, which is unique and absent in most large sample surveys. With such a long panel that covers a period of close to 10 years, the data cover substantial rainfall variations that include severe drought

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[1] Personal communication (February 18, 2016) with Charles L. Vanya (Principal Meteorologist with DCCMS)

in 2005 – a year before first round of data collection, good rainfall distribution in 2006 and 2009, early-season droughts in 2012 and a combination of early-season floods and late-season droughts in 2015. During this period households also witnessed the introduction of FISP that has had both direct and indirect influence on adoption and use of different CSA technologies such as DT maize, inorganic fertilizer, organic fertilizer and maize-legume intercropping.

The second advantage of the data is improved quality. Unlike large sample surveys that either measure only one plot or none, in this data, all household plots were measured with a GPS device. This procedure unlike farmer estimates ensures minimal measurement errors of plot sizes, crop productivity in kilograms per hectare, and input use in kilograms per hectare. Such accuracy is often absent in most large sample surveys.

The third advantage is the merging of household survey data with daily rainfall data. The rainfall information enabled generation of objective dry spell variables instead of relying on farmer perception or memory of recent droughts. The advantage of this variable is that it is not prone to omitted variable bias that self-reported drought shocks would be. The other advantage is the disaggregation of the dry spells variables into early-season and late-season. The early- and late-season droughts affect crop production, maize in particular differently and farmers may respond differently. Using farmer perception variable would therefore not capture this variation accurately. The final advantage of the daily rainfall data in this thesis is that farmer perception variable is likely to be subjective (Holden & Fisher, 2015) because it is influenced by both rational and emotional factors of the farmers (Duinen et al., 2015). Such subjectivity may result in endogeneity because more pessimistic farmers tend to overestimate the probability of a negative outcome and therefore perceive more weather shocks. I however acknowledge the findings of Holden and Quiggin (2017) who failed to find evidence of endogeneity of farmer perception variables. The study (ibid) also pointed out the weakness of the data from the nearest weather station as lacking enough spatial variability among households within the same enumeration area.

4 Summary of Main Findings

In this section, I present a summary of the main findings from the four specific papers used in this thesis. I summarise the methods used and the key results.

4.1 Use of integrated soil fertility management technologies in Malawi: The impact of dry spells exposure (Paper I)

In this paper, we examined use of integrated soil fertility management (ISFM) technologies and how exposure to dry spells influences farmer uptake. ISFM technologies are potentially climate-smart with the capacity to protect crop production against climate risks. We specifically focussed on maize-legume intercropping and organic manure to test two related hypotheses: one, exposure to early-season and late-season dry spells increases the likelihood of using organic manure; two, exposure to early-season and late-season dry spells increases the likelihood of using maize-legume intercropping. We used a four-round panel dataset collected from households in six Malawi districts between 2006 and 2015 and merged with daily rainfall data from the Department of Climate Change and Meteorological Services. Considering the important role of the government and NGOs in enhancing use of CSA technologies in Malawi, we controlled for government and NGO interventions by including agricultural extension services and FISP variables in the model.

We captured the decision to use ISFM technologies, first as a dummy variable equal to one for use and zero otherwise. The next question was intensity of use captured in kilogrammes per hectare for organic manure and farm size share [0,1] for maize-legume intercropping. To test the hypotheses, we used correlated random effects (CRE) models. We used the probit estimator for binary decision, tobit for organic manure use intensity and fractional probit for farm size share under maize-legume intercropping. The CRE was preferred over other approaches in order to control for unobserved heterogeneity (Wooldridge, 2010a). This approach unlike its alternative – the household fixed effects (HHFE) – avoids the incidental parameters problem in non-linear models (Wooldridge, 2009; Wooldridge, 2010a).

Results indicated an increase in use rates from 33% in 2006 to 75% in 2015 for maize-legume intercropping and from 31% (2006) to 55% (2015) for organic manure. While there was also an increase in use intensity of maize-legume intercropping from 26% in 2006 to 36% in 2015, there was a consistent decrease in quantity of organic manure applied from 2195 Kg/ha in 2006 to 1544 Kg/ha in 2015. The regression results revealed that exposure to one-year lag of early-season and late-season dry spells increases the likelihood of use and use intensity of organic manure and maize-legume intercropping. However, there was inconsistent effect of two-year and three-year lags of both early-season and late-season dry spells on use and use intensity of both technologies.

These results depict three important issues. One, farmers build weather expectations from previous exposure and they respond by using climate-smart technologies. We attribute this response to farmers' perceived benefits of the technologies under negative effects of climate change. Two, recent weather events are more influential in forming farmers' weather expectations than long-term weather conditions. The inconsistent effect of two- and three-year lags of both early- and late-season dry spells suggest that farmers are myopic in their decisions as they respond more to recent weather shocks than to long-term weather conditions. Three, the inconsistent impacts of two- and three-year lags on use of CSA technologies could also signify the impact of delayed benefits of the technologies. This explanation is however based on previous studies who reported that organic manure and maize-legume intercropping often take more than two seasons to start manifesting production benefits (Snapp *et al.*, 1998; Silberg *et al.*, 2017). Unfortunately smallholder farmers tend to overweigh immediate needs over future benefits (Corbeels *et al.*, 2014).

Controlling for agricultural extension services, our results showed positive correlation with use of organic manure. This implies that while farmers may fail to consistently use CSA technologies because of myopic weather expectations and possibly because of delayed production benefits, agricultural extension services can stimulate consistent use of the technologies. Agricultural extension services can provide farmers with appropriate information about the technologies and their future and long-term benefits. Finding ways of sharing the risks of delayed benefits with the farmers could be another way of stimulating consistent use of the technologies.

4.2 Adoption of drought tolerant maize varieties under rainfall stress in Malawi (Paper II)

We examined adoption of drought tolerant (DT) maize varieties under rainfall stress conditions in Malawi in this paper. DT maize is potentially a climate-smart technology because it has the capacity to produce 30% of its potential yield after suffering from water stress six weeks before and during grain formation phase (Magorokosho *et al.*, 2009). The technology can also give farmers maize yield advantage of 40% over other maize varieties in severe drought environments (Tesfaye *et al.*, 2016). The technology has received massive support from the government of Malawi with the inclusion of the seed in the FISP package, making it more accessible (Lunduka *et al.*, 2012; Holden & Fisher, 2015).

We examined how past exposure to dry spells affects adoption and the probability that DT maize seed is included in the seed subsidy programme. Farmers in Malawi face a trade-off with respect to maize varieties. DT maize varieties are early maturing and drought tolerant but are low yielding in high rainfall conditions compared with other improved hybrid varieties. Again, both DT maize and other improved hybrids do not yet possess preferred consumption traits that local varieties possess such as taste, storability, poundability and high flour-to-grain ratio (Smale *et al.*, 1995; Denning *et al.*, 2009; Lunduka *et al.*, 2012). Farmers therefore tend to adopt a portfolio of maize varieties. We therefore first modelled farmers' decision on whether to adopt DT maize or not before modelling the decision on area (ha) and area share allocated to DT maize varieties.

We used four-round panel data from six districts collected between 2006 and 2015. The household panel data were merged with daily rainfall data from the Department of Climate Change and Meteorological Services from 2003 to 2015, which allowed us to generate dry spell variables. We used the Mundlak-Chamberlain (MC) models with a Control Function (CF) approach to analyse the data (Mundlak, 1978; Chamberlain, 1984; Wooldridge, 2010b). We modelled the adoption decision as a binary (zero/one) decision using a probit, while the area (ha) and farm size share decisions were respectively modelled using tobit and fractional probit estimators.

Results showed an increase in adoption of DT maize from 3% in 2006 to 43% in 2015. Regression results indicated that past exposure to drought increases the probability of DT maize seed being distributed through FISP. Farmers who accessed maize seed subsidy coupons and were previously exposed to late-season dry spells were more likely to use the seed subsidy coupon to redeem DT maize seed. The likelihood of adoption and adoption intensity (area under DT maize) were positively influenced by previous early-season dry spells and access to seed subsidy with previous late-season droughts also positively affecting adoption intensity. On the other hand, area share under DT maize was positively correlated with early-season dry spells and past exposure to late-season dry spells but negatively related to seed subsidy.

Farmers' adoption of drought tolerant maize, a climate-smart technology is an indication that farmers in drought-prone regions in SSA countries are more willing to adopt a drought-resilient technology. We provided evidence in this paper that previous early droughts affect adoption by increasing farmers' adaptive expectations with respect to duration of the rainy season. On the other hand, previous late droughts affect adoption through risk aversion as farmers adopt technologies that hedge against late-season drought risks. The positive impact of seed subsidy suggests the direct impact of FISP on adoption of DT maize seed. This direct impact is through the availability of the cheap DT seed. Indirectly, FISP also influences adoption by generating farmers' experience of the performance of DT varieties under drought conditions. However adoption outside FISP is relatively low and this may present a sustainability problem. Agricultural extension service should therefore do more to enhance awareness of DT maize seed for more adoption outside FISP.

4.3 Productivity impact of drought tolerant maize varieties under rainfall stress in Malawi: A continuous treatment approach (Paper III)

In paper three, we examined the impact of DT maize variety on maize productivity using a continuous treatment approach. Previous studies have reported inconsistent evidence on the impact of this technology. Holden and Fisher (2015) and Fekadu and Endeshaw (2016) for example, found insignificant yield advantage of DT maize over other improved maize varieties but local maize in Malawi and Uganda respectively. On the other hand, Cenacchi and Koo (2011), Idrisa *et al.* (2014), Makate *et al.* (2017) and Lunduka *et al.* (2017) found positive and significant impact of DT maize varieties on maize yield, food security, and household welfare over other maize varieties. We attributed this inconsistency to different estimation techniques and to use of cross sectional data that does not fully capture heterogeneity effects and variability of rainfall.

We addressed this inconsistency in this paper and make novel contribution to the body of literature in two main ways. Firstly, our paper used panel data of four waves capturing three different rainfall scenarios, namely, normal average rainfall in 2006 and 2009, early droughts in 2012, and early floods with late droughts in 2015. Secondly, we applied a continuous treatment approach (Cerulli,

2015) that allowed assessment of dose response function (DRF) and marginal treatment function (MTF) across different DT maize adoption levels. The dose in our case captured the intensity of DT maize adoption in terms of acreage of land in hectares planted with DT maize varieties while the response referred to the maize productivity (Kg/ha).

The results of yield distribution showed that DT maize yield was higher than other two varieties (other improved maize and local) in 2015, a year with reported late-season droughts. On the other hand, other improved maize varieties reported higher maize yield than DT maize in 2009 and 2012 where no late-season droughts were observed. Regression results of average treatment effects showed that the mean maize yield for adopters of DT maize was above the mean of non-adopters in the study areas. The dose response function results showed that maize yield increased from 371 Kg/ha at 5% level of DT maize adoption level to 1000 Kg/ha at 52% adoption level. On average, a one hectare increase in the area allocated to DT maize varieties increased maize yield by 510 Kg/ha representing a 41% increase from the average maize yield of 1254 Kg/ha for our sample. These results also implied impact heterogeneity of DT maize varieties. The marginal treatment effect showed that the changes on the effect of DT maize adoption on maize yield decreased with the level of adoption at lower levels but increased at higher adoption levels.

Our findings give evidence that DT maize technology has potential to protect smallholder farmers against drought-related production losses. Policies that promote increased allocation of maize area to DT maize varieties hold potential to enhance food security. The impact heterogeneity of DT maize on maize productivity is necessary for Malawian farmers who adopt a portfolio of maize varieties for production and consumption gains. Appropriate allocation of maize area to different varieties can minimise potential yield losses. Full adoption of DT maize varieties may result in yield losses in case of good rains while full adoption of other high yielding non-DT hybrids may also result in yield losses under drought conditions. We therefore recommend that breeders should consider developing drought tolerant maize varieties that are also high yielding across all rainfall conditions. This would minimise the farmers’ dilemma when deciding on maize varieties.

4.4 Maize productivity impact of farm input subsidies vis-à-vis climate-smart technologies: A tale of smallholder farmers in Malawi (Paper IV)

In this paper, I reviewed empirical evidence on maize productivity impacts of subsidized inorganic fertilizer with extension to related climate-smart agriculture technologies. Specifically, I reviewed: a) maize productivity impact of subsidized inorganic fertilizer; b) marginal maize productivity impact of subsidized inorganic fertilizer; c) impact of integrating inorganic and organic fertilizer; and d) maize productivity impact of conservation agriculture. Farm input subsidies in Malawi are historically a strategic agriculture policy instrument for enhancing maize production for sustainable national and household food security. At the same time the National Agriculture Policy emphasizes on investments in CSA technologies to enhance sustainable agricultural production and productivity (Government of Malawi, 2016).

Results show modest maize productivity impact of FISP. While maize production was reportedly high in non-drought years, the maize-fertilizer response rates among FISP beneficiaries were below agronomic average. The studies reviewed measured maize-fertilizer response based on nitrogen use efficiency (NUE) defined as "*amount of additional grain harvested per kilogramme of nitrogen applied to the grain crop*" (Kg/KgN) (Snapp *et al.*, 2014: P1). The agronomic evidence in Malawi indicates NUE of 14-50 Kg/KgN on on-station and on-farm trial plots (Snapp *et al.*, 2014). On farmer-managed plots, the average benchmark NUE used in most impact studies is 16.8 Kg/KgN (Pauw & Thurlow, 2014). FISP beneficiaries however showed very low NUE. Ricker-Gilbert and Jayne (2011, 2012) and Jayne and Rashid (2013) for example reported NUE of 5.5 – 9.6 Kg/KgN with the poorest households reporting 2.4. Dorward *et al.* (2013) found a relatively higher NUE of 15.2 while Snapp *et al.* (2014), Pauw and Thurlow (2014), Chibwana *et al.* (2014) and Arndt *et al.* (2015) found maize-fertilizer response of 7 – 14.5. Ricker-Gilbert and Jayne (2017) reported the smallest NUE of 3 – 4.4 Kg/KgN.

The results also show uncertainty in the long-term impact of FISP. Ricker-Gilbert and Jayne (2017) for example reported limited long-term impacts of FISP on maize production. Messina *et al.* (2017) reported national decline in annual maize productivity trend. An evaluation of 2016/17 subsidy by Centre for Development Management (2017) showed that production and productivity has stagnated in recent years. Sibande *et al.* (2017) also casted doubt of the program's long-term impact and sustainability because the incremental quantities of FISP are too small to generate enough income to allow participating farmers self-finance input purchase in subsequent years.

There are several reasons in literature for modest impact of FISP. These include but not limited to cultivation on degraded soils depleted of essential nutrients and organic matter, targeting errors, poor timing of input delivery, input diversion, displacement of commercial inputs, recipient of less than the required amounts and limited private sector involvement. The problem is worsened by frequent and prolonged dry spells and poor agronomic practices. Conversely, maize productivity was consistently high with enduring effects on experimental plots with integration of inorganic and organic fertilizer. The yield was equally high and sustainable on experimental plots with CA. These technologies ensure efficient and optimal nutrient intake and drought-resilience.

The key insights from this literature review are: one, FISP has relatively increased maize production in Malawi in non-drought years. This implies that the programme remains a key agriculture policy strategy for Malawi in the near future for sustainable agricultural production. Two, marginal maize productivity impact of FISP is modest. Three, long-term impact of FISP is uncertain. Four, the impact of CSA technologies on maize productivity is high, stable and sustainable. This suggests that the impact of FISP can be enhanced if application of subsidized inorganic fertilizer is integrated with CSA technologies such as organic fertilizer and CA. Farmers should be encouraged to adopt CSA technologies as a prerequisite to accessing input subsidies. This approach will yield double benefits in increased crop productivity and soil health, thereby providing the Government of Malawi with a sustainable exit strategy of FISP.

5 Contribution and limitation of the thesis

5.1 Key findings

a. Exposure to previous early-season and late-season dry spells help farmers build weather expectations and influence use of CSA technologies as adaptive mechanisms.

I have argued in papers one and two that smallholder farmers build weather expectations from previous exposure to weather conditions and therefore respond to weather shocks such as dry spells by using CSA technologies. Smallholder farmers who were previously exposed to early-season and late-season dry spells are more likely to use CSA technologies such as organic manure, maize-legume intercropping and DT maize varieties. This observation is necessary among smallholder farmers in SSA who are frequently exposed to weather shocks such as floods, droughts and mid-season prolonged dry spells. The results imply that farmers who were previously exposed to weather risks are aware of the negative effects of such risks and are willing to invest in CSA technologies to hedge against subsequent production losses.

b. *Immediate weather shocks are more influential than long-term weather conditions in forming weather expectations and hence more significant in enhancing use of CSA technologies.*

This is an interesting finding in paper one. While farmers respond to exposure to early-season and late-season dry spells by adopting CSA technologies as adaptive mechanisms, it is the immediate dry spells that are more influential for some technologies. This suggests that farmers are myopic and respond more to recent weather conditions over long-term weather conditions. Another possible explanation is that some CSA technologies such as organic fertilizer and CA have lagged benefits such that farmers may fail to observe the gains during first years of implementation. Failure to observe such benefits under drought conditions may result in dis-adoption in subsequent years.

c. *CSA technologies have potential to protect farmers from drought-related yield losses.*

In paper three, I have argued that adoption of DT maize varieties – a CSA technology – has potential to protect farmers against negative effects of droughts. These findings suggest that with appropriate drought-resilient technologies the poor maize harvests amongst smallholder farmers in Malawi and many parts in SSA, under drought stress conditions could be minimised. While this finding is not new per se, what is new here is the heterogeneity of the impacts. The impacts are heterogeneous suggesting different yield potential at each level of adoption. The literature review in paper four has also shown that adoption of CSA technologies such as integration of organic and inorganic fertilizer and CA has consistent and enduring effects on maize productivity.

d. *Integrating farm input subsidies and CSA technologies is a potential magic bullet.*

FISP is historically a strategic agriculture policy tool for sustainable maize production and productivity in Malawi. However the twin problems of weather shocks and declining soil fertility have reduced efficiency with which subsidised inputs e.g. inorganic fertilizer and improved maize seed are used. The impact of FISP is therefore modest and inconsistent. I discuss in paper four that integrating FISP and CSA technologies is potentially a magic bullet for sustainable maize productivity. The integration would ensure that smallholder farmers adopt CSA technologies first before accessing input subsidies. The CSA technologies are drought-resilient, enhance nitrogen use efficiency of subsidised inorganic fertilizer, build additional nutrients in the soil and improve water and nutrient retention thereby increasing maize production and productivity.

5.2 Limitation of the study and future research

One important limitation of this study is scope of data coverage. My data covered six districts in Malawi out of 28 with an average sample size of 350 households. This data may therefore not be representative enough for Malawi and SSA region as a whole. Another study using nationally representative data is recommended to substantiate my findings.

The second limitation is that I have used daily rainfall data from a nearest weather station to an enumeration area where the household survey data were collected. This data set has limited spatial variability across sample households within the enumeration area. Any future research should consider using rainfall data with enough spatial variations across all households in the enumeration area. It is however relatively difficult to get this data. An alternative should be combining the daily rainfall data from the nearest weather stations and farmer perceptions of recent weather events to generate weather shocks and rainfall distribution variables.

The third limitation is the scope of paper four where I have reviewed literature on maize productivity impacts of FISP and CSA technologies. My paper has limited the scope to one country, Malawi. There are however more countries in SSA that are implementing both farm input subsidies and CSA technologies. For more policy insights, future research should consider expanding coverage of such type of reviews.

Fourth, while I have recommended integration of FISP and CSA technologies in paper four, based on literature review, an analysis with primary data on the topic could give additional and comprehensive evidence.

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Paper one

Use of integrated soil fertility management technologies in Malawi: Impact of dry spells exposure*

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Abstract

Integrated soil fertility management (ISFM) technologies hold potential to protect against climate risks, reduce nutrient depletion and enhance food security. In this paper, we study how exposure to dry spells influences use and use intensity of ISFM technologies, specifically organic manure and maize-legume intercropping. We use a four-round panel dataset collected from households in six Malawi districts over a period of nine years and merged with daily rainfall data from the Department of Climate Change and Meteorological Services. Results indicate an increase in use rates over time for both maize-legume intercropping and organic manure. The regression results using correlated random effects models reveal that exposure to one-year lag of early-season and late-season dry spells increases the likelihood of use and use intensity of both technologies. However, there is inconsistent effect of two-year and three-year lags of both early-season and late-season dry spells on use and use intensity of these technologies. These results suggest that farmers build weather expectations from previous weather conditions and use ISFM technologies as adaptive mechanisms. Immediate dry spells are however more influential in developing those expectations than long-term weather conditions. This could mean that farmers are myopic and value more the impact of recent weather shocks than long-term weather risks.

Key words: Correlated random effects, dry spells, intercropping, organic manure, Malawi

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1. Introduction

Droughts in many parts of sub-Saharan Africa (SSA) are frequent and severe with devastating impacts especially on agriculture and food security (Benson & Clay, 1998). Droughts usually occur when average seasonal rainfall is below 75% of the normal. Occasionally, there are dry spells within a rainfall season and these turn into droughts if last for more than three months (Chabvungma *et al.*, 2015). Coupled with poor soil fertility and poor water retention capacity of the soils, 60% of the region is vulnerable to drought with 30% extremely vulnerable (Benson & Clay, 1998). In Malawi, a country heavily dependent on rain-fed agriculture (Government of Malawi, 2011b), the twin problems of frequent and prolonged dry spells and low levels of nitrogen use are major causes of low crop productivity resulting in persistent food insecurity (Weber et al., 2012). The problem is particularly severe in the country due to over-dependence on maize as a staple crop (Smale, 1995). Maize production is vulnerable to droughts whose productivity can reduce by up to half when a severe drought occurs especially during grain filling phase (CIMMYT, 2013). The past two decades, maize production has been significantly low in drought years such as 1991/92, 2001/02 and 2004/05 resulting in severe food insecurity (Nangoma, 2007; Denning *et al.*, 2009; Mapila *et al.*, 2013; Msowoya *et al.*, 2016).

Efforts to enhance maize productivity through increased drought resilience, nutrient application and nutrient maintenance are thus important to achieve sustainable food security. Such efforts require complementary investments in organic and inorganic integrated soil fertility management (ISFM) technologies and high yielding and drought tolerant crop varieties. ISFM technologies increase nutrient intake, protect the soils, minimize nutrient depletion through enhanced soil organic matter and biological activity and eventually increase crop yields and yield stability (Weidmann & Kilcher, 2011). ISFM ensures nutrient balance and efficient management of soil fertility through combinations of inorganic fertilizer, organic manure, soil and water conservation technologies and crop diversification that include maize-legume intercropping.

In this paper, we use a four-wave panel dataset for central and southern Malawi to examine use and use intensity of two ISFM technologies – organic manure and maize-legume intercropping – and how exposure to dry spells influences use. Organic manure and maize-legume intercropping are old and popular technologies among smallholder farmers in Malawi and our dataset allows us to gain an improved understanding on how the technologies have been used for a period of close to 10 years. In this period the sample farmers have been exposed to several climatic shocks in the form of early-season and late-season dry spells and have also had varying access to input subsidies that indirectly may have affected the intensity of use of these technologies. In the same period the Government of Malawi (GoM) has enhanced efforts to promote use of climate-smart agriculture (CSA) technologies that includes organic manure and maize-legume intercropping through programs such as the Agriculture Sector Wide Approach (ASWAp) (Government of Malawi, 2011a). Several NGOs such as Total Land Care (TLC), Concern Worldwide, Concern Universal, World Vision International, Care Malawi and many more have also worked tirelessly in promoting conservation technologies in the country (Ligowe et al., 2013 in Dougill *et al.*, 2017).

Previous research examined the determinants of farmers' investment decisions in maize-legume intercropping and organic manure in Malawi. Findings suggest that use of organic manure increases with inorganic fertilizer use and fertilizer price (Holden & Lunduka, 2012), tenure security (Kassie *et al.*, 2015), knowledge of manure making (Kilcher, 2007; Mustafa-Msukwa *et al.*, 2011) and household labour availability (Snapp *et al.*, 2002; Mustafa-Msukwa *et al.*, 2011; Chatsika, 2016). The probability of using maize-legume intercropping has been shown to be limited by the yield advantage of maize over legumes, pest susceptibility, and a lack of appropriate legume genotypes (Kerr *et al.*, 2007; Ortega *et al.*, 2016). Other factors shown to influence maize-legume intercropping are market access, output prices, availability and cost of improved legume seeds, farm size and exposure to weather shocks (Kerr *et al.*, 2007; Kilcher, 2007; Asfaw *et al.*, 2014; Kassie *et al.*, 2015; Ortega *et al.*, 2016). Silberg *et al.* (2017) also reported that use of maize-legume intercropping increases with previous sales of legumes and noted that technologies such as organic manure and inorganic fertilizer are likely to be applied on plots with intercropping.

We test two related hypotheses in this paper: one, exposure to early-season and late-season dry spells increases the likelihood of using organic manure; two, exposure to early-season and late-season dry spells increases the likelihood of using maize-legume intercropping. We combine household panel survey data from 2006 to 2015 and daily rainfall data from 2003 to 2015 from the Malawi's Department of Climate Change and Meteorological Services (DCCMS). We use the daily rainfall data from DCCMS to generate dry spell and rainfall distribution variables. While farmers' perception/memory of recent dry spells would be an option to capture a dry spell exposure variable, this perception variable is likely to be subjective as it is influenced not only by rational factors but also emotional factors of farmers (Duinen *et al.*, 2015). Such subjectivity may cause bias. As such, we constructed objective dry spell variables using daily rainfall data to minimise biased estimates.

In this study, dry spells are measured as the number of consecutive days (at least 5 – 15) with a total precipitation below 20 mm after the onset of the rainy season. We then identified the longest early-season and late-season dry spell in each of the previous three seasons of a survey year and these are the dry spell variables included in the regression analysis. Dry spells are common during Malawi's rainfall season and local meteorologists consider a dry spell as drought if their duration is three-to-four months or longer (Chabvungma *et al.*, 2015).

We are interested in examining the degree to which farmers' use of organic manure and maize-legume intercropping is positively associated with previous experiences of dry spells early and late in the maize growing season, holding constant other key factors. It is reported that sustainable conservation agriculture practices can minimize drought sensitivity of crop yields (Kilcher, 2007; Muzari *et al.*, 2012; Makate *et al.*, 2017a; Makate *et al.*, 2017b). However, whether farmers respond to previous exposure to dry spells by using maize-legume intercropping and organic manure, and how early- and late-season dry spells affect use, remains largely unexplored in the literature. Severity of dry spells has been increasing in Malawi and other parts of SSA in recent years and the use of drought-resilient technologies can help farmers adapt.

2. Background

2.1. Major weather patterns in Malawi

Malawi has a sub-tropical climate with three major seasons. First is a cool, dry winter season between May and August before a hot, dry season from September to October. The hot, dry season is followed by the warm-wet season from November to April during which about 95% of the annual rainfall takes place. On average the country receives 725 mm to 2,500 mm of rainfall (DCCMS, 2006). Focusing on the nine-year period of our surveys, the average annual rainfall was lowest in 2014/15 with an average of 918 mm while the highest was reported in 2007/08 (Figure

1). This resulted in low average maize production of about 2.78 million metric tonnes (MT) which was much less than the previous three seasons. In 2014/15 the country experienced early-season floods and late-season prolonged dry spells, which resulted in low maize production. Prior to that the lowest annual average rainfall was reported in 2004/05 of about 822 mm and the country reported very low national maize production of about 1.26 million MT. This resulted in severe food insecurity affecting over four million Malawians (Denning *et al.*, 2009).

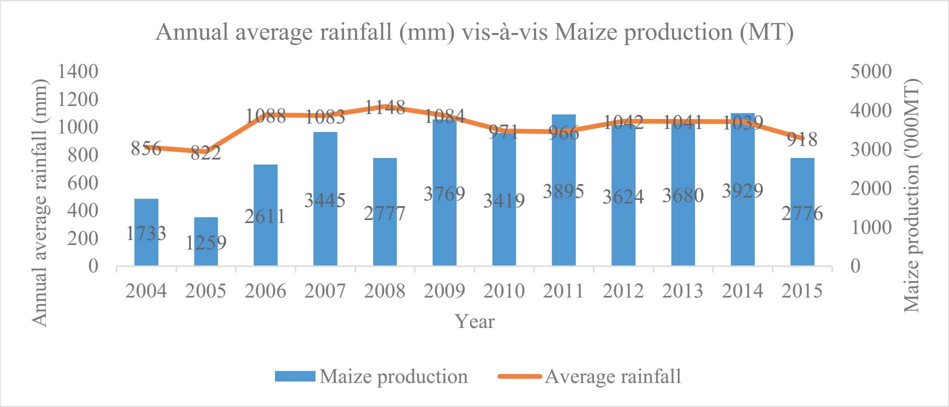

Figure 1: Maize production and rainfall over time

Source: Ministry of Agriculture, Irrigation and Water Development for maize production data while rainfall data is from DCCMS.

2.2. Organic manure

Organic manure is an organic matter-based technology (Snapp *et al.*, 1998) whose sources include farm yard manure (FYM), compost manure, green manure, crop residues and household refuse (Snapp *et al.*, 1998; Chilimba *et al.*, 2005; Kabuli & Phiri, 2006; Government of Malawi, 2012; Holden & Lunduka, 2012). The advantage of this technology is that it enhances soil organic matter and essential nutrients such as nitrogen (N), phosphorus (P) and potassium (K) (NPK) (Mafongoya *et al.*, 2006; Thierfelder *et al.*, 2015a; 2015b). The technology also ensures increase in nutrient and water use efficiency, nutrient maintenance and soil pH (Heerink, 2005; Mafongoya *et al.*, 2006; Nyasimi *et al.*, 2017).

Historically, organic manure is not a new technology among smallholder farmers in Malawi (Andersson & D'Souza, 2014). In fact organic matter-based technologies can be traced back to indigenous knowledge as early as 1970s (Mango *et al.*, 2017). In early 2000s, the government embarked on a campaign to promote use of compost manure, farmyard manure (FYM) and crop residues (Chilimba *et al.*, 2005). Evidence showed use remained very low with national average showing only 15.2% of maize plots using organic manure in 2002/03 and 2003/04 and 12.7% in 2008/09 and 2009/10 (Snapp *et al.*, 2014).

There are several challenges limiting use of organic manure. The first reason is unguaranteed and unbalanced quality of nutrients. Different organic sources contain different quantities of nutrients with varying ranges (Chilimba *et al.*, 2005; Mafongoya *et al.*, 2006). Another reason is bulk quantity requirements to meet nitrogen requirement for maize production (Mafongoya *et al.*, 2006). Third challenge is labour drudgery in making and transporting. The technology demands a lot of labour that may not be readily available. Fourth, limited income, risk aversion and the need for continuous food production. Organic manure technology does not consider immediate needs for food production as it takes time to build soil nitrogen (Snapp *et al.*, 1998). Last but not least is trade-offs of crop residues and household refuses for various options (Valbuena *et al.*, 2012) such as feeding livestock or use for making organic manure and other conservation technologies such as conservation agriculture (CA).

2.3. Maize-legume intercropping

Maize-legume intercropping is a farming practice in which maize crop is mixed with one or more leguminous crops. The technology improves sustainable crop productivity in maize-based cropping systems (Snapp *et al.*, 2002). Empirical evidence has shown that these systems increase soil productivity through biological nitrogen fixation and conservation of soil nutrients (Snapp *et al.*, 1998; Government of Malawi, 2012). Apart from the agronomic benefits, intercropping provides environmental benefits through reduced soil erosion, improved water infiltration and carbon sequestration, and increase crop and food diversity by providing high protein grain and leaves. All these benefits are achieved at a low cost and low risk for the farmer (Woomer *et al.*, 2004; Kerr *et al.*, 2007; Kamanga *et al.*, 2010; Government of Malawi, 2012). In Malawi, the most common legumes that have been intercropped with maize are beans in Central Region and pigeon peas in Southern Region (Waddington, 1990; Waldman *et al.*, 2017).

Maize-legume intercropping is also an old technology among smallholder farmers not only in Malawi but also in Africa as a whole (Okigbo and Greenland (1976) in Silberg *et al.*, 2017). In Malawi, Heisey and Smale (1995) reported that maize-legume intercropping was so common until late 1960s. Since then there have been declining use rates of intercropping.

Several factors are attributed to the decline of intercropping among Malawi smallholders. One key factor is government policy that encourages sole cropping. The 1965 Land Act, for example, promoted production of cash crops, mainly tobacco. The result was an increase in tobacco production and a decline in food production (Kydd & Christiansen, 1982). To enhance food production the government offered higher prices for maize (Silberg *et al.*, 2017). Coupled with minimal effort from the government to promote intercropping, the higher maize price policy strategy resulted in increased sole maize cropping. The farm input subsidy is another policy strategy that encouraged sole cropping of maize and minimal diversification (Harrigan, 2008; Chibwana *et al.*, 2012). Recently, however the program has enhanced access to both maize and legume seed and this may increase maize-legume intercropping. Chinsinga and Poulton (2014) however noted that access to legume seed is relatively poor and the government has not done enough to promote intercropping.

Other problems limiting intercropping are scarcity of factors (especially labour), delayed returns, high opportunity cost and inadequate extension support (Silberg *et al.*, 2017). Sometimes returns to intercropping may take two or more seasons and farmers who rely on immediate gains from the technology are likely to dis-adopt the technology after one or two seasons. Kassie *et al.* (2013) also noted that limited funding to agricultural extension services is another challenge to adoption of intercropping.

3. Methodology

3.1. Conceptual framework

This section discusses a conceptual model of household agricultural production decisions under combined effect of weather risks and low soil fertility. Farmers make input decisions before the weather conditions are revealed and determine production outcomes which subsequently form the basis for consumption decisions in the current year and next year's input decisions. Production decisions are made as a first step to maximize weighted probability utility of returns in different states of nature (Holden & Quiggin, 2017). Given low crop productivity due to low soil fertility and erratic rains and assuming risk averseness, farmers choose a mix of drought-resilient and soil nutrient enhancing technologies to enhance production. Such inputs in our case include inorganic fertilizer (F), organic manure (M), maize-legume intercropping (I), and other inputs (X). Let the production function be specified as:

$$Y = Y[N(F, M, I), X, \varepsilon] \quad (1)$$

where N represents soil nutrients from inorganic fertilizer, organic manure, and maize-legume intercropping, while ε is climate risk which is not known to the farmer at planting time and has a distribution function of G(.) (Koundouri *et al.*, 2006; Ding *et al.*, 2009).

First we consider that farmers are rational and will use a given technology if production (Y) is higher than the situation where the technology is not used. In our case farmers will be motivated to apply organic manure if maize production is higher in plots with organic manure than plots without. Similarly, if maize-legume intercropping increases maize yields, there is high likelihood of farmers using the technology in the following year, otherwise they will dis-adopt (Silberg *et al.*, 2017). These two technologies enhance organic matter and nutrient content in the soil as well as enhancing nutrient retention which is essential for maize production (Snapp *et al.*, 1998; Heerink, 2005; Mafongoya *et al.*, 2006; Government of Malawi, 2012).

Second, farmers are faced with recurring dry spells. A severe drought can reduce maize yields by as much as half its average (CIMMYT, 2013). Production under drought will therefore require drought-resilient technologies. Empirical evidence has shown that sustainable conservation agriculture practices have potential to minimize the negative impact of drought on crop yields (Kilcher, 2007; Muzari *et al.*, 2012; Makate *et al.*, 2017a; Makate *et al.*, 2017b). Organic manure and maize-legume intercropping are potentially drought-resilient because they enhance rain water infiltration and water retention capacity. We therefore expect that maize production under drought conditions would be higher for adopters of organic manure and/or maize-legume intercropping. Assuming farmers observe this high maize production under drought for plots with organic manure and/or maize-legume intercropping vis-à-vis plots without, use of these technologies would increase in the ensuing years.

We test the hypothesis that farmers respond to previous exposure to dry spells by using maize-legume intercropping and organic manure. Given that our data is in three-year intervals, we construct dry spell variables lagged three years. These variables are proxies for adaptive expectations of the farmer for rainfall conditions in the coming year. If a farmer expects a drought year based on previous exposure to dry spells, we expect that farmer to use a technology that has proven to be drought-resilient.

We are more interested in early-season and late-season dry spells. Early-season dry spells affect the germination rate of maize, and a technology that retains water and improves germination rate under water stress would be appealing to farmers. On the other hand, late-season dry spells affect grain filling, a critical growth stage when maize needs enough water. As discussed, organic manure and maize-legume intercropping enhances water retention at this critical stage of maize production. We therefore expect a positive impact of early-season and late-season dry spells on use and use intensity of organic manure and maize-legume intercropping.

3.2. Model specification and estimation strategy

Based on the conceptual model discussed above, we model the farmer's decision to use organic manure and/or maize-legume intercropping first as a binary decision. Farmers will have to decide either to apply organic manure or not. Similarly they will have to decide either to intercrop or not. Having modelled the binary use decision, we then model the intensity of use decision. We decompose these use decisions as follows:

$$C_{it} = \beta_0 + \beta_1 W_{dt} + \beta_2 \mathrm{S}_{it}^{\mathrm{f,s}} + \beta_3 \mathrm{Ex}_{it} + \beta_4 Cr_{it} + \beta_5 Fo_{it} + \beta_6 D_{it} + \beta_7 F_{it} + \beta_8 P_{it}^{f} + \beta_9 P_{dt}^{y} + \beta_{10} R_{it} + \beta_{11} H_{it} + \beta_{12} T_t + \alpha_i + \varepsilon_{it} \qquad (2)$$

where C_{it} is the dependent variable and represents different values for use and intensity of use. In use estimation, $C_{it}$is a dummy, equal to one if household i used organic manure (maize-legume intercropping) in year t, and equal to zero otherwise. For intensity of organic manure use, C_{it} is measured as quantity of organic manure applied in kilograms per hectare (kg/ha) and is log transformed. For maize-legume intercropping use intensity, C_{it} is defined as the share of total cultivated land under intercropping and varies between zero and one [0,1]. W_{dt} is a vector of previous early-season and late-season dry spells (one-to-three-year lag) measured as longest number of days. These are the key variables in our model. $\hat{\beta}_1$ is a vector of coefficients of interest testing the key hypotheses on whether previous exposure to dry spells enhances use of organic manure and/or maize-legume intercropping. We assume that farmers who were previously exposed to early-season and/or late-season dry spells are more likely to use drought-resilient technologies such as organic manure and maize-legume intercropping.

We however acknowledge that presently there are many public and private sector efforts in Malawi promoting use of both organic and inorganic technologies. The Government of Malawi (GoM) has been promoting the use of inorganic fertilizer through the Farm Input Subsidy Program (FISP). The GoM has also through its Agricultural Sector Wide Approach (ASWAp) been promoting sustainable land management (SLM) practices that build soil fertility, prevent soil erosion, and conserve rain water, notably organic manure and maize-legume intercropping (Government of Malawi, 2011a). To control for government interventions in the study areas we have included FISP ($\mathrm{S}_{\mathrm{it}}^{\mathrm{f,s}}$) variable (fertilizer subsidy and seed subsidy) and distance to agricultural markets (D_{it}) a proxy for access to legume seed and inorganic fertilizer. In addition we have estimated models with number of agricultural extension visits (Ex_{it}). These models however exclude the 2006 data because we do not have the extension variable for that year. In these models we have also included social-network variables such as access to input credit (Cr_{it}) and participation in farmer organization (Fo_{it}). Non-governmental organizations (NGOs) have also been actively involved in promoting use of conservation technologies. However, due to data limitation, we did not directly control for NGO interventions but partly controlled with the inclusion of farmer organizations which are either government or NGO facilitated. We also rely on time-invariant controls to partly control for time-invariant government and NGO interventions. Nonetheless, in our study areas, Fisher *et al.* (2017) found that NGOs have insignificant impact in influencing adoption of conservation technologies such as organic manure.

F_{it} is (log of) fertilizer used (kg/ha) by household i at time t and we assume that this may positively influence use of organic manure as reported by Holden and Lunduka (2012). We also control for input and output prices by including the commercial fertilizer[2] real price (NPK and Urea) (P_{it}^{f}) and annual average real maize and legume grain prices[3] in district d at time t (P_{dt}^{y}). We expect the fertilizer price to directly or indirectly affect use of organic manure and maize-legume intercropping. The higher fertilizer price reduces demand for inorganic fertilizer and this may indirectly increase or reduce use of ISFM technologies depending on complementarity or substitution effect. R_{it} is a dummy variable for the southern region. Household characteristics that affect use of organic manure and maize-legume intercropping are represented by a vector H_{it}. These variables include (log of) farm size (ha), distance to the farm (km), (log of) male and female labour (adult equivalent/ha), (log of) off-farm labour (adult equivalent/ha), (log of) livestock endowment (livestock tropical unit), (log of) asset value in Malawi Kwacha (MK), sex of household head (1=female), education of household head (years), age of household head (years), household residence in wife's village, household size and village population density. T_t are year dummies (2006 is the reference) which control for price variation across years, $\mathrm{\alpha_i}$ captures individual time-invariant household fixed effects, while $\mathrm{\varepsilon_{it}}$ is the error term.

The parameters in equation 2 are estimated using the correlated random effects (CRE) estimator. In this approach we include means of time-varying farm household characteristics. The CRE is chosen over other approaches in order to control for unobserved heterogeneity. The approach allows unobserved heterogeneity to be correlated with observed covariates and sample selection (Wooldridge, 2010a). While household fixed effects (HHFE) could be another option, the incidental parameters problem associated with this approach (Wooldridge, 2009; Wooldridge,

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[2] Fertilizer price includes both commercial and subsidized fertilizer and is at farm household level. On the other hand, output price is at farmer district level.

3 Data on annual average output prices is from the Ministry of Agriculture, Irrigation and Water Development.

2010a) makes CRE our preferred option. The CRE model avoids incidental parameters problem in non-linear models, identifies average partial effects (not just parameters), can be combined with the related control function approach (CFA) for nonlinear models with heterogeneity and endogeneity and can be extended to unbalanced panels.

We used the probit estimator for binary decision for maize-legume intercropping and organic manure. For intensity of use, we used tobit for organic manure and fractional probit for farm size share under maize-legume intercropping. The fractional probit estimator constrain the predicted value between [0,1] (Wooldridge, 2011). For robustness check, we also estimated the two-stage model using the double-hurdle (two-tier) estimator proposed by Cragg (1971) for organic manure. Cragg's two-tier model allows the first tier (use decision) to follow a probit model with intensity of use (tier two) determined by a truncated normal model. We also acknowledge that the farmers' decision to use either organic manure or maize-legume intercropping may not be independent from each other. An alternative procedure in such cases is a system approach that captures the error dependence and shed more light into complementarities and substitutability between these technologies. However before we could apply that procedure, we tested for the dependence of the errors by including residuals from organic manure in maize-legume intercropping equation and vice-versa. The residuals were insignificant in both cases and hence we proceeded with independent estimation of the two models.

3.3. Attrition, sample selection, and endogeneity

A common problem in longitudinal data is attrition, which is the loss of sample members between the first and subsequent waves of data collection (Fitzgerald *et al.*, 1998; Wooldridge, 2010b). We first conducted a simple probit test to assess whether attrition was random and therefore ignorable. Separate tests were conducted for organic manure and maize-legume intercropping outcome variables. We found a chi-square of 118.68 and 127.74 in organic manure and maize-legume intercropping outcome variables, respectively, with a very high p-value (0.0000) in both cases. We therefore rejected the null hypothesis that attrition was random.

Fortunately, as noted by Fitzgerald *et al.* (1998), unbiased estimation is possible even when attrition is high, provided that the proper adjustments are made. In this study, attrition bias is addressed by controlling for time-constant unobservable factors that affect attrition by using the CRE models – an alternative to household fixed-effects (HHFE). The second option proposed by Fitzgerald *et al.* (1998) and Wooldridge (2010b) is controlling for attrition bias due to observables by using an inverse probability weights (IPW) approach. IPW is however not available in non-linear models used in this paper – CRE models.

Attrition is not the only problem faced in the empirical modelling. The models could also suffer from sample selection bias due to farmers having non-random access to the Farm Input Subsidy Program and endogeneity bias of fertilizer use as it is a choice variable. To control for sample selection and endogeneity bias, we could use a two-step control function (CF) approach (Petrin & Train, 2010; Wooldridge, 2011) or an instrumental variable (IV) approach (Wooldridge, 2010b). However, we rely on CRE estimator to control for limited endogeneity that reflects unobserved time-invariant factors that are correlated with fertilizer use (or fertilizer subsidy) and the error term in the organic manure (or intercropping) model. We could not apply the IV nor the CF estimations because we were unable to identify convincing instruments.

3.4. Data and study areas

We use four waves of panel data collected through household surveys conducted between 2006 and 2015 in six districts in central and southern Malawi. The districts are Kasungu, Lilongwe in Central Region; Chiradzulu, Machinga, Thyolo and Zomba from Southern Region. These districts are agro-ecologically at different zones and receive different amounts of rainfall. Zomba for example is drought prone (World Bank, 2010) while Thyolo lies in the high plateau and hilly areas receiving over 1200 mm annual rainfall. The rest of the districts lie in the medium altitude zone and enjoy high average rainfall ranging from 800 – 1,200 mm annually (Bunda College, 2008).

The initial sampling of the households in 2006 used a multistage sampling approach following the 2004 Integrated Household Survey Two (IHS2) (Lunduka, 2009). The first stage was purposive sampling of the six districts with the primary goal of capturing dynamics in land issues. Second stage was simple random sampling of enumeration areas (EAs) where two were randomly sampled in Thyolo, Chiradzulu and Machinga districts, while three were sampled in Zomba, Kasungu and Lilongwe. Third, from each EA, 30 households were randomly sampled giving a total of 450 respondents. Of these 450 households, 378 were resurveyed in 2009, 350 in 2012 and 2015, resulting in four rounds of unbalanced panel data (Table 1).

Our sample has one drawback in that the sample size is small and may not be representative enough to the national level (Lunduka *et al.*, 2013). However Chibwana *et al.* (2012) observed that rural households in Malawi share similar characteristics such that our sample may provide important insights with respect to uptake of organic manure and maize-legume intercropping. Our data have also some advantages over large surveys. One, we have a long panel of four waves, which is absent in most large surveys. Two, we have detailed farm level information where plots were measured with GPS with minimal measurement errors. Above all, the districts in our study capture enough variability in rainfall distribution and vulnerability to dry spells as discussed in paragraph one of this section. The data also capture land dynamics (Lunduka, 2009) where households in Southern Region districts have small land holdings (Matchaya, 2007; Tchale, 2009) and likely to intensify use of land-saving technologies such as maize-legume intercropping compared to households in Central Region districts.

The districts exhibit different patterns of use of organic manure and maize-legume intercropping as reported in Table 1. These figures are indicative and are based on balanced data. Maize-legume intercropping is dominant in the Southern Region districts where Chiradzulu reported 85% use rate while Lilongwe in Central Region reported 24%. Some of these areas have had active promotion of intercropping technologies by agricultural extension and development projects (Waldman *et al.*, 2017) hence high use rates. Additionally, the level of farm input subsidy program is high in the Southern Region districts with the highest reported in Thyolo (77%) while Kasungu in the Central Region reported 44%. The level of FISP may have an implication on use of both organic manure and maize-legume intercropping. The FISP package contains maize and legume seed of which better access to both can encourage farmers to increase intercropping while good access to inorganic fertilizer may affect organic manure and maize-legume intercropping use through complementarity or substitution effects. Holden and Lunduka (2012) reported a complementarity relationship between fertilizer subsidy and organic manure.

Table 1: Study areas

District	Sample size					Technology use by district		FISP
	2006	2009	2012	2015	Total	Organic manure	Intercropping	
Thyolo	62	51	47	47	207	0.53	0.62	0.77
Zomba	86	84	76	79	325	0.39	0.66	0.64
Chiradzulu	53	35	36	34	158	0.63	0.85	0.64
Machinga	51	49	47	45	192	0.44	0.54	0.49
Kasungu	102	88	83	81	354	0.43	0.36	0.44
Lilongwe	96	71	61	64	292	0.41	0.24	0.44
Total	**450**	**378**	**350**	**350**	**1528**	**0.45**	**0.51**	**0.55**

Figures on organic manure, intercropping and FISP are based on balanced data with 315 households for each panel.

A semi-structured questionnaire was used to collect data on household and plot level characteristics but our primary unit of analysis in this paper is farm household. The household panel data were merged with daily rainfall data from the Department of Climate Change and Meteorological Services from 2003 to 2015. We collected the rainfall data from weather stations in our survey districts. These include: Chiradzulu in Chiradzulu district; Kaluluma and Kasungu in Kasungu; Bunda, Chitedze and Kamuzu International Airport in Lilongwe; Chikwewo, Liwonde and Ntaja in Machinga, Bvumbwe and Thyolo in Thyolo and Chancellor College, Chingale and Makoka in Zomba district. We used data from a weather station close to the enumeration area where the household data were collected in each district. These weather stations were Chiradzulu, Kasungu, Chitedze, Ntaja, Bvumbwe and Chancellor College. We merged the household and rainfall data at enumeration area level.

The rainfall data allowed us to generate dry spell and rainfall distribution variables. As discussed in section one, we defined a dry spell as the consecutive number of days (at least 5 – 15) where total rainfall precipitation is below 20 mm after the onset of the rains. We identified the longest early- and late-season dry spells in each of the three previous seasons of a survey year. The early-season dry spell coincides with the planting period that is from November/December. We first identified the onset of the rains in each year at each weather station and constructed an early-season dry spell variable. On the other hand, the late-season dry spell coincides with the maize flowering period that is between February and early March. We used maize as a benchmark for calculations since maize is the main staple crop in Malawi and is grown by over 90% of smallholder farmers (Denning *et al.*, 2009). The assumption is that farmers would develop adaptive expectations of dry spell occurrence having experienced the same for the past three seasons. This expectation would then result in an increase in use and use intensity of organic manure and maize-legume intercropping if the technologies are proved to minimize the impact of drought on crop yield. We also included rainfall distribution variables such as average rainfall (lagged three seasons (mm)) and December and February average rainfall (mm) for the survey years.

The dependent variables organic manure and maize-legume intercropping were measured differently. First, use of organic manure and maize-legume intercropping were measured as dummy variables, equal to one for households using the technology and equal to zero otherwise. Intensity of use for organic manure was measured as quantity of organic manure applied in kilograms per hectare (kg/ha) while for maize-legume intercropping use intensity was defined as the share of total cultivated land under intercropping. For organic manure, respondents were asked how much organic manure was applied on each plot they used organic manure. We used standard measures of collecting this data such as ox-carts, wheelbarrows, 50-Kg and 90-Kg bags, and 5-Litre and 20-Litre buckets. We then used the standard conversion rates to estimate the quantity of manure in kilograms applied per hectare of land.

The data indicate an increase in use of organic manure from 31% in 2006 to 55% in 2015 and from 33% to 75% for maize-legume intercropping (Table 2) based on balanced panel data. On intensity, the data show a decrease for organic manure use between 2006 (2195 kg/ha) and 2015 (1544 kg/ha), but there is an increase in the share of farmed area allocated to maize-legume intercropping from 26% (2006) to 36% (2015).

Table 2: Use of organic manure and maize-legume intercropping

Year	**Statistic**	Applied manure (1=yes)		Manure quantity (Kg/ha)		Intercropping (1=yes)		Farm size share-Intercropping	
2006	Mean	0.31		2194.63		0.33		0.26	
	[95% Conf. Interval]	0.26	0.36	1423	2966	0.28	0.39	0.21	0.30
2009	Mean	0.45		1653.93		0.44		0.23	
	[95% Conf. Interval]	0.40	0.51	1112	2196	0.38	0.49	0.20	0.27
2012	Mean	0.50		1662.73		0.51		0.32	
	[95% Conf. Interval]	0.45	0.56	310	3015	0.46	0.57	0.28	0.37
2015	Mean	0.55		1543.51		0.75		0.36	
	[95% Conf. Interval]	0.49	0.60	745	2342	0.70	0.79	0.33	0.40

These figures are based on balanced data with 315 households for each panel

3.5. Summary statistics of independent variables by year

Table 3 presents summary statistics (means and proportions) for the explanatory variables used in this paper for each panel round based on balanced data. The data show considerable variation over time in exposure to early- and late-season dry spells. For example 2006 has the longest one-year lag of late-season dry spells of about 13 days on average while 2012 has the longest two-year lag of early-season dry spell of about 11 days. The three-year average annual rainfall is lowest for 2012 in our sample area and highest in 2009. For government intervention variables, we notice an increase in seed subsidy from 38% in 2006 to 64% in 2015 while there is a decrease for fertilizer subsidy from 73% in 2012 to 54% in 2015. Number of extension visits decreased from 2.8 times in 2009 to 1.1 in 2015. This decrease could affect use of organic manure in particular as the technology requires training to prepare and apply appropriately (Ngwira *et al.*, 2013).

Input and output prices show that fertilizer real price has increased from 57 Malawi Kwacha (MK)/Kg in 2006 to MK129/Kg in 2015. On output prices, one-year lag of maize grain real price was higher in 2009 than in 2006, lower in 2012 than in 2009, and increased between 2012 and 2015. Some of the observed price variations could be explained by policy and weather changes. The data also shows that the quantity of inorganic fertilizer applied per hectare of land increased between 2006 and 2009, but has been decreasing since then. This trend could reflect the scale of FISP, which has been scaled back in recent years. The combined effect of availability of fertilizer through FISP and good rains, for example, enhances output supply, which also affects output price. We expect these factors to affect farmers' investment decisions in organic manure and maize-legume intercropping directly or indirectly. The data also suggest that there has been a slight change in owned farm size from 2006 to 2015.

Table 3: Summary statistics of independent variables by year

Variable	2006	2009	2012	2015	Total
Drought and rainfall distribution					
Longest early dry spell (1-year lag), days	7.65	6.46	5.61	4.92	6.16
Longest early dry spell (2-year lag), days	10.10	9.49	10.49	7.66	9.43
Longest early dry spell (3-year lag), days	7.77	7.88	7.84	7.75	7.81
Longest late dry spell (1-year lag), days	12.71	11.67	10.65	6.20	10.31
Longest late dry spell (2-year lag), days	9.35	6.30	7.80	10.25	8.43
Longest late dry spell (3-year lag), days	8.21	8.14	8.20	8.13	8.17
3 year average rainfall (mm)	919.19	925.91	765.54	893.26	875.97

December average rainfall (mm)	6.36	7.41	7.41	7.40	7.15
February average rainfall (mm)	5.58	6.38	6.37	6.37	6.18
Government interventions					
Seed subsidy (1=yes)	0.38	0.34	0.56	0.64	0.48
Fertilizer subsidy (1=yes)	0.38	0.56	0.73	0.54	0.55
Number of extension visits		2.79	0.54	1.08	1.47
Social networks					
Input credit access (1=yes)		0.10	0.07	0.08	0.08
Farm organization (=yes)		0.19	0.20	0.17	0.19
Distance to market (km)	4.35	4.36	4.20	4.24	4.29
Inputs, input price and output prices					
Fertilizer quantity (Kg/ha)	154.39	233.57	198.26	155.66	185.47
Fertilizer price (MK^a/kg)	57.28	77.95	116.85	129.11	95.30
Maize price - 1 year lag (MK^a/Kg)	38.20	53.31	26.90	45.19	40.90
Pigeon peas price - 1 year lag (MK^a/Kg)	101.94	72.88	119.54	138.10	108.11
Household characteristics					
Household head sex (1=male)	0.21	0.22	0.23	0.37	0.25
Age of household head (years)	40.92	45.63	50.03	48.81	46.35
Education of household head (years)	7.43	5.25	5.21	5.37	5.81
Household size	5.38	5.38	5.38	5.59	5.43
Population density	4.65	4.62	4.62	4.62	4.63
Off-farm labor (# of adults)	0.14	0.20	0.35	0.26	0.24
Male family labor (adult equivalent/ha)	2.83	3.64	3.60	4.13	3.55
Female family labor (adult equivalent/ha)	2.54	3.47	3.26	3.78	3.26
Residence in wife's village	0.38	0.45	0.26	0.41	0.38
Household physical and livestock assets					
Tropical livestock unit	1.09	1.52	1.18	0.53	1.08
Asset value (MK^a)	3724.90	4223.64	2566.23	6466.24	4245.25
Farm size (ha)	1.25	1.22	1.21	1.24	1.23
Plot distance (Km)	1.03	3.00	3.74	3.20	2.74
Southern region (1=yes)	0.57	0.57	0.57	0.57	0.57

^{a}Values in Malawi Kwacha (MK) are deflated with consumer price indices (CPI) using 2010 prices. The figures in this table are based on balanced data of 315 households for each panel.

4. Results and Discussions

Table 4 presents results for use and use intensity of organic manure and maize-legume intercropping. The first two columns are for the organic manure models, while the third and fourth columns are for models where maize-legume intercropping is the dependent variable. In Appendix 1, we present full results of Table *4*able 4 with all the control variables including means of time-variant farm household characteristics. In Appendix 2 we present results where we included additional control variables such as number of visits of agricultural extension officers, access to input credit dummy and participation in farmer organization dummy. These models are run without 2006 data because these variables are not available for 2006. Appendix 3 presents results for the Cragg (1971)'s double hurdle model for organic manure for robustness check. The two-tier model results are for both full sample and the sample without 2006 data.

The first main hypothesis we test in this paper is that exposure to dry spells increases the likelihood of using organic manure. The results show that one-year lag of early-season dry spells is positive and significantly associated with use of organic manure at the 5% level of significance. This result is similar with results for models with additional controls in (Appendix 2). Similarly, one-year lag of late-season dry spells is positive and significantly correlated with use and use intensity of organic manure. We also find similar results using the double hurdle model in Appendix 3. On the other hand, there is inconsistent effect of two-year and three-year lags of both early-season and late-season dry spells on use and use intensity of organic manure. Two-year and three-year lags of early season dry spells are insignificant at the 10% level of significance or lower, two-year lag of late-season dry spells are negative and significantly correlated with both use and use intensity of organic manure while three-year lag of late-season dry spells is positive and significantly associated with use of organic manure.

The second main and related hypothesis we test is that exposure to previous dry spells increases use and use intensity of maize-legume intercropping. The results show positive and significant correlation of one-year lag of early-season and late-season dry spells with use and use intensity. The results are similar with models containing additional controls in Appendix 2. With respect to two-year and three-year lags of both early-season and late-season dry spells, we find inconsistent effect on use and use intensity of maize-legume intercropping. Two-year lags of early- and late-season dry spells are negative and significantly related to both use and use intensity of maize-legume intercropping while the three-year lags of both early- and late-season dry spells are positive and significantly correlated with use and use intensity of maize-legume intercropping.

These results show three important issues. One, farmers in our sample respond to exposure to previous dry spells by using organic manure and maize-legume intercropping as drought-resilient ISFM technologies. This suggests that farmers develop weather expectations from previous weather conditions and influence production decisions of the following season. Crop production, maize in particular, which dominates in Malawi, is susceptible to dry spells, particularly late-season dry spells and farmers are willing to invest in technologies that minimize the impacts. While irrigation is an option, the high investment and maintenance costs in SSA (Inocencio, 2007; Woodhouse *et al.*, 2017) limit most smallholder farmers from using this technology. Organic manure and maize-legume intercropping offer farmers options to hedge against late-season dry spells in particular by enhancing rainwater infiltration rates and conserving soil moisture through organic matter and soil cover.

Two, the results show the recent weather shocks (i.e. one-year lag of early-season and late-season dry spells) are more influential than long-term weather conditions (e.g. two- and three-year lags) in building farmers' weather expectations. Smallholder farmers appear to be myopic as they respond more to recent weather shocks than to long-term weather risks. While research indicates that occurrence of climatic shocks creates fear and worry among smallholder farmers of a reoccurrence and leads to increased investments in adaptive mechanisms that hedge against resulting losses (Van Den Berg *et al.*, 2009), this is only the case for an immediate dry spell shock for some technologies among our sample households.

Three, the inconsistent correlation between long-term weather conditions and use of ISFM technologies could mean that farmers do not observe production benefits of these technologies under early- and late-season dry spells after one year of experience. This could be related to the observation by Snapp *et al.* (1998) and Silberg *et al.* (2017) that the agronomic benefits of organic manure and maize-legume intercropping, respectively, may delay for more than two seasons. Thus, the positive impact of one-year lag could be associated with perceived impacts of the technologies on crop production under dry spells while the inconsistent impact of two- and-three-year lags could be associated with delayed benefits. We leave an assessment of the impact to another study.

Farmers are impatient for immediate production gains and are more likely to dis-adopt or reduce usage of a technology with poor first year results. Corbeels *et al.* (2014) reported that farmers tend to put more weight on immediate needs over future benefits of a given technology. Thus, the inconsistent impact of two- and three-year lags of early- and late-season dry spells may not necessarily mean that farmers are not responding to long-term dry spell exposure but rather they are more interested in present benefits over medium to long-term benefits. This underscores the critical role agricultural extension services should play in promoting use of these technologies. Munthali (2007) observed that farmers lack appropriate awareness and knowledge of such technologies for appropriate and effective use.

Related to that we notice that number of agricultural extension visits is positive and significantly correlated with both use and use intensity of organic manure (Appendix 2 and Appendix 3). Similarly, participation in farmer organisation is associated with high likelihood of using organic manure. We used extension visits as a proxy for government interventions in the areas. The results show great potential of agricultural extension services on promoting use of organic manure. While farmers may not observe immediate or consistent gains of organic manure under dry spells, government active involvement would enhance awareness on long-term benefits and appropriate use of the technology and may increase use and subsequent impact on production. Ngwira *et al.* (2013) stated that agricultural extension service should enhance training and advice on smallholders on preparation and application of organic manure.

Controlling for input and output prices, the results show positive and significant correlation of commercial fertilizer price with use of organic manure. There is also positive and significant relationship between legume price and use and use intensity of maize-legume intercropping as well use of organic manure. These results suggest that farmers are somewhat price responsive. The higher price for commercial fertilizer, which effectively reduces demand for inorganic fertilizer, is associated with higher likelihood of using organic manure. This indirect effect of fertilizer price on organic manure indicates that inorganic fertilizer and organic manure technologies are substitutes. Farmers make a systematic trade-off by investing in organic manure when the fertilizer price is increased. On output prices, higher legume prices from the previous season present incentive potential for farmers to use organic manure and practice maize-legume intercropping. Relative to the opportunity cost for labour for making organic manure, a higher and significant output price signifies higher expected profits and increases the probability of using the technology. These results partly concur with the findings of Silberg *et al.* (2017) where previous sales of legumes enhanced use of maize-legume intercropping.

It is also interesting to note that male household labour has a negative and significant relationship with both use and use intensity of maize-legume intercropping. The results suggest that the technology is labour-saving. With respect to farm size, we notice interesting results where there is a positive correlation with use of both organic manure and maize-legume intercropping but negatively correlated with their intensities. We however only found significant result on use of maize-legume intercropping. The result in appendix 2 and appendix 3, respectively show negative and significant correlation with use intensity of maize-legume intercropping and organic manure. This implies large farm sizes reduce intensity of using both maize-legume intercropping and organic manure. These findings suggest that these technologies are perceived as land-saving. The results are directly linked to the Southern Region dummy results. We found a positive correlation of Southern Region and use and use intensity of both organic manure and maize-legume intercropping. Households in Southern Region have smaller farm sizes compared to Central Region (Matchaya, 2007; Tchale, 2009) and this may increase the likelihood of land intensification by using land-saving technologies. A final result worth noting in Table 4 is for the sex of household head dummy variable, which has a positive and significant association with use of maize-legume intercropping. This finding suggests that this technology is more commonly used by female-headed households. While this would make sense because female-headed households are more land and labour constrained in Malawi (FAO, 2011), we see that this result holds even after controlling for labour endowment and farm size.

Table 4: CRE model results on use and use intensity of organic manure and intercropping

Variable	**Organic Manure**		**Maize-legume intercropping**	
	Use (Probit)	**Use Intensity (Log - Kg/ha with Tobit)**	**Use (Probit)**	**Use Intensity (Farm size share with Fractional Probit)**
Longest early dry spell (1-year lag), days	0.05**	0.06	0.12***	0.02***
	(0.02)	*(0.13)*	*(0.03)*	*(0.01)*
Longest early dry spell (2-year lag), days	0.01	-0.02	-0.03**	-0.01**
	(0.02)	*(0.09)*	*(0.02)*	*(0.00)*
Longest early dry spell (3-year lag), days	0.03	-0.07	0.09***	0.02***
	(0.03)	*(0.15)*	*(0.03)*	*(0.01)*
Longest late dry spell (1-year lag), days	0.03***	0.18***	0.05***	0.01***
	(0.01)	*(0.06)*	*(0.01)*	*(0.00)*
Longest late dry spell (2-year lag), days	-0.08***	-0.44***	-0.07***	-0.02***
	(0.02)	*(0.13)*	*(0.03)*	*(0.01)*

Longest late dry spell (3-year lag), days	0.08**	0.11	0.11***	0.02***
	(0.03)	*(0.18)*	*(0.03)*	*(0.01)*
3 year average rainfall (mm)	0.00	0.00	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
December average rainfall (mm)	-0.06	-0.13	0.14***	0.04***
	(0.04)	*(0.25)*	*(0.04)*	*(0.01)*
February average rainfall (mm)	-0.08	-0.45*	-0.22***	-0.05***
	(0.05)	*(0.27)*	*(0.05)*	*(0.01)*
Fertilizer price (Mk/Kg)	0.00**	0.00	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
1-year lag maize price (Mk/Kg)	0.01	-0.01	0.02	0.00*
	(0.01)	*(0.08)*	*(0.01)*	*(0.00)*
1-year lag legume price (Mk/Kg)	0.00***	0.00	0.00**	0.00***
	(0.00)	*(0.01)*	*(0.00)*	*(0.00)*
Distance to market (km)	-0.04**	-0.17	0.02	0.01**
	(0.02)	*(0.11)*	*(0.02)*	*(0.00)*
Log-commercial fertilizer (Kg/ha)	0.01	0.04	0.01	0.00
	(0.02)	*(0.11)*	*(0.02)*	*(0.00)*
Fertilizer subsidy, dummy	0.14	0.85	0.13	0.01
	(0.09)	*(0.52)*	*(0.13)*	*(0.03)*
Seed subsidy, dummy			-0.09	-0.01
			(0.12)	*(0.03)*
Log-farm size (ha)	0.16	-0.24	0.35*	-0.04
	(0.18)	*(1.00)*	*(0.19)*	*(0.04)*
Log-male labour (adult equivalent/ha)	0.13	0.92	-0.37**	-0.06**
	(0.15)	*(0.89)*	*(0.16)*	*(0.03)*
Sex of household head (1=female)	0.01	0.55	0.29***	0.04*
	(0.09)	*(0.50)*	*(0.10)*	*(0.02)*
Southern region dummy	0.44*	3.04**	2.00***	0.36***
	(0.24)	*(1.37)*	*(0.27)*	*(0.05)*
2009 year dummy	0.25	1.77	0.31	-0.07
	(0.27)	*(1.51)*	*(0.29)*	*(0.06)*
2012 year dummy	0.77***	3.21**	1.28***	0.17***
	(0.23)	*(1.30)*	*(0.26)*	*(0.05)*
2015 year dummy	0.94***	5.90***	2.06***	0.20***
	(0.23)	*(1.27)*	*(0.26)*	*(0.05)*
	(2.47)	*(14.05)*	*(2.44)*	*(0.52)*
Prob > chi2	0.000	0.000	0.000	0.000
Rho	0.21	0.15	0.16	
Observations	1494	1494	1494	1494

Significance levels: *10%, **5%, ***1%. The full table with all control variables is presented in Appendix 1.

5. Conclusions and policy implications

Using four waves of panel data for nine years, this paper indicates an increase in use from 33% in 2006 to 75% in 2015 for maize-legume intercropping and for organic manure increasing from 31% in 2006 to 55% in 2015. Our results demonstrate that use and use intensity of organic manure and maize-legume intercropping are positively associated with exposure to early-season and late-season dry spells. The positive impact of dry spells on use of maize-legume intercropping and organic manure implies that farmers respond to occurrence and risks associated with dry spells and may perceive that maize-legume intercropping and organic manure help them to hedge against resulting production losses. We leave for future research to investigate how efficient these technologies are in achieving this. However with the Government of Malawi taking an active role in promoting these technologies, there is need for collective and coordinated efforts to ensure that appropriate climate-smart agriculture technologies are available and disseminated to the farmers. While irrigation technology is an expensive option due to high investment and maintenance costs, organic manure and maize-legume intercropping offer smallholder farmers lower-cost options to hedge against late-season dry spells by conserving soil moisture.

We however notice inconsistent effect of two- and three-year lags of early-season and late-season dry spells on use and use intensity of both organic manure and maize-legume intercropping. This could be linked to myopic weather expectations of farmers as recent weather shocks appear more influential than long-term weather conditions. another possible explanation is delayed benefits of the technologies as literature reports that the benefits may take long to manifest (Snapp *et al.*, 1998; Silberg *et al.*, 2017). While another research is needed to investigate this, our observation underscores the need for agricultural extension services to go beyond promoting use of these technologies and ensure that farmers are aware of potential long-term benefits, preparation and use of the technologies. Related to that we notice that agricultural extension service has a positive and significant impact on use and use intensity of organic manure. Thus, while farmers may fail to consistently use these technologies because of myopic expectations and delayed benefits, extension services should cover the gap with appropriate messages to allow farmers make informed use decisions. Finding ways of sharing the risks of delayed production benefits with the farmers could be another option for enhancing use and use intensity. This could be in the form of incentives in the first two to three seasons of use.

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Appendix 1: CRE full results for use and use intensity organic manure and intercropping

	Organic Manure		**Maize-legume intercropping**	
Variable	**Use (Probit)**	**Use Intensity (Log - Kg/ha with Tobit)**	**Use (Probit)**	**Use Intensity (Farm size share with Fractional Probit)**
Longest early dry spell (1-year lag), days	0.05**	0.06	0.12***	0.02***
	(0.02)	*(0.13)*	*(0.03)*	*(0.01)*
Longest early dry spell (2-year lag), days	0.01	-0.02	-0.03**	-0.01**
	(0.02)	*(0.09)*	*(0.02)*	*(0.00)*
Longest early dry spell (3-year lag), days	0.03	-0.07	0.09***	0.02***
	(0.03)	*(0.15)*	*(0.03)*	*(0.01)*
Longest late dry spell (1-year lag), days	0.03***	0.18***	0.05***	0.01***
	(0.01)	*(0.06)*	*(0.01)*	*(0.00)*
Longest late dry spell (2-year lag), days	-0.08***	-0.44***	-0.07***	-0.02***
	(0.02)	*(0.13)*	*(0.03)*	*(0.01)*
Longest late dry spell (3-year lag), days	0.08**	0.11	0.11***	0.02***
	(0.03)	*(0.18)*	*(0.03)*	*(0.01)*
3 year average rainfall (mm)	0.00	0.00	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
December average rainfall (mm)	-0.06	-0.13	0.14***	0.04***
	(0.04)	*(0.25)*	*(0.04)*	*(0.01)*
February average rainfall (mm)	-0.08	-0.45*	-0.22***	-0.05***
	(0.05)	*(0.27)*	*(0.05)*	*(0.01)*
Fertilizer price (Mk/Kg)	0.00**	0.00	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
1-year lag maize price (Mk/Kg)	0.01	-0.01	0.02	0.00*
	(0.01)	*(0.08)*	*(0.01)*	*(0.00)*
1-year lag legume price (Mk/Kg)	0.00***	0.00	0.00**	0.00***
	(0.00)	*(0.01)*	*(0.00)*	*(0.00)*
Distance to market (km)	-0.04**	-0.17	0.02	0.01**
	(0.02)	*(0.11)*	*(0.02)*	*(0.00)*
Log-commercial fertilizer (Kg/ha)	0.01	0.04	0.01	0.00
	(0.02)	*(0.11)*	*(0.02)*	*(0.00)*
Fertilizer subsidy, dummy	0.14	0.85	0.13	0.01
	(0.09)	*(0.52)*	*(0.13)*	*(0.03)*
Seed subsidy, dummy			-0.09	-0.01
			(0.12)	*(0.03)*
Log-farm size (ha)	0.16	-0.24	0.35*	-0.04
	(0.18)	*(1.00)*	*(0.19)*	*(0.04)*
Log asset value (MK)	0.01	0.15*	0.02	0.00

	(0.01)	*(0.08)*	*(0.01)*	*(0.00)*
Log TLU	0.00	0.68	0.03	0.00
	(0.08)	*(0.44)*	*(0.08)*	*(0.02)*
Plot distance (Km)	0.03	0.16	-0.01	0.00
	(0.02)	*(0.12)*	*(0.02)*	*(0.00)*
Log-male labour (adult equivalent/ha)	0.13	0.92	-0.37**	-0.06**
	(0.15)	*(0.89)*	*(0.16)*	*(0.03)*
Log-female labour (adult equivalent/ha)	-0.06	0.09	0.13	0.04
	(0.16)	*(0.86)*	*(0.16)*	*(0.03)*
Log-off farm labour (adult equivalent/ha)	0.38*	2.24**	0.07	0.01
	(0.21)	*(1.13)*	*(0.22)*	*(0.05)*
Sex of household head (1=female)	0.01	0.55	0.29***	0.04*
	(0.09)	*(0.50)*	*(0.10)*	*(0.02)*
Education of household head (years)	0.02**	0.13**	0.02**	0.00**
	(0.01)	*(0.06)*	*(0.01)*	*(0.00)*
Household size	0.03	0.12	0.02	0.01
	(0.03)	*(0.19)*	*(0.04)*	*(0.01)*
Log-population density	-3.20	-24.24*	0.87	0.57
	(2.34)	*(13.32)*	*(2.28)*	*(0.50)*
Age of household head (years)	0.03**	0.17**	0.01	0.00
	(0.01)	*(0.07)*	*(0.01)*	*(0.00)*
Age squared	-0.00**	-0.00***	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
Household residence (1=wife village)	0.05	-0.29	-0.15	-0.04**
	(0.09)	*(0.51)*	*(0.10)*	*(0.02)*
Southern region dummy	0.44*	3.04**	2.00***	0.36***
	(0.24)	*(1.37)*	*(0.27)*	*(0.05)*
2009 year dummy	0.25	1.77	0.31	-0.07
	(0.27)	*(1.51)*	*(0.29)*	*(0.06)*
2012 year dummy	0.77***	3.21**	1.28***	0.17***
	(0.23)	*(1.30)*	*(0.26)*	*(0.05)*
2015 year dummy	0.94***	5.90***	2.06***	0.20***
	(0.23)	*(1.27)*	*(0.26)*	*(0.05)*
Mean farm size	-0.09	-0.95	-0.18	-0.03
	(0.13)	*(0.70)*	*(0.13)*	*(0.03)*
Mean male labour	-0.05	-0.20	0.00	0.00
	(0.03)	*(0.19)*	*(0.03)*	*(0.00)*
Mean female labour	0.05	0.12	-0.01	0.00
	(0.04)	*(0.16)*	*(0.04)*	*(0.00)*
Mean off-farm labour	-0.25	-2.04	-0.10	-0.01
	(0.25)	*(1.36)*	*(0.25)*	*(0.05)*
Mean household size	0.00	-0.04	0.04	-0.01
	(0.04)	*(0.24)*	*(0.05)*	*(0.01)*
Mean population density	0.98**	5.95***	-0.21	-0.09

	(0.40)	*(2.26)*	*(0.39)*	*(0.08)*
Mean asset value	0.00	0.00	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
Mean TLU	0.05	0.25	-0.04	-0.01
	(0.04)	*(0.22)*	*(0.04)*	*(0.01)*
Mean age	0.00	0.03	0.01	0.00
	(0.01)	*(0.03)*	*(0.01)*	*(0.00)*
Constant	-2.34	5.24	-5.84**	-1.04**
	(2.47)	*(14.05)*	*(2.44)*	*(0.52)*
Prob > chi2	0.000	0.000	0.000	0.000
Rho	0.21	0.15	0.16	
Observations	1494	1494	1494	1494

Significance levels: *10%, **5%, ***1%, ****0.1%

Appendix 2: CRE models for use and use intensity of organic manure and intercropping without 2006 data

Variable	**Organic Manure**		**Maize-legume intercropping**	
	Use (Probit)	**Use Intensity (Log - Kg/ha with Tobit)**	**Use (Probit)**	**Use Intensity (Farm size share with Fractional Probit)**
Longest early dry spell (1-year lag), days	0.09***	0.16	0.24***	0.04***
	(0.03)	*(0.14)*	*(0.04)*	*(0.01)*
Longest early dry spell (2-year lag), days	0.02	0.03	-0.05**	-0.01**
	(0.02)	*(0.09)*	*(0.02)*	*(0.00)*
Longest early dry spell (3-year lag), days	0.03	-0.09	0.15***	0.02**
	(0.04)	*(0.18)*	*(0.05)*	*(0.01)*
Longest late dry spell (1-year lag), days	0.02	0.10	0.08***	0.01***
	(0.02)	*(0.07)*	*(0.02)*	*(0.00)*
Longest late dry spell (2-year lag), days	0.05	0.08	0.04	-0.01
	(0.05)	*(0.21)*	*(0.05)*	*(0.01)*
Longest late dry spell (3-year lag), days	0.06	0.21	0.13	0.02
	(0.08)	*(0.36)*	*(0.09)*	*(0.02)*
3 year average rainfall (mm)	0.00	0.00	0.00***	0.00***
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
December average rainfall (mm)	-0.1	-0.93	0.12	0.01
	(0.25)	*(1.15)*	*(0.27)*	*(0.05)*
February average rainfall (mm)	-0.03	-0.74	-0.34	-0.09**
	(0.19)	*(0.86)*	*(0.21)*	*(0.04)*
Number of extension visits	0.12***	0.23***	0.01	0.00
	(0.02)	*(0.04)*	*(0.01)*	*(0.00)*
Input credit access (1=yes)	-0.01	-0.15	0.12	-0.01
	(0.18)	*(0.82)*	*(0.19)*	*(0.04)*
Farm organization (=yes)	0.35***	0.5	-0.06	-0.01
	(0.13)	*(0.58)*	*(0.14)*	*(0.03)*

Fertilizer price (Mk/Kg)	0.00	0.00	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
1-year lag maize price (Mk/Kg)	-0.05*	-0.19*	-0.06**	-0.01
	(0.03)	*(0.11)*	*(0.03)*	*(0.00)*
1-year lag legume price (Mk/Kg)	0.00	-0.01	0.00	0.00**
	(0.00)	*(0.01)*	*(0.00)*	*(0.00)*
Distance to market (km)	-0.05**	-0.17	0.04	0.01**
	(0.02)	*(0.11)*	*(0.03)*	*(0.00)*
Log-commercial fertilizer (Kg/ha)	0.01	0.04	0.05	0.01*
	(0.03)	*(0.12)*	*(0.03)*	*(0.01)*
Fertilizer subsidy, dummy	0.11	0.78	0.07	0.00
	(0.11)	*(0.52)*	*(0.14)*	*(0.03)*
Seed subsidy, dummy			-0.07	-0.02
			(0.14)	*(0.02)*
Log-farm size (ha)	0.19	1.28	0.04	-0.12**
	(0.25)	*(1.11)*	*(0.26)*	*(0.05)*
Log asset value	-0.02	0.00	-0.01	0.00
	(0.02)	*(0.09)*	*(0.02)*	*(0.00)*
Log TLU	0.01	0.40	0.06	0.00
	(0.11)	*(0.45)*	*(0.11)*	*(0.02)*
Plot distance (Km)	0.06**	0.25**	0.00	0.00
	(0.03)	*(0.12)*	*(0.03)*	*(0.01)*
Log-male labour (adult equivalent/ha)	0.45	1.65	-0.40	0.03
	(0.34)	*(1.49)*	*(0.36)*	*(0.06)*
Log-female labour (adult equivalent/ha)	-0.39	0.26	0.00	-0.07
	(0.34)	*(1.51)*	*(0.36)*	*(0.06)*
Off farm labour (adult equivalent/ha)	0.49**	2.33**	-0.09	-0.01
	(0.24)	*(1.09)*	*(0.26)*	*(0.05)*
Sex of household head (1=female)	-0.06	0.22	0.20*	0.01
	(0.11)	*(0.48)*	*(0.12)*	*(0.02)*
Education of household head (years)	0.01	0.05	0.03**	0.00
	(0.01)	*(0.06)*	*(0.02)*	*(0.00)*
Household size	0.01	-0.15	0.06	0.01
	(0.04)	*(0.18)*	*(0.05)*	*(0.01)*
Log-Population density	-8.38*	-42.81**	-0.72	0.14
	(4.29)	*(18.52)*	*(4.21)*	*(0.79)*
Age of household head (years)	0.03*	0.12*	0.01	0.00
	(0.01)	*(0.07)*	*(0.02)*	*(0.00)*
Age squared	-0.00*	-0.00*	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
Household residence (1=wife village)	0.05	-0.01	-0.28**	-0.06***
	(0.11)	*(0.51)*	*(0.12)*	*(0.02)*
Southern region dummy	-0.03	6.11	2.34	0.60
	(1.85)	*(8.55)*	*(2.00)*	*(0.37)*

2012 year dummy	-0.95	-2.88	-0.81	0.02
	(0.74)	*(3.30)*	*(0.86)*	*(0.14)*
2015 year dummy	0.02	1.65	1.34***	0.22***
	(0.43)	*(1.88)*	*(0.49)*	*(0.08)*
Mean farm size	-0.09	-0.49	-0.15	-0.02
	(0.16)	*(0.72)*	*(0.17)*	*(0.03)*
Mean male labour	0.00	0.04	0.02	0.00
	(0.05)	*(0.20)*	*(0.05)*	*(0.01)*
Mean female labour	-0.01	-0.02	0.03	0.01
	(0.06)	*(0.25)*	*(0.06)*	*(0.01)*
Mean off-farm labour	-0.32	-1.13	0.15	0.07
	(0.31)	*(1.37)*	*(0.32)*	*(0.06)*
Mean household size	0.01	0.03	0.01	-0.01
	(0.05)	*(0.23)*	*(0.06)*	*(0.01)*
Mean population density	1.97***	9.09***	0.14	0.00
	(0.74)	*(3.17)*	*(0.72)*	*(0.14)*
Mean asset value	0.00	0.00	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
Mean TLU	0.04	0.21	-0.01	0.00
	(0.05)	*(0.23)*	*(0.06)*	*(0.01)*
Mean age	0.00	0.01	0.01	0.00
	(0.01)	*(0.03)*	*(0.01)*	*(0.00)*
Constant	4.61	35.62*	-3.14	-0.34
	(4.73)	*(20.81)*	*(4.69)*	*(0.88)*
Prob > chi2	0.000	0.000	0.000	0.000
Rho	0.24	0.15	0.24	
Observations	1051	1051	1051	1051

Significance levels: *10%, **5%, ***1%

Appendix 3: Double hurdle model results for use and use intensity of organic manure

Variable	**Full sample**		**Minus 2006 data**	
	Tier 1	**Tier 2**	**Tier 1**	**Tier 2**
Longest early dry spell (1-year lag), days	0.00	0.07*	0.04	0.02
	(0.02)	*(0.04)*	*(0.03)*	*(0.04)*
Longest early dry spell (2-year lag), days	0.00	-0.02	0.01	-0.03
	(0.01)	*(0.03)*	*(0.02)*	*(0.03)*
Longest early dry spell (3-year lag), days	-0.01	-0.01	0.00	-0.06
	(0.02)	*(0.04)*	*(0.03)*	*(0.05)*
Longest late dry spell (1-year lag), days	0.02**	0.05***	0.02	0.05**
	(0.01)	*(0.02)*	*(0.01)*	*(0.02)*
Longest late dry spell (2-year lag), days	-0.06**	-0.08*	0.05	-0.16**
	(0.02)	*(0.04)*	*(0.04)*	*(0.07)*
Longest late dry spell (3-year lag), days	0.03	-0.13***	0.04	-0.03

	(0.03)	*(0.05)*	*(0.07)*	*(0.12)*
3 year average rainfall (mm)	0.00	0.00***	0.00	0.00**
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
December average rainfall (mm)	-0.01	-0.23***	-0.07	-0.68*
	(0.04)	*(0.07)*	*(0.21)*	*(0.38)*
February average rainfall (mm)	-0.05	-0.05	-0.06	-0.33
	(0.04)	*(0.08)*	*(0.16)*	*(0.28)*
Number of extension visits			0.04***	0.04***
			(0.01)	*(0.01)*
Input credit access (1=yes)			-0.09	0.50**
			(0.16)	*(0.25)*
Farm organization (=yes)			0.16	-0.42**
			(0.11)	*(0.17)*
Fertilizer price (Mk/Kg)	0.00	0.00	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
1-year lag maize price (Mk/Kg)	-0.01	0.05**	-0.06***	0.11***
	(0.01)	*(0.02)*	*(0.02)*	*(0.03)*
1-year lag legume price (Mk/Kg)	0.00	0.00	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
Distance to market (km)	-0.03*	-0.03	-0.03*	-0.02
	(0.02)	*(0.03)*	*(0.02)*	*(0.03)*
Log-commercial fertilizer (Kg/ha)	0.01	0.04	0.01	0.06
	(0.02)	*(0.04)*	*(0.02)*	*(0.04)*
Fertilizer subsidy, dummy	0.18**	0.15	0.17*	0.07
	(0.09)	*(0.16)*	*(0.10)*	*(0.17)*
Log-farm size (ha)	0.08	-1.17***	0.30	-0.57
	(0.17)	*(0.34)*	*(0.22)*	*(0.36)*
Log asset value	0.02*	0.02	0.00	0.01
	(0.01)	*(0.03)*	*(0.02)*	*(0.03)*
Log TLU	0.12	0.26*	0.09	0.06
	(0.08)	*(0.13)*	*(0.09)*	*(0.14)*
Plot distance (Km)	0.03	-0.02	0.05**	0.00
	(0.02)	*(0.03)*	*(0.02)*	*(0.03)*
Log-male labour (adult equivalent/ha)	0.10	0.61*	0.17	0.81*
	(0.15)	*(0.31)*	*(0.29)*	*(0.49)*
Log-female labour (adult equivalent/ha)	0.06	-0.49	0.15	-0.30
	(0.14)	*(0.31)*	*(0.29)*	*(0.48)*
Off farm labour (adult equivalent/ha)	0.35*	0.36	0.46**	0.41
	(0.20)	*(0.35)*	*(0.22)*	*(0.35)*
Sex of household head (1=female)	0.12	-0.18	0.07	-0.23
	(0.08)	*(0.15)*	*(0.10)*	*(0.15)*
Education of household head (years)	0.02*	0.00	0.01	-0.01
	(0.01)	*(0.02)*	*(0.01)*	*(0.02)*
Household size	0.02	0.01	-0.02	-0.05

	(0.03)	*(0.06)*	*(0.04)*	*(0.06)*
Log-Population density	-3.20	-8.85**	-6.79**	-6.25
	(2.23)	*(4.09)*	*(3.40)*	*(5.25)*
Age of household head (years)	0.03**	-0.01	0.03**	-0.03
	(0.01)	*(0.02)*	*(0.01)*	*(0.02)*
Age squared	-0.00**	0.00	-0.00**	0.00
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
Household residence (1=wife village)	-0.03	0.06	0.00	-0.05
	(0.08)	*(0.16)*	*(0.10)*	*(0.16)*
Southern region dummy	0.45**	-0.07	0.43	3.30
	(0.22)	*(0.44)*	*(1.57)*	*(2.77)*
2009 year dummy	0.43*	-1.15**		
	(0.25)	*(0.48)*		
2012 year dummy	0.41*	-0.44	-1.08*	2.59***
	(0.21)	*(0.41)*	*(0.62)*	*(1.00)*
2015 year dummy	1.00***	-0.76*	0.09	1.15**
	(0.22)	*(0.40)*	*(0.36)*	*(0.57)*
Mean farm size	-0.15	0.38*	-0.11	0.29
	(0.11)	*(0.21)*	*(0.13)*	*(0.21)*
Mean male labour	-0.03	0.02	0.00	0.05
	(0.03)	*(0.05)*	*(0.04)*	*(0.05)*
Mean female labour	0.02	0.06	0.00	0.04
	(0.02)	*(0.07)*	*(0.04)*	*(0.07)*
Mean off-farm labour	-0.31	-0.34	-0.26	-0.16
	(0.21)	*(0.40)*	*(0.26)*	*(0.41)*
Mean household size	0.00	-0.14**	0.00	-0.06
	(0.04)	*(0.07)*	*(0.04)*	*(0.07)*
Mean population density	0.86**	1.98***	1.52***	1.34
	(0.38)	*(0.69)*	*(0.59)*	*(0.91)*
Mean asset value	0.00	0.00**	0.00	0.00**
	(0.00)	*(0.00)*	*(0.00)*	*(0.00)*
Mean TLU	0.04	-0.09	0.03	0.01
	(0.03)	*(0.06)*	*(0.04)*	*(0.06)*
Mean age	0.00	-0.01	0.00	0.00
	(0.00)	*(0.01)*	*(0.01)*	*(0.01)*
Constant	0.26	13.47***	5.27	10.35*
	(2.33)	*(4.35)*	*(3.79)*	*(6.19)*
Prob > chi2	0.000	0.000	0.000	0.000
Observations	1494	1494	1051	1051

Significance levels: *10%, **5%, ***1%

Paper two

Adoption of drought tolerant maize varieties under rainfall stress in Malawi

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Abstract

We examine adoption of drought tolerant (DT) maize varieties using a four-round panel dataset from six districts in Malawi. There is an increase in adoption of DT maize from 3% in 2006 to 43% in 2015 in our data. We focus on the effect of past drought exposure on adoption and the likelihood of DT maize being distributed under the Farm Input Subsidy Programme (FISP). Results show that past exposure to drought increases the probability of DT maize seed being distributed through FISP. Farmers who accessed maize seed subsidy coupons and were previously exposed to late season dry spells are more likely to use the seed subsidy coupon to redeem DT maize seed. The likelihood of adoption and adoption intensity (area under DT maize) are positively influenced by previous early season dry spells and access to seed subsidy. Previous late season droughts also positively affect adoption intensity. On the other hand, area share under DT maize is positively correlated with early season dry spells and past exposure to late season dry spells but negatively related to seed subsidy. FISP in Malawi appears to have stimulated adoption of DT maize directly through subsidy and indirectly through generating farmers' experiences of the performance of DT varieties under drought conditions.

Keywords: Drought tolerant maize adoption; drought exposure; Farm Input Subsidy Programme; Mundlak-Chamberlain; Malawi

JEL Classifications: O13, O33, Q18, Q56.

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Introduction

Weather shocks such as droughts and floods undermine crop yields and aggregate production thereby reducing food availability and agricultural incomes (Kassie et al., 2009, Davies et al., 2009, Pauw et al., 2011). Farm households' failure to adapt to climate change could aggravate the negative effects and can inhibit further investment and economic growth (Kato et al., 2011, Kassie et al., 2015, Nangoma, 2007). Weather shocks can cascade through low production to food insecurity and local and national economic disruption (Devereux, 2007). The problem is particularly serious among smallholder farmers in sub-Saharan Africa (SSA), who are repeatedly exposed to weather extremes but with limited adaptation options. For example, Malawi has experienced several weather shocks during the last two decades that have led to severe crop losses, infrastructure damage and occasional displacement of people (Pauw et al., 2010, Nangoma, 2007). The most recent shocks include the droughts of 2001/02, 2004/05 and 2011/12 (Nangoma, 2007, Denning et al., 2009, Msowoya et al., 2016, Holden and Fisher, 2015) and the 2014/15 flash floods early in the growing season and droughts thereafter.

Investing in agricultural production methods to boost farmers' resilience against weather shocks is a key strategy to reduce negative impacts (Davies et al., 2009, Pangapanga et al., 2012). In a country like Malawi and most countries in the SSA region, with poor or missing markets for insurance and credit and limited off-farm employment opportunities, adoption of agricultural management strategies that reduce production risks is an important option for smallholder farmers (Kassie et al., 2015). Drought tolerant (DT) maize is one potential technology that has the capacity to help smallholders adapt to drought risks. It is estimated that DT maize can produce up to 30% of their potential yield after six weeks of water stress, before and during flowering and grain-formation (Magorokosho et al., 2009). It is also estimated that DT maize can give a yield advantage of up to 40% over other maize varieties in severe drought environments (Tesfaye et al., 2016).

We examine the adoption of DT maize among smallholder farmers in Malawi, focusing on how past exposure to dry spells affects adoption and the probability that DT maize is included in the seed subsidy programme. The paper combines household panel data spanning nine years from 2006 to 2015 and daily rainfall data from 2003 to 2015 from Malawi's Department of Climate Change and Meteorological Services. Previous studies across several countries in SSA identify several major factors affecting adoption of DT maize varieties, including: unavailability of improved seed; inadequate information; lack of resources; high seed prices (Fisher et al., 2015). Other authors report farming experience with DT maize, access to DT seed and awareness of DT maize varieties as key drivers of adoption in Nigeria (Idrisa et al., 2014, Radda, 2015, Awotide et al., 2016). In Malawi, Holden and Fisher (2015) and Holden and Quiggin (2017a) identify the Farm Input Subsidy Programme (FISP), recent droughts and farmer risk aversion as the major drivers of adoption.

Building on these findings, our paper extends the empirical analysis of Holden and Quiggin (2017a) in several ways. First, while Holden and Quiggin reported FISP as a major driver of DT maize seed adoption, we examine how past exposure to droughts affects the probability that DT seed was included and distributed through FISP. We also examine how past exposure to dry spells affects use of DT seed, conditional on access to subsidised DT seed. Second, Holden and Quiggin combined experimental data to derive prospect theory parameters with cross-sectional survey data from 2012 and perception data on lagged exposures to weather shocks (drought). In contrast, we use four rounds of household panel data to assess changes in DT adoption over the period 2006-2015, which includes substantial variation in rainfall shocks, and controlling for (stable) household preferences. We construct a more independent dry spell variable using measured daily rainfall data as opposed to farmers' perception/memory of recent droughts. We define a dry spell as a period of 5 – 15 days with a total rainfall of less than 20 mm following a rainy day of at least 20 mm.[3] Using this definition, we identified the length (days) of the longest dry spell in each of the survey years, namely 2006, 2009, 2012 and 2015, and the previous three seasons of each survey year.

We hypothesise that the length of dry spells should have a positive effect on adoption of DT maize in later years (assuming farmers have learnt that DT maize performs better than other maize varieties). To learn about the relative performance, farmers need to be able to observe the performance of alternative varieties under those growth conditions. Conversely, lack of recent droughts may reduce the likelihood of adopting DT maize. Areas with higher average rainfall are

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[3] Personal communication (February 18, 2016) with Charles L. Vanya (Principal Meteorologist with the Department of Climate Change and Meteorological Services)

less likely to have droughts or have longer growing seasons and this may reduce the probability of farmers planting early-maturing DT maize varieties.

Our third difference from the Holden and Quiggin study (*ibid.*) is that we disaggregate the dry spell variable into early season and late season dry spells. The early dry spells cover a period between December and early January that coincides with planting time while late dry spells coincide with maize grain formation between February and early March. DT maize performs relatively better than other maize varieties in case of late season droughts. Exposure to late droughts may have revealed this to farmers who have seen this on their own or neighbouring farms. Our expectation is that exposure to late droughts is more likely to have a significant positive effect on adoption of DT maize among farmers that have observed this through exposure to late droughts in earlier years. Such exposure, in combination with the FISP, should enhance adoption of DT maize.

Maize varieties in SSA

Maize varieties cultivated in the SSA region are classified into three major categories: traditional/local, hybrid and open pollinated variety (OPV) (Lunduka et al., 2012, Abate et al., 2017). The hybrids and OPVs are improved varieties whose breeding programme dates back to the 1930s in Zimbabwe (Magorokosho, 2007) and 1940s in Malawi (Mason and Ricker-Gilbert, 2013). The locally bred hybrid (LH7) in Malawi was first distributed in 1959 (Cromwell and Zambezi, 1993). Since then over 1700 varieties have been released between 1950 and 2014 across countries in SSA, of which 68% are hybrids and 32% OPVs. As of 2014, improved maize occupied 57% of land area under maize production in SSA (Abate et al., 2017). The hybrid maize varieties are high yielding while OPVs are early maturing, compared with local varieties, hence providing farmers with yield advantage (Lunduka et al., 2012). However, local varieties are still popular among farm households, despite proliferation of hybrids and OPVs, because of favourable processing and consumption traits such as taste, storability, poundability, high flour-to-grain ratios and lower requirements for inorganic fertilizer (Smale et al., 1995, Denning et al., 2009, Lunduka et al., 2012). Thus, while hybrids and OPVs have production advantage over local varieties, they do not yet have the consumption attributes that farm households prefer in local maize.

Considering the subsistence nature of most smallholder farmers who produce mainly for own consumption, and non-separable household production and consumption decisions, farmers face a trade-off between planting improved maize varieties with good production attributes and a local variety with preferred consumption characteristics. Farmers tend to adopt a portfolio of maize varieties combining both traditional and improved (Smale et al., 1995, Lunduka et al., 2012). Smale et al. (1995) reported risk aversion, future utility prospects of the variety and rationing in input supply markets or credit as some of the reasons for joint production of local and modern varieties. Abate et al. (2017) report adoption rates of: 32% hybrids; 23% OPVs; 46% local in SSA. Farmers weigh options as to whether to allocate more land to high yielding varieties with poor post-harvest attributes or put more weight on post-harvest attributes at the expense of high yields. With the apparent recent increase in droughts, farmers not only weigh high yielding against post-harvest characteristics, but also drought tolerance as a hedge against droughts.

Drought tolerant maize variety

Drought tolerant maize seed became an integral component in breeding programmes across SSA countries during the late 1990s because of recurrent droughts (Bänziger et al., 2006). The programme received support from the International Maize and Wheat Improvement Centre (CIMMYT) and International Institute of Tropical Agriculture (IITA) with the launch of the Drought Tolerant Maize for Africa (DTMA) project in the mid 2000s. The project supported production and dissemination of DT maize varieties in 13 countries in SSA. Over 200 varieties were released before the project phased out in December 2015. The project was implemented jointly with national agricultural research systems who were responsible for seed delivery with support from public and private seed companies (Wawa, 2016, Setimela et al., 2013).

In Malawi, as of December 2015, 18 DT maize varieties (15 hybrids and 3 OPVs) were released under the DTMA project. There are also other varieties developed outside the DTMA project that have been certified as drought tolerant by maize breeders (Holden and Fisher, 2015, Unpublished report, Abate, 2015). The Government of Malawi includes DT seed in the FISP, making it more accessible (Lunduka et al., 2012, Holden and Fisher, 2015). FISP beneficiaries are officially entitled to two 50-kg bags of fertilizer and either one 2-kg bag of hybrid maize seed or a 4-kg bag of OPV seed (Ricker-Gilbert and Jones, 2015).

Theoretical Framework, Model Specification and Estimation Strategy

Theoretical framework

Production under uncertainty can be presented as a state-contingent production function as proposed by Chambers and Quiggin (2000) and Quiggin and Chambers (2006). The model assumes y distinct outputs, x distinct inputs and s possible states of nature. A farm household allocates input $x \in \Re_{+}^{X}$ and chooses state contingent output $y \in \Re_{+}^{S*Y}$ before the state of nature is revealed (ex ante), where; $\Re_{+}$ implies that x and y are positive real numbers. Inputs are then fixed and output produced ex post (Quiggin and Chambers, 2006). If the household chooses output y and state of nature s is realized then the observed output is y_s.

The technology can then be summarized as $T = [(x, y): x \; can \; produce \; y]$. Given p_y as output price and p_x as the price of inputs, we can express the technology as a cost function $C\left(p_{x,}y\right) = min[p_x x: (x, y) \; \in \; T]$, or as a demand function $x\left(p_{x,}y\right) = argmin[p_x x: (x, y) \; \in T]$. Assuming a simple case of two states of nature, one of which is unfavourable, the farmer's interest is to maximize output (y). The producer's problem is choice under uncertainty whereby state one is unfavourable if and only if output $y_1 < y_2$. We may distinguish between inputs that are risk-complementary or risk-substituting in this kind of setting. If a shift from a state-contingent output vector y to a riskier output y' leads to an increase in demand for an input x_j that is $x_j(p_x, y) < x_j(p_x, y')$, then input x_j is risk-complementary, otherwise it is a risk-substitute if $x_j(p_x, y) > x_j(p_x, y')$ (Holden and Quiggin, 2017b). An increase in probability of a less favourable state will lead to an increased share of risk-substituting inputs in the input mix for a given expected output.

Given that the farmer's objective is to maximize expected utility [EU(.)] from output y under the expected utility theory, the adoption decision of alternative inputs can be modelled as an optimal land allocation problem (Ding et al., 2009). Since smallholder farmers are price takers, and prices are assumed non-random, the only source of uncertainty are climatic risks. An individual farmer will allocate a mix of inputs to maximize expected utility from output (y). The farmer's optimal land allocation problem can therefore be specified as $\underset{X}{Max} \; E[U(\pi)] = Max \; EU[p_y y - p_X(X)]$. Our hypothesis is that experience of droughts will increase the likelihood of adopting DT maize.

On the other hand, other improved maize (OIM) varieties are considered risk-complementary because they are optimal only under normal rainfall.

However, the farmer's adoption decision will not only be affected by production factors but also consumption characteristics of the seeds. The risk-averse farmer is likely to adopt a portfolio of maize varieties to meet both production and consumption needs (Lunduka et al., 2012, Smale et al., 1995). DT maize will be preferred for early maturing and drought tolerant traits but is low yielding compared to other improved hybrids under normal rainfall, while local maize varieties will be chosen for consumption traits. The key question is the land area allocated to each variety. We first model the farmer's decision on whether to adopt DT maize varieties as a binary decision and then model the decision on area (ha) and area share allocated to DT maize varieties.

Model specification

The farmers' decision to adopt DT maize can be modelled using the latent variable approach (Wooldridge, 2014). The choice is based on the seed's characteristics and weather expectations for that season (Ding et al., 2009), and maximizing utility implies partial adoption and farmers choosing a portfolio of seeds. Both market imperfections and household circumstances mean that production and consumption decisions are inseparable. The seed demand functions are therefore based on both wealth (consumption) and production characteristics. We therefore model the adoption decision of DT maize as follows:

$$DT_{it} = \alpha_0 + \alpha_1 R_{dt} + \alpha_2 S_{it} + \alpha_3 M_{it} + \alpha_4 H_{it} + \alpha_5 P_{it} + \alpha_6 T_{it} + \alpha_i + \varepsilon_{it} \qquad 2$$

where DT_{it} is the dependent variable representing the adoption of DT maize by household *i* in year *t*. R_{dt} is a vector of variables capturing rainfall stress in the farmer' district *d*. Lagged dry spell variables are included to capture adaptive expectations of farmers on rainfall pattern for the forthcoming season. S_{it} is a dummy for access to the FISP package of seed and fertilizer subsidies.

M_{it} represents market factors, including distance to agricultural markets (km) and the real price of inorganic fertilizer. H_{it} denotes household characteristics such as education (years), age (years) and sex (1=female) of household head, male and female labour (adult equivalent/ha), off-farm labour (adult equivalent/ha), household size (number of persons), tropical livestock units (TLU) and asset values in Malawi Kwacha (MK). P_{it} controls for observable farm characteristics such as farm size (ha) and number of plots. $\mathrm{T_{it}}$ represents year dummies with 2006 as base year. $\mathrm{\alpha_i}$ captures unobservable time-invariant characteristics of households and plots such as time-invariant observable and unobservable preferences, managerial ability and land quality. $\mathrm{\varepsilon_{it}}$ is normally distributed error term.

Estimation strategy

Parameters in equation (1) are estimated using the Mundlak-Chamberlain (MC) models with a Control Function (CF) approach (Mundlak, 1978, Chamberlain, 1984, Wooldridge, 2010). In this MC framework, we include means and deviations of all household and farm characteristics. We model the adoption decision as a binary (zero/one) decision, using a probit estimator (Wooldridge, 2010). For adopters, the second hurdle (decision) is how much land area (ha) to plant with DT maize varieties. We use a tobit estimator to account for those who do not adopt DT maize, assuming normal distribution of the error term, ε_{it}, (that is $\varepsilon_{it}|X_{it} \sim Normal(0, \sigma^2)$) (Tobin, 1958). Finally, we model the area share planted with DT maize varieties, using a fractional probit estimator to constrain the predicted value between zero and one (Wooldridge, 2011).

Attrition bias, sample selection and endogeneity

Estimation of equation (1) can suffer from attrition bias due to non-random loss of sample households between the first and subsequent waves. Following Wooldridge (2010) we test whether attrition is random, and the results give evidence of attrition bias. Fortunately, with proper adjustments, unbiased estimation is possible even with high attrition. Using the MC device, for instance, allows us to control for time-constant unobservable factors that affect attrition. On the other hand, attrition bias due to observables can be controlled using an inverse probability weighting (IPW) approach (Fitzgerald et al., 1998, Wooldridge, 2010). IPW is, however, not available for our non-linear models.

Another problem in this model could be sample selection bias and endogeneity due to non-random access to FISP by the households. To control for sample selection and endogeneity bias, we use a two-step control function (CF) approach (Wooldridge, 2011, Petrin and Train, 2010). In the first step, S_{it} variable is written as a function of all exogenous variables entering the adoption model and the instruments that do not enter the adoption equation.

$$S_{it} = \alpha_0 + \alpha_i X_{it} + \beta_i Z_{it} + \varepsilon_{it} \tag{3}$$

where Z_{it} are instrumental variables (IV) that can affect access to FISP but have no direct impact on adoption. Our choices for IV are: the number of children residing in the household; whether the area has a Member of Parliament (MP) from the ruling party, which can influence access to FISP based on previous studies (e.g. Mason and Ricker-Gilbert, 2013, and Holden and Lunduka, 2012).

We estimate two separate probit reduced form equations for seed subsidy and fertilizer subsidy as a first stage in this procedure and observe the significance of the instruments. If the instruments are jointly significant and hence relevant we then predict the error terms from each equation that are used to create control functions ($\bar{\mu}_{it}$ & $\bar{\gamma}_{it}$). Equation (2) is also used to test the first hypothesis on whether recent droughts increases the probability that DT maize was distributed related to the seed subsidy program. Having ascertained appropriateness of the instruments, we compute residuals ($\bar{\mu}_{it}$ & $\bar{\gamma}_{it}$.) from both reduced form equations to include in the structural equation. The structural equation is thus estimated as:

$$DT_{it} = \alpha_0 + \alpha_1 R_{dt} + \alpha_2 S_{it} + \alpha_3 M_{it} + \alpha_4 H_{it} + \alpha_5 P_{it} + \alpha_6 T_{it} + \alpha_7 \bar{\mu}_{it} + \alpha_8 \bar{\gamma}_{it} + \alpha_i + \varepsilon_{it} \tag{4}$$

Data and Descriptive Statistics

Data

We use four-round panel data from six districts in Malawi, namely Chiradzulu, Kasungu, Lilongwe, Machinga, Thyolo and Zomba. The initial sample of 450 households was drawn in 2006 following the 2004 Integrated Household Survey Two (IHS 2) (Lunduka, 2009). In 2009, 378 were resurveyed while 350 were resurveyed in both 2012 and 2015. Dropping households with invalid observations leaves 449 households in 2006, 373 in 2009 and 345 in 2012 and 2015 (Table 3). Our primary unit of analysis is farm household. The household panel data are combined with daily rainfall data from the Department of Climate Change and Meteorological Services from 2003 to 2015, which allows us to generate dry spell variables that include lags for the past three seasons of each survey year. We use three seasons as the basis for farmers' expectations and experience in comparing the performance of alternative maize varieties under varying rainfall patterns. For previous early dry spells, the third season coincides with the early dry spell for the survey year, hence we limit the lags for the early dry spells to the past two seasons.

Table 3: Number of households (HHs) and plots by study area (district)

District	2006		2009		2012		2015		Total	
	HHs	Plots	HHs	Plots	HHs	Plots	HHs	Plots	HHs	Plots
Thyolo	61	105	47	137	47	135	47	168	202	545
Zomba	86	181	82	158	77	137	79	270	324	746
Chiradzulo	53	117	39	104	35	97	34	123	161	441
Machinga	56	87	43	142	46	156	43	156	188	541
Kasungu	97	166	90	337	79	325	79	329	345	1,157
Lilongwe	96	173	72	178	61	157	63	224	292	732
Total	449	829	373	1056	345	1007	345	1270	1512	4162

In Table 4 we show adoption of DT maize disaggregated according to access to seed subsidy. Adoption was measured on whether farmers reported buying and using a DT maize variety. We consider both buying the seed through FISP or commercially at market price. The results show that adoption of DT maize varieties increased from 3% in 2006 to 43% in 2015. It is interesting however to notice that adoption of DT maize outside FISP is very low.

Table 2 suggests some correlation between adoption of DT maize seed and possession of seed subsidy coupons. However these results also show that while seed subsidy may contribute significantly to adoption of DT seed, some adopters buy the seed commercially. The seed subsidy package contains hybrid and OPV seed coupons, which are both DT and non-DT seed so farmers have an option to redeem either DT or non-DT maize seed. Lunduka et al. (2012) reported that 98% of the beneficiaries preferred hybrid seed, with Holden and Fisher (2015) finding 69-82% redeeming DT maize seed.

Table 4: DT maize seed adopters by seed subsidy beneficiaries

Year	Adopted DT	Received seed subsidy coupon		
		No	Yes	Total
2006	No	67%	30%	97%
	Yes	1%	2%	3%
	Total	68%	32%	100%
2009	No	53%	23%	75%
	Yes	14%	11%	25%
	Total	66%	34%	100%
2012	No	32%	28%	60%
	Yes	14%	26%	40%
	Total	46%	54%	100%
2015	No	23%	34%	57%
	Yes	12%	32%	43%
	Total	34%	66%	100%

Descriptive statistics of dependent and explanatory variables

Table 5 shows the descriptive statistics for the dependent and independent variables. The dependent variables are "adoption" equal to one if the household bought and used DT maize variety and zero otherwise, "maize area" (ha) allocated to DT maize and "area share" under DT maize varieties. The key explanatory variables in this paper are "dry spells". The results show that, on average, the longest early dry spell lasted 9.3 days in 2006, 9 days (2009), 7 days (2012) and 5.7 days in 2015. In previous years to the survey year, farmers were exposed to the longest early dry spells in 2004 with an average of 10 days, while the longest late dry spell was in 2005 with an average of 13 days. We expect early dry spells in survey years to affect adoption as early warning of potential drought and/or a short rainy season. On the other hand, we expect previous exposure to late droughts to affect adoption through risk aversion. Also included in Table 5 are seed and fertilizer subsidy variables and household and farm level factors. The farm size (ha) variable is a total of all the plots cultivated by the household in a particular year. To enhance accuracy, all the plots were measured with a Global Positioning System (GPS) device.

Table 5: Definitions and summary statistics of variables by year

Variable	2006	2009	2012	2015	Total
Adoption of DT maize, dummy	0.03	0.24	0.40	0.44	0.26
Area under DT maize (ha)	0.02	0.10	0.15	0.17	0.10
Area share under DT	0.02	0.12	0.15	0.17	0.11
Longest early dry spell	9.27	9.10	6.96	5.71	7.89
1 year Lag longest early dry spell, days	8.04	7.12	6.68	4.90	6.78
2 years Lag longest early dry spell, days	12.61	10.44	11.68	6.19	10.40
1 year Lag longest late dry spell, days	10.08	8.01	10.55	7.66	9.13
2 years Lag longest late dry spell, days	9.61	6.54	8.02	10.33	8.66
3 years Lag longest late dry spell, days	7.95	9.42	7.97	10.68	8.94
3 year lag of average rainfall in mm	5.24	6.17	5.60	5.53	5.62
Seed subsidy, dummy	0.23	0.34	0.54	0.66	0.43
Fertilizer subsidy, dummy	0.45	0.53	0.72	0.69	0.59
Distance to agricultural market (Km)	4.00	4.30	4.23	4.21	4.18
Fertilizer real price (MK[1]/Kg)	59.92	75.68	131.38	135.23	97.38
Age of household head (years)	41.40	46.21	50.74	48.85	46.42
Sex of household head, dummy (1=female)	0.25	0.22	0.25	0.35	0.26
Education of household head (years)	7.04	5.10	5.12	5.29	5.73
Household size	5.28	5.33	5.28	5.62	5.37
Male labour force (adult equiv./ha)	2.47	3.75	3.53	4.13	3.41
Female labour force (adult equiv./ha)	2.28	3.56	3.19	3.78	3.14
Off-farm labour (adult equiv./ha)	0.14	0.21	0.35	0.24	0.23
Tropical livestock units	1.08	1.47	1.11	0.50	1.05
Asset value (MK[1])	3352	4102	2488	5985	3940
Farm size (ha)	0.80	1.10	0.97	1.09	0.98
Number of plots	1.85	2.80	2.92	3.68	2.74
Number of children in a household	3.29	2.81	2.77	2.82	2.95
Member of parliament from ruling party	0.52	0.40	0.46	0.47	0.47

[1]Values in Malawi Kwacha (MK) are deflated with consumer price index using 2010 prices

Results and Discussion

Impact of recent droughts on DT seed distribution through FISP

Table 6 presents results for access to seed and fertilizer subsidy and use of DT maize seed conditional on seed subsidy access. All the models are estimated using the MC framework. We include variables, ruling party Member of Parliament (MP) and number of children in the households, in seed subsidy and fertilizer subsidy models as instruments to compute residuals for the structural equations for the second hypothesis. The variable ruling party MP is positive and significant suggesting that the area whose Member of Parliament is from the ruling party is more likely to access seed and fertilizer subsidy coupons. With respect to exposure to recent dry spells, there is a positive correlation with DT seed distribution and use. Two- and three-year lags of longest late season dry spells are positive and significant on the probability that the household received seed subsidy coupons. Further, one-year lag of early season dry spells and two-year lag of late season dry spells significantly increase the likelihood that the household used the seed subsidy coupon to redeem drought tolerant maize seed. On the other hand, three-year lag of average rainfall (mm), a proxy for rainfall distribution is associated with less likelihood of a household using the seed subsidy coupon to redeem DT maize seed.

These results suggest that areas that have been exposed to more droughts in recent years are more likely to choose and redeem DT maize seed in the farm input subsidy package. Our results also suggest that farmers who were previously exposed to late dry spells are more likely to use the maize seed subsidy coupon to redeem DT maize seed varieties. Although the Government of Malawi tries to match seed varieties with appropriate agro-ecological zones and with farmer preferences (from demonstration trials), it does not relate varieties to recent weather experience.

Table 6: Factors affecting access to seed and fertilizer subsidy coupons and use of DT seed conditional on seed subsidy access

Variables	**Seed subsidy coupon**	**Fertilizer subsidy coupon**	**Redeemed DT seed conditional on seed subsidy access**
Longest early dry spell (days)	*0.04*** *(0.02)*	*0.01* *(0.02)*	*0.05* *(0.03)*
1-year lag longest early dry spell (days)	0.00 *(0.02)*	0.05*** *(0.02)*	0.05* *(0.03)*
2-years lag longest early dry spell (days)	-0.01 *(0.02)*	0.01 *(0.02)*	0.04 *(0.03)*
1-year lag longest late dry spell (days)	-0.03** *(0.01)*	-0.05**** *(0.01)*	0.01 *(0.02)*
2-years lag longest late dry spell (days)	0.08**** *(0.02)*	0.03 *(0.02)*	0.09*** *(0.03)*
3-years lag longest late dry spell (days)	0.05**** *(0.01)*	0.03** *(0.01)*	0.03 *(0.02)*
3-years lag average rainfall (mm)	0.11** *(0.05)*	0.28**** *(0.05)*	-0.20** *(0.08)*
Distance to agricultural markets (Km)	0.03 *(0.02)*	0.06*** *(0.02)*	0.00 *(0.03)*
Fertilizer price (MK)	-0.00**** *(0.00)*	-0.00**** *(0.00)*	-0.00** *(0.00)*

Year 2009, dummy	0.27**	-0.02	1.83****
	(0.14)	*(0.13)*	*(0.32)*
Year 2012, dummy	1.14****	1.00****	2.08****
	(0.14)	*(0.15)*	*(0.31)*
Year 2015, dummy	1.05****	0.61***	2.03****
	(0.18)	*(0.19)*	*(0.34)*
Ruling party member of parliament	0.24**	0.29**	
	(0.12)	*(0.12)*	
Number of children in a household	-0.05	-0.01	
	(0.05)	*(0.05)*	
Constant	-2.98****	-2.65****	-3.44****
	(0.51)	*(0.55)*	*(0.86)*
Prob > chi2	0.000	0.000	0.000
Rho	0.06	0.11	0.04
Observations	1506	1506	641

Notes: Significance levels *10%, **5%, ***1%, ****0.1%. The mean and deviation of household and farm characteristics are included in this MC framework but are left out of the table to save space. The full table can be accessed through the appendix.

Impact of recent droughts on adoption and adoption intensity of DT maize seed varieties

Table 7 presents our adoption results, estimated with the MC device with a control function (CF) approach. Columns one to three are: (i) DT adoption (Probit), (ii) area (ha) under DT maize (Tobit); (iii) area share allocated to DT maize varieties (Fractional Probit). The fertilizer subsidy residual is significant in area and area share models while the seed subsidy residual is significant in the area share model. Thus, we reject exogeneity of fertilizer subsidy and seed subsidy variables in these models[4] and, therefore, our CF approach is appropriate.

The results show that the likelihood of adoption of drought tolerant maize varieties is positively correlated with a two-year lag of longest early dry spells and seed subsidy access, but there is negative correlation with 3-year lag of average rainfall. Intensity of adoption measured as area (ha) under DT maize is positively correlated with one-year and two-year lag of early longest dry spells, two-year and three-year lag of longest late dry spells and seed subsidy but inversely related to one-year lag of late dry spells and fertilizer subsidy. Area share under DT maize has a positive and significant relationship with early longest dry spell and two-year and three-year lag of late dry spells but is negatively correlated with seed subsidy access.

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[4] We failed to reject exogeneity of seed subsidy and fertilizer subsidy variables for adoption model hence we re-estimated the model excluding residuals.

This positive impact of early dry spells can be explained by the fact that early drought acts as a warning to farmers for a potential drought season such that farmers are more likely to increase area share under maize varieties that are drought tolerant. Another possible explanation is that early drought signifies a short rainy season, such that the previous exposure increases the likelihood of adopting early maturing maize varieties to fit into the growing season as Malawi has a unimodal type of rainy season. Although other hybrids are also early maturing, the 2012 experience shows that most farmers opt for DT early maturing maize varieties (Holden and Fisher, 2015) such as SC403 (*Kanyani*) which matures within 90 days after planting. Such varieties are not only drought tolerant but also suitable for replanting after an early drought.

For late droughts, the positive impact of two-year and three-year lags suggest that farmers respond to previous late drought by adopting technologies that hedge against resulting yield losses. These results suggest that farmers are influenced by previous exposure to droughts. The most important advantage of DT maize is its performance over other maize varieties under rainfall stress before and during the flowering period for maize, as reported by Magorokosho et al. (2009). If farmers' experience is in line with this, then more adoption will follow in years after early droughts where DT and other maize varieties were planted and their relative performance could be assessed. However, the negative impact of one-year lag of late dry spells on DT area is unexpected and not easily explained.

The findings overall suggest that the more severe (longer) the dry spells, the more the farmers become aware of the risks associated and hence a need to adopt DT seed. These results are consistent with our expectations and the findings of Holden and Fisher (2015) and Holden and Quiggin (2017a) that farmers who previously were exposed to drought are more likely to adopt DT maize as an adaptive mechanism. Ding et al. (2009) also reported that farmers' experience with drought increases their likelihood of adopting risk reducing agricultural systems such as conservation tillage. Our results however, have specifically shown how early and late dry spells affect adoption and adoption intensity, a component not addressed by either Holden and Fisher (2015) or Holden and Quiggin (2017a).

Access to seed subsidy is positive and significant in adoption and area models (consistent with Holden and Fisher, 2015) but negative in the area share model. On the other hand, fertilizer subsidy is negative on adoption and area but positive though insignificant on area share under DT maize varieties. The negative impact of seed subsidy on area share could be related to the small quantities of subsidized maize seed (2-kg bag of hybrid seed or 4-kg bag of OPV seed (Ricker-Gilbert and Jones, 2015)). Such quantities are too small to allow a significant increase on area share under DT maize varieties.

Table 7: Factors affecting adoption and adoption intensity of DT maize varieties

Variables	**DT adoption (Probit)**	**DT area (Tobit)**	**DT area share (Fractional Probit)**
Longest early dry spell (days)	*0.03*	*0.00*	*0.02***
	(0.02)	*(0.01)*	*(0.01)*
1-year lag longest early dry spell (days)	0.03	0.02**	-0.01
	(0.02)	*(0.01)*	*(0.01)*
2-years lag longest early dry spell (days)	0.05**	0.03***	0.00
	(0.02)	*(0.01)*	*(0.00)*
1-year lag longest late dry spell (days)	0.01	-0.03**	0.00
	(0.01)	*(0.01)*	*(0.00)*
2-years lag longest late dry spell (days)	0.03	0.02*	0.04***
	(0.02)	*(0.01)*	*(0.01)*
3-years lag longest late dry spell (days)	0.02	0.02**	0.02***
	(0.02)	*(0.01)*	*(0.01)*
3-years lag average rainfall (mm)	-0.13**	0.11*	-0.02
	(0.06)	*(0.06)*	*(0.04)*
Seed subsidy, dummy	0.56***	0.25***	-0.48**
	(0.12)	*(0.05)*	*(0.20)*
Fertilizer subsidy, dummy	-0.16	-0.51***	0.29
	(0.12)	*(0.19)*	*(0.19)*
Distance to agricultural markets (Km)	0.00	0.02	-0.01
	(0.02)	*(0.02)*	*(0.01)*
Fertilizer price (MK)	-0.00**	-0.00**	0.00
	(0.00)	*(0.00)*	*(0.00)*
Year 2009, dummy	1.65***	0.56***	0.29***
	(0.19)	*(0.08)*	*(0.07)*
Year 2012, dummy	1.95***	1.04***	0.44***
	(0.20)	*(0.19)*	*(0.09)*
Year 2015, dummy	2.12***	0.92***	0.56***
	(0.22)	*(0.13)*	*(0.12)*
Error from seed subsidy		0.43**	-0.33*
		(0.19)	*(0.19)*

Error from fertilizer subsidy			0.55*** *(0.20)*
Constant	-3.10*** *(0.59)*	-2.18*** *(0.59)*	-0.80*** *(0.23)*
Prob > chi2	0.000	0.000	0.000
Rho	0.08	0.000	
Observations	1506	1506	1505

Notes: Significance levels *10%, **5%, ***1%, ****0.1%. Standard errors are bootstrapped with 400 replications, resampling households. The mean and deviation of household and farm characteristics are included in this MC framework but are left out of the table to save space. The full table can be accessed through the appendix.

Conclusion and Policy Implications

Weather extremes, especially recurrent droughts, threaten agricultural productivity and food security in many countries especially in sub-Saharan Africa whose population largely depends on agriculture and maize for food. Drought tolerant maize is one promising technology to minimize the impact of droughts. Several drought tolerant maize varieties have been developed by national research institutions in collaboration with international research institutions such as CIMMYT and have been distributed across the countries. Examining determinants of adoption and adoption intensity of this promising technology is becoming increasingly important. Following Holden and Fisher (2015), Fisher et al. (2015) and Holden and Quiggin (2017a), we use a Mundlak-Chamberlain device with a Control Function approach to understand adoption of DT maize varieties in Malawi under rainfall stress.

We combine data from farm households in six districts collected in three-year intervals between 2006 and 2015 with experience of previous dry spells computed from daily rainfall data from 2003 to 2015. We include lagged early and late season drought variables in the panel data analysis to assess how adoption and adoption intensity is affected by drought exposure experience. We define adoption intensity in terms of maize area (ha) allocated to DT maize varieties and area share under DT maize. DT maize is known by scientists to perform better than other maize varieties under late drought conditions but not necessarily under early drought conditions, except that DT maize varieties are early maturing. We also extend the Holden and Quiggin (2017a) analysis by examining how recent droughts affect distribution of DT seed under FISP and how choice of DT seed is conditioned by access to seed subsidy.

Adoption has increased from 3% in 2006 to 43% in 2015, DT maize area per household has increased from 0.02ha in 2006 to 0.17ha in 2015, with an increase in area share under DT maize varieties from 2% in 2006 to 18% in 2015. We find positive impacts of the late season droughts on the probability of DT seed being used under the seed subsidy programme. Farmers previously exposed to late season dry spells are more likely to redeem DT maize seed varieties using the seed subsidy coupon. We also find positive correlations between the likelihood of adoption of DT maize seed and two-year lagged longest early dry spells and also seed subsidy access. Areas under DT maize are positively influenced by one-year and two-year lag of early season longest dry spells, two-year and three-year lag of longest late season dry spells and seed subsidy, but there is an unexpected and unexplained negative effect of one-year lag of late season droughts and fertilizer subsidy. We also find positive correlations between area share under DT maize and early season longest dry spell, two-year and three-year lag of late season dry spells, though, again unexpectedly, a negative correlation with seed subsidy access.

Our results suggest that farmers respond to occurrence of early dry spells in current and previous seasons and exposure to previous late dry spells by adopting technologies that can minimize drought-related yield losses. Early droughts may signal a short rainy season, hence farmers are more likely to adopt early maturing varieties of which some are drought tolerant. Farmers' response to late droughts suggest that they are aware of the negative effects of late droughts and one way of hedging against such risks is by adopting drought tolerant maize varieties. Finally, the positive impact of seed subsidy on likelihood of adoption and area under DT maize is consistent with previous studies (e.g. Holden and Fisher, 2015) that FISP is a strong driver of DT maize adoption in Malawi. However the negative impact of seed subsidy on area share may reflect the small quantities of seed eligible for subsidy, suggesting that increasing the quantities of maize seed eligible for subsidy could significantly increase the area share allocated to DT maize seed.

Our paper has generated new evidence that previous early droughts affect adoption by increasing farmers' adaptive expectations with respect to duration of the rainy season. Farmers previously affected by early droughts are more likely to adopt early maturing DT maize varieties. On the other hand, previous late droughts affect adoption through risk aversion as farmers adopt technologies that hedge against late drought risks. In a country facing persistent weather shocks, mainly droughts and floods coupled with missing or poor markets for weather insurance and credit, these findings are of great importance to enhance agricultural productivity. Farmers' adoption of drought tolerant maize, a drought risk-substituting technology is an indication that farmers in drought-prone regions in SSA countries are more willing to adopt a drought-resilient technology. As discussed in the conceptual framework, late drought risks increases adoption of risk-substituting technologies such as DT maize varieties at the expense of other hybrids and local maize.

The understanding that farmers respond to exposure to weather shocks is an important observation not only for Malawi but other countries in the SSA region for the promotion of climate risk reducing technologies. Promotion of technologies that are perceived by farmers themselves as climate-smart based on their experience are more likely to receive high adoption rates and make an impact on general household livelihood conditions. As the Government of Malawi is promoting adoption of climate-smart agriculture (CSA) technologies (Government of Malawi, 2016), extension messages should emphasize drought tolerant maize seed as a key component in the CSA campaign, with extension and promotion messages on the significance of DT maize under drought. Ensuring availability and affordability of the DT seed should continue being the priority strategy for the Government of Malawi. The government should make deliberate efforts to distribute more DT maize seed varieties in areas previously and frequently exposed to drought shocks, and consider increasing seed subsidy quantities from the current 2 – 4 Kgs. However since adoption outside FISP is low and this may present a sustainability problem, the agricultural extension service should do more to enhance awareness of DT maize seed so that farmers can continue using it even after FISP.

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Appendix 1: Factors affecting access to seed and fertilizer subsidy coupons and use of DT seed conditional of seed subsidy access

Variables	**Seed subsidy coupon**	**Fertilizer subsidy coupon**	**Redeemed DT seed conditional on seed subsidy access**
Longest early dry spell (days)	*0.04***	*0.01*	*0.05*
	(0.02)	*(0.02)*	*(0.03)*
1-year lag longest early dry spell (days)	0.00	0.05***	0.05*
	(0.02)	*(0.02)*	*(0.03)*
2-years lag longest early dry spell (days)	-0.01	0.01	0.04
	(0.02)	*(0.02)*	*(0.03)*
1-year lag longest late dry spell (days)	-0.03**	-0.05****	0.01
	(0.01)	*(0.01)*	*(0.02)*
2-years lag longest late dry spell (days)	0.08****	0.03	0.09***
	(0.02)	*(0.02)*	*(0.03)*
3-years lag longest late dry spell (days)	0.05****	0.03**	0.03
	(0.01)	*(0.01)*	*(0.02)*
3-years lag average rainfall (mm)	0.11**	0.28****	-0.20**
	(0.05)	*(0.05)*	*(0.08)*
Distance to agricultural markets (Km)	0.03	0.06***	0.00
	(0.02)	*(0.02)*	*(0.03)*
Fertilizer price (MK)	-0.00****	-0.00****	-0.00**
	(0.00)	*(0.00)*	*(0.00)*
Year 2009, dummy	0.27**	-0.02	1.83****
	(0.14)	*(0.13)*	*(0.32)*
Year 2012, dummy	1.14****	1.00****	2.08****
	(0.14)	*(0.15)*	*(0.31)*
Year 2015, dummy	1.05****	0.61***	2.03****
	(0.18)	*(0.19)*	*(0.34)*
Ruling party member of parliament	0.24**	0.29**	
	(0.12)	*(0.12)*	
Number of children in a household	-0.05	-0.01	
	(0.05)	*(0.05)*	
Deviations from mean of household and farm characteristics			
Sex of household head (1=female)	0.04	0.05	-0.17
	(0.10)	*(0.11)*	*(0.15)*
Age of household head (years)	0.00	0.00	-0.01
	(0.00)	*(0.00)*	*(0.01)*

Education of household head (years)	-0.01	0.00	0.02
	(0.01)	*(0.01)*	*(0.02)*
Household size	-0.01	-0.02	0.01
	(0.05)	*(0.05)*	*(0.05)*
Male household labour (adult equivalent/ha)	-0.02	0.00	-0.01
	(0.04)	*(0.04)*	*(0.07)*
Female household labour (adult equivalent/ha)	0.03	0.00	-0.03
	(0.04)	*(0.04)*	*(0.07)*
Off-farm labour (adult equivalent/ha)	0.15	0.21	-0.03
	(0.14)	*(0.15)*	*(0.20)*
Asset value (MK)	0.00	-0.00*	0.00
	(0.00)	*(0.00)*	*(0.00)*
TLU	0.03	0.03	-0.02
	(0.02)	*(0.02)*	*(0.03)*
Farm size (ha)	0.03	0.08**	0.00
	(0.03)	*(0.03)*	*(0.03)*
Number of plots	0.03	0.05	0.10*
	(0.03)	*(0.04)*	*(0.05)*
Mean of household and farm characteristics			
Sex of household head (1=female)	-0.02	-0.23	-0.05
	(0.15)	*(0.16)*	*(0.24)*
Age of household head (years)	0.00	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*
Education of household head (years)	0.02**	0.01	0.01
	(0.01)	*(0.01)*	*(0.02)*
Household size	0.10**	0.07	0.06
	(0.05)	*(0.05)*	*(0.04)*
Male household labour (adult equivalent/ha)	0.05	0.07	0.00
	(0.05)	*(0.06)*	*(0.10)*
Female household labour (adult equivalent/ha)	-0.08	-0.09	-0.02
	(0.06)	*(0.06)*	*(0.11)*
Off-farm labour (adult equivalent/ha)	0.20	0.41**	0.06
	(0.17)	*(0.18)*	*(0.26)*
Asset value (MK)	0.00	-0.00*	0.00
	(0.00)	*(0.00)*	*(0.00)*
TLU	0.02	-0.04	-0.01
	(0.03)	*(0.03)*	*(0.05)*
Farm size (ha)	-0.45**	-0.36	-0.18
	(0.22)	*(0.22)*	*(0.35)*
Number of plots	0.02	0.08**	0.05
	(0.04)	*(0.04)*	*(0.06)*
Constant	-2.98****	-2.65****	-3.44****
	(0.51)	*(0.55)*	*(0.86)*
Prob > chi2	0.000	0.000	0.000

Rho	0.06	0.11	0.04
Observations	1506	1506	641

Notes: Significance levels *10%, **5%, ***1%, ****0.1%.

Appendix 2: Factors affecting adoption and adoption intensity of DT maize varieties

Variables	**DT adoption (Probit)**	**DT area (Tobit)**	**DT area share (Fractional Probit)**
Longest early dry spell (days)	*0.03*	*0.00*	*0.02***
	(0.02)	*(0.01)*	*(0.01)*
1-year lag longest early dry spell (days)	0.03	0.02**	-0.01
	(0.02)	*(0.01)*	*(0.01)*
2-years lag longest early dry spell (days)	0.05**	0.03***	0.00
	(0.02)	*(0.01)*	*(0.00)*
1-year lag longest late dry spell (days)	0.01	-0.03**	0.00
	(0.01)	*(0.01)*	*(0.00)*
2-years lag longest late dry spell (days)	0.03	0.02*	0.04***
	(0.02)	*(0.01)*	*(0.01)*
3-years lag longest late dry spell (days)	0.02	0.02**	0.02***
	(0.02)	*(0.01)*	*(0.01)*
3-years lag average rainfall (mm)	-0.13**	0.11*	-0.02
	(0.06)	*(0.06)*	*(0.04)*
Seed subsidy, dummy	0.56***	0.25***	-0.48**
	(0.12)	*(0.05)*	*(0.20)*
Fertilizer subsidy, dummy	-0.16	-0.51***	0.29
	(0.12)	*(0.19)*	*(0.19)*
Distance to agricultural markets (Km)	0.00	0.02	-0.01
	(0.02)	*(0.02)*	*(0.01)*
Fertilizer price (MK)	-0.00**	-0.00**	0.00
	(0.00)	*(0.00)*	*(0.00)*
Year 2009, dummy	1.65***	0.56***	0.29***
	(0.19)	*(0.08)*	*(0.07)*
Year 2012, dummy	1.95***	1.04***	0.44***
	(0.20)	*(0.19)*	*(0.09)*
Year 2015, dummy	2.12***	0.92***	0.56***
	(0.22)	*(0.13)*	*(0.12)*
Error from seed subsidy		0.43**	-0.33*
		(0.19)	*(0.19)*
Error from fertilizer subsidy			0.55***
			(0.20)
Deviations from mean of household and farm characteristics			
Sex of household head (1=female)	-0.29***	-0.07	-0.04**
	(0.11)	*(0.05)*	*(0.02)*
Age of household head (years)	0.00	0.00	0.00

	(0.00)	*(0.00)*	*(0.00)*
Education of household head (years)	0.01	0.01	0.00
	(0.02)	*(0.01)*	*(0.00)*
Household size	0.05	0.00	-0.02**
	(0.03)	*(0.02)*	*(0.01)*
Male household labour (adult equivalent/ha)	-0.01	0.00	-0.02**
	(0.05)	*(0.02)*	*(0.01)*
Female household labour (adult equivalent/ha)	-0.03	-0.01	0.02**
	(0.05)	*(0.02)*	*(0.01)*
Off-farm labour (adult equivalent/ha)	0.14	0.13*	0.03
	(0.15)	*(0.07)*	*(0.03)*
Asset value (MK)	0.00	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*
TLU	-0.02	0.00	0.00
	(0.02)	*(0.01)*	*(0.00)*
Farm size (ha)	0.00	0.03	-0.01
	(0.02)	*(0.02)*	*(0.01)*
Number of plots	0.07*	0.07***	-0.01*
	(0.04)	*(0.01)*	*(0.01)*
Mean of household and farm characteristics			
Sex of household head (1=female)	-0.17	-0.19***	0.03
	(0.18)	*(0.07)*	*(0.04)*
Age of household head (years)	0.00	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*
Education of household head (years)	0.00	0.00	0.01**
	(0.01)	*(0.00)*	*(0.00)*
Household size	0.09***	0.08***	0.03***
	(0.03)	*(0.02)*	*(0.01)*
Male household labour (adult equivalent/ha)	0.02	0.02	0.00
	(0.07)	*(0.03)*	*(0.01)*
Female household labour (adult equivalent/ha)	-0.04	-0.05	-0.01*
	(0.08)	*(0.03)*	*(0.01)*
Off-farm labour (adult equivalent/ha)	0.21	0.30***	0.00
	(0.19)	*(0.11)*	*(0.05)*
Asset value (MK)	0.00	0.00	0.00
	(0.00)	*(0.00)*	*(0.00)*
TLU	0.01	-0.03*	0.02*
	(0.04)	*(0.02)*	*(0.01)*
Farm size (ha)	-0.32	-0.22	-0.15***
	(0.27)	*(0.14)*	*(0.05)*
Number of plots	-0.02	0.04*	-0.04***
	(0.04)	*(0.02)*	*(0.01)*
Constant	-3.10***	-2.18***	-0.80***
	(0.59)	*(0.59)*	*(0.23)*

Prob > chi2	0.000	0.000	0.000
Rho	0.08	0.000	
Observations	1506	1506	1505

Notes: Significance levels *10%, **5%, ***1%, ****0.1%. Standard errors are bootstrapped with 400 replications, resampling households.

Paper three

Productivity impact of drought tolerant maize varieties under rainfall stress in Malawi: A continuous treatment approach

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Abstract

Drought tolerant (DT) maize varieties have received massive support in sub-Saharan Africa because of their potential to protect smallholder farmers against drought-related maize yield losses. Using four-waves of panel data from six districts in Central and Southern Malawi, we examined the impact heterogeneity of this technology on maize productivity using a continuous treatment approach. We found strong evidence of positive correlation between maize yield and adoption of DT maize varieties. Maize yield increased from 371 Kg/ha at 5% level of DT maize adoption to 1000 Kg/ha at 52% adoption level. On average, a one hectare increase in the area allocated to DT maize varieties increased maize yield by 510 Kg/ha representing a 41% increase from the average maize yield of 1254 Kg/ha for our sample. The marginal treatment effect showed that the changes on the effect of DT maize adoption on maize yield decreased with the increase in level of adoption at lower adoption levels but increased with the increase in level of adoption at higher adoption levels. Our findings give evidence that DT maize technology has potential to protect smallholder farmers against drought-related production losses. Policies that promote increased allocation of maize area to DT maize varieties hold potential to enhance food security.

Key words: Dose response function, drought tolerant, maize, productivity, rainfall stress

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1. Introduction

Maize is a single most important food crop in Malawi whose availability equates to food security (Smale, 1993). Annual consumption per capita is one of the highest in Africa estimated at 129 kilograms and makes approximately 90% and 54% of total cereals and caloric per capita intake, respectively (Derlagen, 2012). Production takes over 90% of productive land under cereals and is dominated by smallholder farmers where nearly 97% of them grow maize (Denning *et al.*, 2009). The crop is heavily dependent on rain-fed during a single rainy season which covers at least four months from November/December to March (Nicholson *et al.*, 2014), and therefore greatly affected by the country's erratic and unpredictable rainfall (Jayne & Rashid, 2013; Kassie *et al.*, 2015b). The rainfall uncertainty in frequency and distribution coupled with frequent dry spells reduces maize productivity by more than half and hence exacerbates the country's food insecurity problems (CIMMYT, 2013).

In a country characterized by poor and/or missing markets for credits, insurance and off-farm participation, investing in agricultural technologies that reduce vulnerability and risks of yield loss due to weather related shocks is a more realistic option (Davies *et al.*, 2009; Pangapanga *et al.*, 2012; Kassie *et al.*, 2015a). Drought tolerant (DT) maize variety is one potential technology that has been developed to help smallholder farmers cope with drought and drought-related constraints. It is estimated that DT maize can produce up to 30% of their potential yield after six weeks of water stress, before and during flowering and grain-filling (Magorokosho *et al.*, 2009). On-farm field experiments conducted across several countries in Southern Africa indicate that DT maize varieties can give a yield advantage of up to 40% over other maize varieties under severe drought environments (Tesfaye *et al.*, 2016). It is also projected that full adoption of DT maize varieties can result in both production and economic gains with significant number of producers and consumers out of poverty (La Rovere *et al.*, 2014).

Given potential relevance of this technology to Malawi and several countries in sub-Saharan Africa (SSA), empirical evidence beyond ex ante analysis, and on-farm and on-station experiments is of particular importance. This paper adds to the body of literature by examining the impact of DT maize varieties on maize productivity in Malawi. This analysis is necessary because the increase of dry spells in the region is one of the major causes of low maize production and productivity besides low levels of nitrogen intake and soil depletion (Weber *et al.*, 2012). Investment in appropriate technologies with hedging effect against dry spells has potential to increase yield or reduce yield loss. Thierfelder *et al.* (2017) for example reported that investment in conservation agriculture has a yield impact of 38-66% when a drought occurs while Arndt *et al.* (2015) reported double dividends of improved yield and drought tolerance when DT maize seed is included in Farm Input Subsidy Programme (FISP) in Malawi.

There have been some studies on this subject across countries in SSA and the results are mixed. Holden and Fisher (2015) and Fekadu and Endeshaw (2016) for example, found insignificant yield advantage of DT maize over other improved maize varieties but local maize in Malawi and Uganda respectively. On the other hand, other authors show positive impact of DT maize on maize production, yield and food security over other varieties. Cenacchi and Koo (2011) reported positive impact of DT maize adoption on yields across all agro-ecological zones in several countries in SSA. Idrisa *et al.* (2014), Radda (2015) and Awotide *et al.* (2016) observed that adoption of DT maize significantly reduced food insecurity, increased crop yield and household welfare among farmers in Nigeria. In Zimbabwe, Makate *et al.* (2017) and Lunduka *et al.* (2017) reported that adoption of DT maize significantly enhanced overall maize productivity and consequently market surplus and household consumption. We attribute this inconsistency to different estimation techniques and to use of cross sectional data that does not fully capture heterogeneity effects and variability of rainfall. DT may not have yield advantage over other improved maize varieties under normal rainfall conditions and this may lead to underestimation of the impact.

We address this inconsistence in this paper and make novel contribution to the body of literature in two main ways. Firstly, our paper uses panel data to examine the impact of DT maize on maize yield. To the best of our knowledge, the reviewed studies have used cross-sectional data that fails to capture unobserved heterogeneity. Our data spans nine years from 2006 to 2015 and is of interest to this particular study as it captures three different rainfall scenarios, namely, normal-to-average rainfall in 2006 and 2009, early droughts in 2012, and early floods with late droughts in 2015. Secondary, we apply a continuous treatment approach (Cerulli, 2015), unlike the studies reviewed that have used binary treatment variable. The continuous treatment method allows assessment of dose response function (DRF) and marginal treatment function (MTF) across different DT maize adoption levels. The DRF is synonymous to average treatment effect on the treated (ATET) while the MTF is equivalent to marginal treatment effect on the treated (MTET). The dose in our case captures the intensity of DT maize adoption in terms of acreage of land in hectares (ha) planted with DT maize varieties while the response refers to the maize productivity.

1.1. DT maize varieties in sub-Saharan Africa

Drought tolerant maize seed has been a vital component in breeding programs since late 1990s across countries particularly in SSA because of recurrent droughts (Bänziger *et al.*, 2004). In mid 2000s, the International Maize and Wheat Improvement Centre (CIMMYT) and the International Institute of Tropical Agriculture (IITA) launched a Drought Tolerant Maize for Africa (DTMA) project to support development and dissemination of DT maize varieties in SSA. Since then over 200 DT maize varieties have been released across 13 DTMA countries (Angola, Benin, Ethiopia, Ghana, Kenya, Malawi, Mali, Mozambique, Nigeria, Tanzania, Uganda, Zambia and Zimbabwe) reaching over 43 million smallholder farmers (Wawa, 2016b, unpublished report by CIMMYT). The DTMA project was jointly implemented among National Agricultural Research systems (NARS) by CIMMYT and IITA and concluded in December 2015 (Wawa, 2016a, unpublished report by CIMMYT).

In Malawi, DT maize has received enormous support from the government, private and other public institutions where among other avenues, the seed has been an integral component in the Farm Input Subsidy Programme (FISP). FISP effectively enhances availability and affordability of the seed (Holden & Fisher, 2015). As of December 2015, 18 DT maize varieties (15 hybrids and three open pollinated varieties) were released under the DTMA project (Abate, 2015). Adoption has since been increasing over the years (Fisher *et al.*, 2015; Holden & Fisher, 2015; Holden & Quiggin, 2017; Katengeza *et al.*, 2017). In addition to the FISP, exposure to recurrent droughts has been another important factor driving adoption. This could be related to the varieties' better performance under rainfall stress assuming farmers are able to observe and compare yield of different maize varieties under drought growth conditions.

2. Conceptual Framework, Empirical Model and Estimation Strategy

2.1. Conceptual framework

Production under uncertainty where different states of nature are possible but not known to the producer at planting time, can be presented as a state-contingent production framework (Chambers & Quiggin, 2000; Quiggin & Chambers, 2006). The state-contingent model assumes x different inputs, s possible states of nature and y distinct outputs. Input $x \in \Re_{+}^{X}$ allocation decision and the choice for a state contingent output $y \in \Re_{+}^{S*Y}$ are made ex ante (that is before the state of nature is revealed). Inputs are then fixed and output produced ex post (Quiggin & Chambers, 2006). The technology can then be summarized as $T = [(x, y){:}\, x\ can\ produce\ y]$. Given output price ($p_y$) and input price ($p_x$), the technology can be expressed as a cost function $C\left(p_{x,}y\right) = min[p_x x|(x, y)\ \in\ T]$ or as a demand function $x\left(p_{x,}y\right) = argmin[p_x x|(x, y) \in T]$.

Assuming two states of nature (s_1 & s_2) of which state one (s_1) is unfavorable, the farmer's interest is to maximize output (y). The farmer's problem is choice under uncertainty whereby s_1 is unfavorable if and only if $y_1 < y_2$. In this case, a farmer can decide to adopt more risk-substituting or risk-complementary inputs. Holden and Quiggin (2017) noted that an increase in probability of s_1 will lead to an increase in adoption of risk-substituting inputs for a given expected output. In the context of this paper, farmers in Malawi are more likely to adopt risk-substituting maize varieties in order to adapt to frequent dry spells. An input x_j is a risk-substituting (complementary) at y^0 (state-contingent output) if $y^0 \preccurlyeq y' \Rightarrow x_j(p_x, y') \geq x_j(p_x, y^0)$ $(x_j(p_x, y') \leq x_j(p_x, y^0))$ where y' is a riskier output. This implies that for a given expected output, less risk-averse producers will choose more risky state-contingent output plan while more risk-averse producers will use more risk-substituting than risk-complementary inputs (Chambers & Quiggin, 2000).

Given that the farmer's objective is to maximize expected utility [EU(.)] from output y, the adoption decision of alternative inputs can be modelled as an optimal land allocation problem (Ding *et al.*, 2009). If we assume p_x and p_y are non-random and that smallholder farmers are price takers, the only source of uncertainty is climatic risks. An individual farmer will allocate a mix of inputs (X) to maximize expected utility from output (y). We can therefore specify the farmer's optimal land allocation problem as $\underset{X}{Max}\, E[U(\pi)] = Max\ EU[p_y y - p_X(X)]$. Thus, farmers will adopt DT maize variety if and only if $[EU(\pi_1^{DT})] > [\mathrm{EU}(\pi_1^{nonDT})]$. Our interest in this paper is to examine whether maize yield under drought stress (y_1) is greater for DT maize adopters than those who grew other maize varieties such as other improved non-DT maize (OIM) and local maize (LM) varieties. If yield for DT maize is higher than other maize varieties under rainfall stress growth conditions, then DT maize variety is a risk-substituting technology, otherwise it is risk-complementary. Given that the majority of smallholder farmers in Malawi adopts a portfolio of maize varieties due to differences in consumption, drought tolerance and production traits (Lunduka *et al.*, 2012), we are more interested in the level of adoption as opposed to whether one adopts DT maize or not. We therefore adopts the dose response function (DRF) (Cerulli, 2015) to examine the impact of DT maize varieties on maize yield.

2.2. Empirical model specification

We examine the impact of DT maize varieties on maize productivity using the dose-response function (DRF) following the approach by Cerulli (2015). We follow other authors such as Kassie *et al.* (2014) who used a continuous treatment approach to evaluate the impact of improved maize varieties on food security in Tanzania. Shiferaw *et al.* (2014) also adopted the continuous treatment approach to asses the impact of improved wheat varieties on household food security in Ethiopia. In this approach, we consider the fact that in some instances what is important is not just whether one adopts a given technology or not but also the level (or dose) of adoption. Once farmers adopt a given technology, they differ in the intensity of adoption. The DRF therefore, enables assessment of the impact heterogeneity of adoption. In our study, we expect both spatial and temporal variations in the level of adoption of DT maize varieties such that using intensity of adoption as a treatment variable, increases precision of results than just relying on binary treatment.

In impact literature the DRF is equivalent to average treatment effect (ATE) given the level of treatment (t), where (t) is the continuous treatment variable. The dose (or treatment) in our case is the level of DT maize adoption measured in hectares of land under DT maize varieties while the response is the maize yield measured in kilograms per hectare (Kg/ha). The DRF represents the conditional expectation of maize yield variations given confounding variables. The derivative of the DRF stands for the Marginal Treatment Effect (MTE), which illustrates how the effects of DT maize on maize yield change as the intensity of DT maize use increases.

Let the level of treatment (t) range from zero to 100 where non-adopters of DT maize varieties take the value of zero while adopters take values greater than zero. Our interest is to examine the causal effect of treatment (t) on maize productivity (y) assuming adopters and non-adopters respond differently to both treatment and confounding factors (x). We are interested in estimating the DRF of y on t, where t is endogenous. The approach allows endogenous treatment variable by applying instrumental variable (IV) estimation and allows assessment of heterogeneity of impact.

Given these notations, let y_{1i} and y_{0i} be outcome variable (maize productivity) for individual i with treatment (w_1) and without treatment (w_0), respectively, where $i = 1, \dots, N$. N is the total number of households where N_1 are adopters and N_0 are non-adopters of DT maize varieties. We define $x = x_1, x_2, x_3, \dots, x_m$ as a vector of M exogenous observable characteristics, $g_1(x)$ & $g_0(x)$ as response functions associated with and without DT adoption respectively and assume μ_1 and μ_0 as two scalars, and e_1 and e_0 as two random variables with zero unconditional mean and constant variance. The treatment (t) takes the continuous values in the range [0,100] and we define $h(x)$ as the intrinsic response of a given level of treatment (t). The outcome equations for a given population is then expressed as:

$$\begin{cases} w = 1: & y_1 = \mu_1 + g_1(x) + h(t) + e_1 \\ w = 0: & y_0 = \mu_0 + g_0(x) + e_0 \end{cases} \tag{1}$$

The x variables included in the model include productive inputs, household and plot characteristics and rainfall stress variables. Productive inputs include fertilizer use (Kg/ha – natural log), farm size (ha – natural log), organic manure (Kg/ha – natural log) and male and female family labour (adult equivalent/ha – natural log). We also include dummies for local maize varieties and access to seed and fertilizer subsidy. Household characteristics include age (years), sex and education (years) of household head, household size (number of persons) and off-farm labour (adult equivalent/ha – natural log). At plot-level we control for observable farm plot characteristics such as plot size (ha – natural log), number of plots, plot distance (Km), soil type, slope and soil fertility as reported by the farmer. The rainfall stress variables are longest early and late dry spells (days) and December average rainfall (mm). Other variables included are average distance to agricultural input markets (Km) and year-specific and district-specific dummies. We also include averages of time-varying variables in order to control for unobserved heterogeneity in our model.

From equation (1) we can then define the treatment effect (TE) as $TE = (y_1 - y_0)$. Assuming a linear-in-parameters parametric form for $g_0(x) = x\delta_0$ and for $g_1(x) = x\delta_1$, we can state Average Treatment Effect (ATE) conditional on x and t as:

$$ATE(x,t,w) = w * [\mu + x\delta_1 + h(t)] + (1-w) * [\mu + x\delta_0] \tag{2}$$

where $\mu = \mu_1 - \mu_0$ and $\delta = \delta_1 - \delta_0$.

To estimate the ATE, we can use the following regression approach:

$$y_i = \mu_0 + w_i * ATE + x_i\delta_0 + w_i * (x_i - \bar{x})\delta_1 + w_i[h(t_i) - \bar{h}] + \eta_i \tag{3}$$

where $\eta_i = e_{0i} + w_i * (e_{1i} - e_{0i})$

Equation (3) is necessary for estimating the parameters of interest $(\mu_0, \mu_1, \delta_0, \delta_1, ATE)$. However estimation of equation (3) to identify ATEs and DRF in our context requires that the assumption of unconfoundedness or conditional mean independence (CMI) is met. CMI means that:

$$E(y_{ji}|w_i, t_i, x_i) = E(y_{ji}|x_i) \quad with \quad j = [0,1] \tag{4}$$

This CMI assumption may not hold in our context because the treatment (DT maize adoption) is endogenous due to non-random self-selection into adoption. We therefore, restate equation (3) as follows:

$$\begin{cases} y_i = \mu_0 + x_i\delta_0 + w_iATE + w_i(x_i - \bar{x})\delta_1 + aw_iT_{1i} + bw_iT_{2i} + cw_iT_{3i} + \eta_i & (4.1) \\ w_i^* = x_{w,\,i}\beta_w + \epsilon_{w,i} & (4.2) \\ t_i' = x_{t,\,i}\beta_t + \epsilon_{t,i} & (4.3) \end{cases}$$

where $T_{1i} = t_i - \mathrm{E}(t_i)$, $T_{2i} = t_{2i} - \mathrm{E}(t_{2i})$, and $T_{3i} = t_{3i} - \mathrm{E}(t_{3i})$. w_i^* is the latent treatment variable; t_i is fully observed only when $w_i = 1$ (and $t_i = t_i^*$); $x_{w,i}$ and $x_{t,i}$ are two sets of exogenous regressors explaining treatment while $\epsilon_{w,i}$, $\epsilon_{t,i}$, and η_i are error terms and are correlated with one another with zero unconditional mean. Equation (4.2) is the selection equation, which defines the regression explaining the treatment indicator w^* with the vector of covariates $x_{w,i}$ used to set treated and untreated groups. Equation 8.3 is the treatment-level equation that defines how the level of DT maize adoption is decided, and it only considers eligible treated units. The treatment level is determined by the vector of covariates $x_{t,i}$.

The terms w_i, T_{1i}, T_{2i} and T_{3i} are endogenous and the latter three are functions of the endogenous t. Having two endogenous variables ($w_i^*$and t_i^*) would therefore require at least two IVs ($z_{w,i}\ and z_{t,i}$) to identify equations (4.1-4.3). These should be correlated with $w_i^*$and t_i^* but not with y_i to satisfy exclusion restriction and uncorrelated with $\epsilon_{w,i}$, $\epsilon_{t,i}$ and η_i for exogeneity to hold. In our case we identify the IV that is correlated with w_i^*as distance to agricultural markets while we take variables distance to agricultural markets, asset value and tropical livestock unit (TLU) as IVs correlated with t_i^*. The choice of these instruments is based on economic theory. We assume distance to agricultural markets as a supply factor that can enhance access to DT seed and hence adoption but is not directly correlated to maize yield. Asset value and TLU are wealthy indicators that can also enhance adoption and intensity of adoption of DT maize varieties but are not directly related to maize yield. While TLU can influence yield through animal traction, such cases are very rare among smallholder farmers in Malawi as production labour is almost 100% hand hoe.

2.3. Estimation strategy

Equations 4.2 and 4.3 are jointly estimated by the type-2 tobit model using a Heckman two-step procedure. The first step of this procedure involves a probit estimation of w_i^* on $x_{w,i}$ using only N_1 observations. The second step is the ordinary least squares (OLS) of t_i^* on $x_{t,i}$ utilizing the Mill's ratio from the first step and using all N observations. Having jointly estimated 4.2 and 4.3, we obtain the predicted values of $w_i\ and\ t_i$ from the previous type-2 tobit estimation. We then perform a two-stage least squares (2SLS) to get consistent estimation of the basic parameters ($\mu_0, \delta_0, ATE, \delta_1, a, b\ and\ c$) in 4.1. Once the basic coefficients are consistently estimated, the causal parameters of interest (ATEs and DRF) are consistently estimated using the OLS.

2.4. Data and descriptive statistics

The data in this paper comes from household panel surveys from six districts in Malawi, namely, Chiradzulu, Kasungu, Lilongwe, Machinga, Thyolo and Zomba. The districts are located in different agro-ecological zones and receive different amounts of rainfall. Machinga and Zomba for example are partly located in a drought prone zone (World Bank, 2010; Mangisoni et al., 2011; Katengeza et al., 2012) while Thyolo lies in the high plateau and hilly areas (Bunda College, 2008). The first round of the survey took place in 2006 where an initial sample of 450 households was drawn using a simple random sampling technique following the 2004 Integrated Household Survey Two (IHS2) (Lunduka, 2009). Data collection used a semi-structured questionnaire on household and plot level characteristics with detailed plot-level information that include area measurements using the Global Positioning System (GPS). In 2009, 378 of the households were resurveyed and 350 households in 2012 and 2015 giving a four-round unbalanced household panel data. Our paper uses plot-level information from 449 households in 2006, 373 in 2009 and 345 in 2012 and 2015 with valid observations (Table 3).

Table 1: Study areas and sample households by year

District	**2006**		**2009**		**2012**		**2015**		**Total**	
	HHs	Plots	HHs	Plots	HHs	Plots	HHs	Plots	HHs	Plots
Thyolo	61	94	47	100	47	98	47	91	202	383
Zomba	86	139	82	114	77	167	79	149	324	569
Chiradzulu	53	98	39	77	35	70	34	60	161	305
Machinga	56	77	43	84	46	85	43	65	188	311
Kasungu	97	122	90	183	79	141	79	99	345	545
Lilongwe	96	128	72	114	61	119	63	113	292	474
Total	449	658	373	672	345	680	345	577	1512	2587

We present only maize plots

Table 2 and 3 present list of the definitions and summary statistics of the explanatory variables used in this paper. We first present adoption of DT maize varieties. As discussed in section two, DT varieties are both OPV and hybrids. Smallholder farmers in Malawi adopt a portfolio of maize varieties given different production and consumption attributes of the varieties (Lunduka *et al.*, 2012). While DT maize is preferred for drought tolerant traits, other improved non-DT hybrids are high yielding under normal rainfall while local varieties have preferred processing and consumption characteristics. Adoption is in this paper measured both as a binary variable (one if DT maize variety was planted on a given plot and zero otherwise) and continuous variable in acreage (ha). Katengeza *et al.* (2017) reported an increase in adoption from 3% in 2006 to 43% in 2015. We use plot-level adoption in this paper and we find an increase from 3% in 2006 to 31% in 2015 for DT maize varieties while other improved non-DT maize varieties (OIM) have decreased from 54% in 2006 to 33% in 2015 with local maize decreasing from 45% to 36%, respectively (Table 2). In this paper OIM is used as a reference variety. For an area variable, there is an increase from 0.01 ha in 2006 to 0.15 ha in 2015 for DT maize varieties with OIM and LM varieties respectively decreasing from 0.24 ha and 0.18 ha to 0.13 ha and 0.15 ha.

We control for household heterogeneity by including household characteristics such as age (years), education (years) and sex of household head, household size and *ganyu* (off-farm) labour. We further included household endowments such as operational farm size (ha), asset value in Malawi Kwacha (MK) and tropical livestock unit (TLU). There is a slight decrease for farm size from 0.96 ha in 2006 to 0.85 ha in 2015 and we expect an increase in maize productivity as farm size decreases. We include asset value and livestock ownership in tropical livestock unit (TLU) as a proxy for wealthy indicator and we assume that ownership of livestock and physical assets will enhance access to and use of agricultural inputs and technologies such as inorganic and organic fertilizer. Asset value increased from 2006 to 2015 in real terms but there is a decrease in TLU.

Access to FISP is measured on whether household accessed seed subsidy and/or fertilizer subsidy. We notice that seed subsidy access increased from 21% in 2006 to 64% in 2015 but there is a decrease from 2012 to 2015 for fertilizer subsidy. The dropping of fertilizer subsidy access may affect maize yield via reduced inorganic fertilizer use intensity. We also include distance to agricultural input market as a supply factor likely to influence access to drought tolerant maize seed and inorganic fertilizer.

Table 2: Maize type, household and institutional variables

Variable	2006	2009	2012	2015	Total
Maize type					
DT maize (1=yes)	0.03	0.16	0.33	0.31	0.20
OIM (1=yes)	0.54	0.29	0.31	0.33	0.37
Local maize (1=yes)	0.45	0.55	0.37	0.36	0.43
DT maize area (ha)	0.01	0.07	0.17	0.15	0.10
OIM area (ha)	0.24	0.10	0.14	0.13	0.16
LM area (ha)	0.18	0.24	0.16	0.15	0.19

Household characteristics and endowments					
Age of household head (years)	41	47	51	49	47
Sex of household head (1=male)	0.24	0.21	0.22	0.33	0.25
Household size (# of persons)	5.27	5.39	5.55	5.81	5.50
Number of children	3.28	2.86	2.91	2.92	2.99
Off-farm labour (adult equiv/ha)	0.15	0.22	0.40	0.20	0.24
Asset value (Malawi kwacha)	4038	4059	4306	5174	4367
Tropical Livestock Unit	1.07	1.47	1.45	0.53	1.15
Farm size (ha)	0.96	0.87	0.79	0.85	0.87
Institutional variables					
Household accessed maize seed subsidy (1=yes)	0.21	0.35	0.55	0.64	0.43
Household accessed fertilizer subsidy (1=yes)	0.35	0.57	0.74	0.50	0.54
Distance to agricultural market (Km)	4.00	4.28	4.34	4.28	4.22

Key inputs to maize production apart from seed are inorganic fertilizer, organic manure, male labour and female labour as presented in Table 3. Inorganic fertilizer use intensity increased from 2006 to 2009 but decreased in 2012 and 2015. We disaggregate male and female household labour to capture household heterogeneity effects. Availability of male labour endowment is key to maize production in Malawi (FAO, 2011). Plot-specific variables include plot size (ha), plot distance (KM), number of plots, perceived soil fertility, slope, and soil type. These variables control for observable plot heterogeneity. We also include drought and rainfall stress variables constructed using daily rainfall data from the Department of Climate Change and Meteorological Services under the Ministry of Natural Resources, Energy and Mining. We include longest period of a dry spell (days) and December mean rainfall in mm. A dry spell is defined as a period of 10 – 15 days with a total rainfall of less than 20 mm following a rainy day of at least 20 mm. We identify how long in days there was a dry spell early in the season (December – early January) and later in the season (February – early March). We define these as early dry spells and late dry spells, respectively.

Table 3: Inputs, plot characteristics and drought variables by year

Variable	**2006**	**2009**	**2012**	**2015**	**Total**
Inputs					
Fertilizer quantity (Kg/ha)	178	218	206	216	204
Organic manure (Kg/ha)	1181	1310	464	1074	1002
Male household labour (adult equivalent/ha)	2.35	3.29	3.28	4.25	3.26
Female household labour (adult equivalent/ha)	2.07	3.03	2.91	3.84	2.93
Plot Characteristics					
Plot size (ha)	0.44	0.41	0.38	0.37	0.40
Plot distance (Km)	0.96	2.86	2.81	3.27	2.46
Number of plots (#)	2.27	3.49	4.89	4.31	3.73

Sandy soil (dummy)	0.31	0.26	0.17	0.22	0.24
Loam soil (dummy)	0.53	0.49	0.64	0.64	0.57
Clay soil (dummy)	0.16	0.25	0.19	0.14	0.19
Flats slope (dummy)	0.62	0.56	0.73	0.51	0.61
Moderate slope (dummy)	0.32	0.37	0.23	0.40	0.33
Steep slope (dummy)	0.06	0.07	0.04	0.09	0.07
High soil fertility (dummy)	0.19	0.15	0.14	0.08	0.14
Medium soil fertility (dummy)	0.50	0.61	0.80	0.69	0.65
Low soil fertility (dummy)	0.31	0.23	0.05	0.23	0.21
Drought and rainfall variables					
December average rainfall (mm)	6.78	7.27	7.23	7.57	7.20
Longest early dry spell (days)	8.84	9.30	6.67	5.76	7.70
Longest late dry spell (days)	9.68	7.17	10.51	9.83	9.28

3. Results and Discussion

We begin by presenting an overview of maize yield distribution for the three maize varieties in Figure 1 disaggregated by year. In 2006, maize yield was higher on plots with DT maize followed by other improved maize (OIM) varieties and local maize (LM) varieties. However the plots for DT adopters were very few such that the yield difference between adopters and non-adopters of DT could be misleading. In 2009 and 2012, the mean yield is higher on plots with OIM varieties followed by DT and LM. It was reported by Holden and Fisher (2015) that DT maize did not perform any better than OIM in 2012, a year characterized by early-season droughts but good late-season rains. In 2015, a year where most parts of the country were affected by floods early in the season and late-season droughts, mean maize yield is higher on DT plots. The 2012 and 2015 results are critical in our setting. Without making conclusive causality relationship, maize productivity is higher on OIM plots than DT during late-season good rains, but the situation reverses when late-season droughts occur. For causality analysis we present the dose response function in Figures 2-4. Nonetheless, the results in Figure 1 could suggest that OIM varieties possess high fertilizer response rates under good rainfall conditions than DT maize varieties. On the other hand, DT maize varieties have yield advantage over OIM in drought growth conditions but low yielding under good rainfall conditions. We however leave investigation of maize varietal-fertilizer response to another study.

Figure 2 shows average treatment effect (ATE), average treatment effect on the treated (ATET) and average treatment effect on non-treated (ATENT). The plots show that the ATET is skewed to the right suggesting the mean lies on the right of ATE and ATENT. Thus, the mean maize yield for adopters of DT maize is relatively above the average individual of maize producers in the study area. This could be evidence of yield advantage of DT maize varieties over other maize varieties.

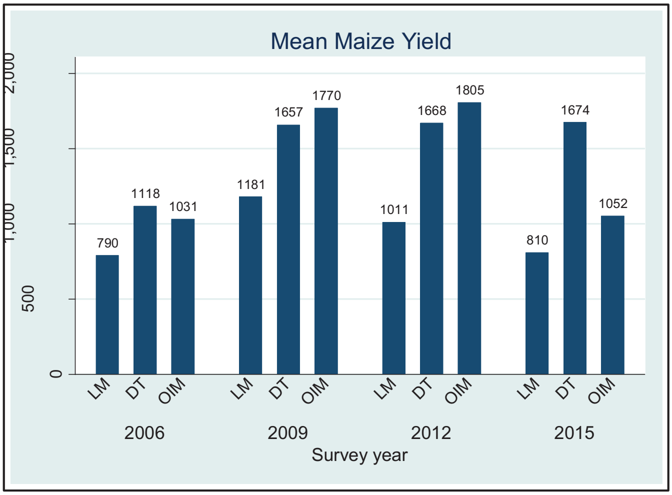

Figure 1: Maize yield distribution by variety and by year

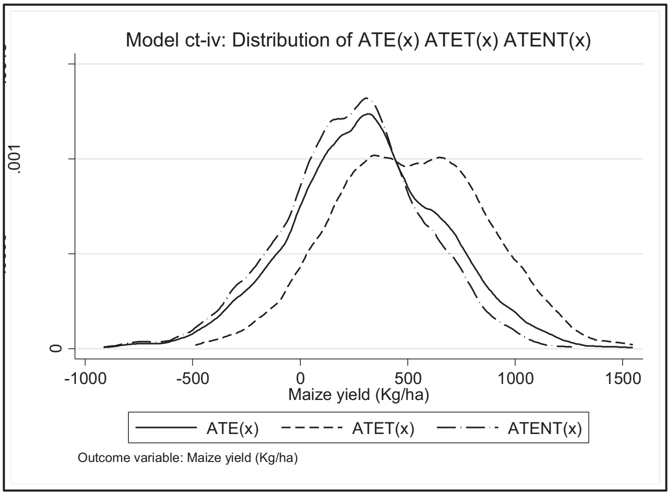

Figure 2: Average treatment effects (ATEs)

In Table 4 and Figures 3 and 4 we report results of dose response function (DRF) and marginal treatment effect (MTE). The regression results used to estimate the DRF and MTE are presented in the Appendix. We show results for an instrumental variable (IV) approach and an IV where mean variables of time varying variables are included as additional regressors to control for unobserved heterogeneity. These results show that maize yield is positive but insignificantly correlated with the level of adoption of DT maize varieties but negative and significantly correlated with LM varieties in reference to OIM varieties. We do not discuss these results in detail as the focus of our procedure is the DRF and MTE.

The DRF results show that maize yield increased with the level of DT maize adoption. Maize yield increased from 371 Kg/ha at 5% DT maize adoption level to 1000 Kg/ha at 52% level of adoption. We observe a flat graph after 52% up to 100%, roughly implying no substantial increase in maize yield after 52% level of adoption. On average an increase of one hectare of land allocated to DT maize varieties increases maize productivity by 510 Kg/ha. This represents 41% increase from an average maize yield of 1254 Kg/ha for all sample households. The results also imply heterogeneity of the impact of DT maize adoption on maize productivity. The MTE results show a u shape where at low levels of DT adoption, maize yield change decreases with an increase in adoption level. The minimum is at 69% thereafter an increasing but flatter slope is observed. This result suggest that at higher levels of DT maize adoption, the change on the effect of DT maize varieties on maize productivity increases with an increased change in levels of adoption.

Table 4: Predicted ATE and MTE at some specific DT Maize Adoption Levels

DT Maize Adoption Level (%)	Productivity (Kg/ha)		
	ATE	MTE	ATET
5	370.73	40.08	510.13
10	552.36	32.65	510.13
20	813.48	19.74	510.13
30	964.48	8.99	510.13
38	1008.58	3.49	510.13
52	1003.04	-3.33	510.13
69	930.22	-4.29	510.13
87	906.54	3.23	510.13
100	1010.72	13.81	510.13

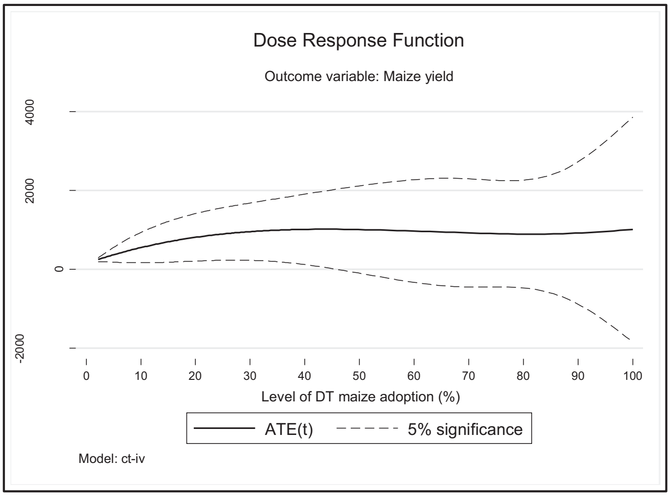

Figure 3: Estimated dose response function (Average DT maize impact)

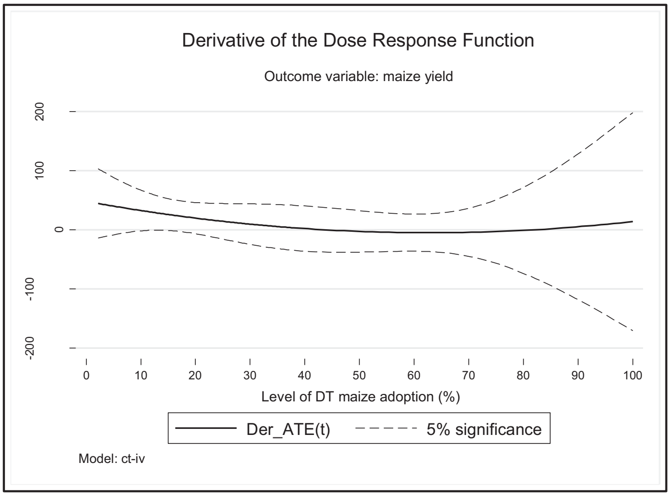

Figure 4: Marginal Treatment Effect of maize productivity

There are several implications of the DRF and MTE results presented in Table 4 and Figures 2-4. First, results from a dummy treatment variable could be misleading. We notice from the results presented in the appendix that the correlation between maize yield and adoption of DT maize is positive but insignificant using OIM varieties as reference varieties. One would be tempted to conclude that DT maize varieties have no yield advantage over OIM but local varieties as reported by Holden and Fisher (2015) and Fekadu and Endeshaw (2016). The DRF results however show that the impact of DT maize varieties is low at low levels of DT maize adoption but increases as adoption levels increase. Failure to find yield advantage of DT maize varieties could simply reflect low adoption levels. As adoption level increases farmers are likely to realise higher and more significant yield increase. These results therefore present methodological challenge to impact studies who solely rely on dummy treatment variables.

Second and related to the first point above, we notice that the impacts of DT maize varieties are heterogeneous. There is an increase in the impact from low levels of DT maize adoption up to 52% adoption level when the graph flattens up to 100%. The flat graph from 52% up to 100% suggest that beyond a certain threshold the impact of DT maize varieties on maize yield does not increase. The possible explanation is that DT maize varieties are less yielding compared to OIM varieties under good rainfall conditions but drought-resilient under drought conditions. Since farmers face production uncertainty because of uncontrollable production factors such as weather, a decision to grow a DT variety is a gamble, as a state of nature is not known at a time of decision-making. Full adoption of DT maize varieties (i.e. 100% allocation of maize area to DT maize) may result in loss of yield when a good state (good rainfall) reveals but may result in yield gains when a bad state especially drought occurs. The reverse is true with OIM varieties. In such situations, risk averse farmers are better off adopting a portfolio of maize varieties. Our results are thus, showing that allocating at least 50% of land under maize cultivation to DT maize varieties would result in a win-win situation to farmers who face a trade-off of growing DT maize and OIM varieties.

Third, the results provide additional evidence that adoption of DT maize varieties result in substantial increase in maize yield under rainfall stress conditions. Thus, DT maize varieties hold potential to protect farmers against late-season droughts. Our results are a substantial addition to on-station and on-farm trials where adoption of DT maize increases maize productivity under weather stress conditions. Experimental evidence shows that DT maize varieties have yield advantage over other maize varieties when faced with droughts during grain formation, as they are developed to withstand late-season dry spells (La Rovere *et al.*, 2010; Setimela *et al.*, 2013; Kostandini *et al.*, 2015; Tesfaye *et al.*, 2016). Our results confirm the experimental evidence and in particular, shows how maize productivity changes at different levels of DT maize adoption. Our findings also add value to the ex post studies by Radda (2015) and Awotide *et al.* (2016) in Nigeria, Makate *et al.* (2017) and Lunduka *et al.* (2017) in Zimbabwe and Cenacchi and Koo (2011) in several countries in SSA. These studies (ibid) used a dummy treatment variable and cross sectional data to examine the impacts of DT maize varieties. Our results using the panel data and a continuous treatment variable authenticate the empirical conclusion that DT maize varieties have potential to increase maize productivity during rainfall stress conditions and hence improve household food secuirty.

The overall significance of the results in this paper to smallholder farmers in Malawi and the SSA region who are consistently exposed to dry spells is that, the poor harvests most of them get when dry spells occur can be minimised with adoption of appropriate technologies. Maize production is significantly low in the presence of drought because majority of smallholder farmers lack alternative technologies to sustain production (Giller *et al.*, 1997 in Chilimba et al., 2005). Thus, with proper use of agricultural technologies such as DT and other climate-smart agriculture practices, farmers should be able to hedge against drought-related yield losses. Such technologies could be complements or alternatives to other technologies with hedging effect against drought stress such as irrigation when such are not available or expensive to the farmer.

4. Conclusion and Recommendations

Weather extremes especially recurrent droughts threaten agricultural productivity and food security in Malawi whose population largely depend on maize for food. Drought tolerant maize is one potential technology to minimize the negative impacts of drought. In recent times, several drought tolerant maize varieties have been developed and disseminated across the country. Examining the impact of this promising technology in enhancing maize productivity under drought is increasingly becoming important. Following the works of Holden and Fisher (2015) this paper has used a continuous treatment approach to understand the impact of DT maize in Malawi under rainfall stress. The data is from farm households in six districts collected in three-year intervals between 2006 and 2015.

We have found strong evidence suggesting that maize yield is positively and significantly correlated with adoption of DT maize varieties. Maize yield increased from 371 Kg/ha at 5% rate of DT adoption to 1000 Kg/ha at 52% DT maize adoption level. On average an increase by one hectare of maize area allocated to DT maize varieties increases maize yield by 510 Kg/ha representing a 41% increase from a sample average of 1254 Kg/ha. The marginal treatment effect shows that at lower levels of DT maize adoption the changes on the effect of adoption on maize yield decrease with increased adoption levels but the results reverse at higher levels of DT maize adoption level. Our findings could be evidence that DT maize varieties have potential to hedge against negative effects of droughts on maize yield. The poor harvests amongst the majority of smallholder farmers in Malawi, under rainfall stress growth conditions could be because of poor technology adoption. Smallholder farmers lack alternative technologies to hedge against drought-related yield losses. Thus, with good and proper packaged technologies, farmers can still get good harvests, despite persistent dry spells.

The paper therefore recommends enhancement of policies that promote access to and availability of DT maize varieties particularly in drought prone areas. With FISP facilitating access and use of DT maize seed, there is need for deliberate efforts to increase allocation of DT maize varieties in drought-prone areas. The FISP package should be accompanied by extension messages to enhance awareness of DT seed and related benefits under rainfall stress growth conditions. Farmers in high rainfall areas with good access to inorganic fertilizer should be encouraged to grow high yielding hybrids under such growth conditions. Promoting DT maize in such areas would result in low yielding as the variety is low yielding compared to non-DT hybrids under good rainfall conditions. Breeding programs of DT maize should however consider not only drought tolerance but also high yielding under all weather conditions.

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Appendix: ATE-regression for assessing the impact of DT maize variety on maize yield

Variable	Instrumental Variable		Instrument Variable with Mean Variables	
	Coefficient	**Std. Err.**	**Coefficient**	**Std. Err.**
Level of DT maize adoption	202.224	*(317.27)*	312.118	*(298.64)*
_ws_logmal~a	95.055	*(568.07)*	-70.016	*(569.71)*
_ws_logfem~a	233.247	*(628.18)*	334.226	*(627.85)*
_ws_headsex	154.63	*(237.17)*	196.058	*(235.05)*
_ws_age	-12.912	*(25.55)*	2.589	*(25.10)*
_ws_age2	0.088	*(0.26)*	-0.069	*(0.26)*
_ws_educ	-7.76	*(30.59)*	-8.483	*(29.53)*
_ws_hhsize	-174.849***	*(55.47)*	-151.382***	*(54.68)*
Tw_1	62.844*	*(35.57)*	48.223	*(34.32)*
Tw_2	-0.911	*(1.20)*	-0.844	*(1.17)*
Tw_3	0.004	*(0.01)*	0.004	*(0.01)*
Local maize (dummy)	-317.147***	*(106.47)*	-306.107***	*(102.17)*
Ln(fertilizer use -Kg/ha)	69.404***	*(12.38)*	59.871***	*(12.55)*
Fertilizer subsidy (1=yes)	110.4	*(72.17)*	118.296	*(71.99)*
Seed subsidy (1=yes)	-68.192	*(74.48)*	-70.306	*(74.48)*
Ln(organic manure -Kg/ha)	7.384	*(8.04)*	2.113	*(8.87)*
Ln(male labor -adult equiv./ha)	-294.026**	*(132.69)*	-375.749**	*(146.20)*
Ln(female labor -adult equiv./ha)	151.937	*(138.27)*	113.71	*(150.62)*
Sex of household head	-254.335***	*(88.31)*	-346.861***	*(111.48)*
Age of household head (years)	11.488	*(10.46)*	9.022	*(10.50)*
Age squared	-0.129	*(0.11)*	-0.096	*(0.11)*
Education of household head (years)	15.552	*(9.94)*	-12.42	*(14.27)*
Household size	29.175	*(21.34)*	47.347*	*(28.63)*
Off farm labor (adult equiv./ha)	365.974***	*(109.34)*	155.378	*(150.29)*
Ln(farm size -ha)	-182.891*	*(102.54)*	-114.634	*(127.15)*
Ln(plot size -ha)	-1148.811***	*(165.84)*	-1083.255***	*(174.93)*
Plot distance (Km)	-6.782	*(13.18)*	-11.155	*(13.19)*
Number of plots	-32.798*	*(18.75)*	-102.532***	*(23.15)*
Loam soil (1=yes)	42.601	*(69.85)*	9.209	*(69.89)*
Clay soil (1=yes)	-7.53	*(83.84)*	-24.371	*(83.63)*
Moderate slope (1=yes)	22.31	*(59.74)*	19.411	*(59.56)*
Steep slope (1=yes)	148.243	*(118.71)*	148.99	*(119.32)*
Medium fertility (1=yes)	19.642	*(77.39)*	37.868	*(77.25)*
Low fertility (1=yes)	-126.119	*(93.62)*	-89.917	*(93.68)*
December average rainfall (mm)	95.019***	*(24.96)*	100.887***	*(24.74)*
Longest early dry spell (days)	-18.354	*(12.54)*	-23.433*	*(12.52)*
Longest late dry spell (days)	-7.055	*(8.58)*	-5.692	*(8.56)*
Year 2009	277.474***	*(103.55)*	328.277***	*(103.70)*
Year 2012	130.853	*(141.20)*	233.758*	*(138.82)*
Year 2015	53.831	*(132.80)*	111.169	*(133.14)*
Zomba district	-200.381	*(122.89)*	-122.763	*(123.62)*
Chiradzulo district	-71.011	*(123.34)*	16.458	*(125.33)*
Machinga district	57.953	*(159.26)*	193.492	*(159.58)*
Kasungu district	436.360***	*(157.01)*	547.476***	*(160.12)*
Lilongwe district	502.650***	*(184.40)*	657.051***	*(182.29)*
Mean fertilizer use (Kg/ha)			0.186	*(0.15)*

Mean household head sex			145.062	*(130.31)*
Mean household head education			34.235**	*(15.72)*
Mean male labor			66.15	*(45.81)*
Mean female labor			-1.713	*(49.81)*
Mean age			-2.023	*(3.53)*
Mean household size			-51.493*	*(30.27)*
Mean off-farm labor			255.012*	*(152.14)*
Mean farm size			-22.924	*(100.92)*
Mean manure use (Kg/ha)			0.021	*(0.02)*
Mean plot size (ha)			-70.755	*(194.26)*
Mean number of plots			119.879***	*(28.23)*
Constant	535.018	*(409.53)*	314.27	*(428.26)*
Prob > chi2	0.000		0.000	
Number of plots	2637		2637	

Significance levels: *10%, **5%, ***1%

Paper four

Maize productivity impact of farm input subsidies vis-à-vis climate-smart technologies: A tale of smallholder farmers in Malawi

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Abstract

Farm input subsidies in Malawi are historically a strategic agriculture policy tool, particularly, for enhancing maize production for national and household food security. In this paper, I review maize productivity impact of access to inorganic fertilizer through Farm Input Subsidy Program (FISP). I extend the review on impact of climate-smart agriculture (CSA) technologies, specifically, integration of inorganic and organic fertilizer, and conservation agriculture (CA). Results show modest maize productivity impact of FISP. Maize-fertilizer response rates among FISP beneficiaries are below agronomic average and long-term impact of the program is uncertain. The main reason is that majority of Malawians including FISP beneficiaries are cultivating on degraded soils depleted of essential nutrients and organic matter. The problem is exacerbated by frequent dry spells, poor timing of input delivery, beneficiaries receiving less than the required amount of inorganic fertilizer and targeting errors. Conversely, maize productivity impact is high, consistent and enduring on experimental plots with CA and integration of inorganic and organic fertilizer. These CSA technologies ensure efficient and optimal nutrient intake and drought-resilience. This suggests that the impact of FISP can be enhanced if application of subsidized inorganic fertilizer is integrated with CSA technologies such as CA and organic fertilizer. FISP implementation strategy should therefore consider abandoning the current farmer-based targeting system and subsidize adopters of these CSA technologies. This approach has potential to provide the Government of Malawi with an exit strategy from FISP.

Key words: Conservation agriculture, drought-resilience, farm input subsidies, maize yield, organic fertilizer

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1. Introduction

Sustainable maize production and productivity dominates agriculture policy priorities in many developing countries especially in sub-Saharan Africa (SSA) where majority of the rural population depends on maize for food security. There is a knock-on effect that starts from poor and low maize production and productivity to limited access to quality and nutritious food (Hawkes & Ruel, 2008). In Malawi, a country heavily dependent on rain-fed agriculture, low levels of soil fertility and frequent dry spells are two major causes of low maize production and productivity (Weber *et al.*, 2012; Ngwira *et al.*, 2013a). Increasing nitrogen intake, maintenance and use efficiency, and drought-resilience is an important avenue to achieve sustainable increase in maize harvests (Snapp *et al.*, 2014). Malawi National Agriculture Policy (NAP) therefore, emphasizes on timely and equitable access to high quality productive inputs such as inorganic and organic fertilizer and promotion of climate-smart agriculture (CSA) technologies such as conservation agriculture (CA) (Government of Malawi, 2016b).

Among key policy instruments is the Farm Input Subsidy Program (FISP) that enhances access to and use of inorganic fertilizer (Dorward *et al.*, 2008). The program started in 2005/06 cropping season and officially subsidizes two 50-Kg bags of inorganic fertilizer for maize production (Chirwa & Dorward, 2013). The expectation is that the program would break low input/low output poverty trap among smallholder farmers, kick-start growth and raise agricultural incomes and food security (Ricker-Gilbert & Jayne, 2017). Early evidence showed that the country achieved 53% national food surplus in 2006/07 from a food deficit of 43% in 2004/05. Average maize productivity jumped from 1.05 tons per hectare (t/ha) in 2003/04 and 0.76 t/ha in 2004/05 to 1.59 t/ha in 2005/06 and 2.04 t/ha in 2006/07 (Denning *et al.*, 2009). Since then the program has become a strategic policy instrument to boost maize production and productivity and achieve sustainable national and household food security.

In this paper, I review empirical evidence on maize productivity impacts of subsidized inorganic fertilizer with extension to related CSA technologies. Specifically, I review: a) maize productivity impact of subsidized inorganic fertilizer; b) marginal maize productivity impact of subsidized inorganic fertilizer; c) impact of integrating inorganic and organic fertilizer on maize productivity; and d) maize productivity impact of conservation agriculture. Inorganic and organic fertilizer and related CA technology are potentially complements and are vital for sustainable maize production (Munthali, 2007) but could also be substitutes and compete for resources (Holden & Lunduka, 2012).

I conceptualize the symbiotic relationship of inorganic and organic fertilizer and related CA in Figure 1. Specifically I focus on inorganic fertilizer accessed through FISP and adoption of organic fertilizer and CA through investment in agricultural extension services. Path 1 shows that government investment in FISP would reduce costs for inorganic fertilizer thereby increasing input profitability for smallholder farmers (Lunduka *et al.*, 2013). This would then encourage participating farmers to invest in other productivity enhancement inputs such as organic fertilizer and CA (Lunduka *et al.*, 2013; Karamba & Winters, 2015). Investment in organic fertilizer and CA would increase soil response to subsidized inorganic fertilizer as complements and improve input use efficiency (Snapp *et al.*, 2014; Karamba & Winters, 2015; Ricker-Gilbert & Jayne, 2017). This cyclic and mutual relationship would result in parallel increase in use intensity of organic and inorganic fertilizer and CA and hence nitrogen and water use efficiency thereby increasing maize production and productivity.

However investments in large-scale input subsidies tend to have high costs that may outweigh long-term program benefits. To fund such programs, governments are likely to substitute resources from other agricultural programs (Lunduka *et al.*, 2013; Carr, 2014). For instance, as shown in path 2, government may scale down (or fail to increase) investments in agricultural extension services to fund input subsidies and this may affect adoption of organic fertilizer and CA. Although FISP may increase profitability of inputs as reported by Lunduka *et al.* (2013), farmers' response is lagged and without extension services, propensity to adopt organic fertilizer and CA is low. Consequently, soil responsiveness to inorganic fertilizer will be low and long-term returns to input subsidies will be insignificant (Ricker-Gilbert & Jayne, 2017). On the other hand, high investment in programs that promote adoption of organic fertilizer and CA with minimal investment in inorganic fertilizer is neither a panacea (Carr, 2014) as shown in path 3. The soils in Malawi are too depleted of vital nutrients (Carr, 1997; Drechsel *et al.*, 2001) and require supplementary input of inorganic fertilizer (Snapp *et al.*, 1998; 2014).

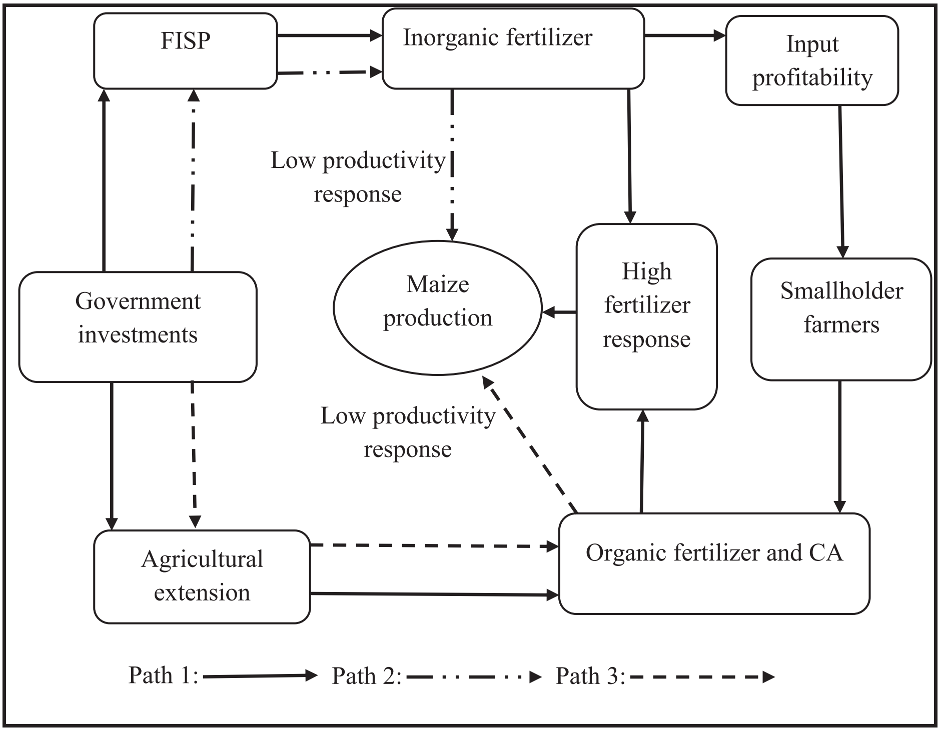

Figure 1: Symbiotic relationship between inorganic and organic fertilizer

From this discussion, it is clear that investment in FISP affects investment in other programs that affect adoption of CSA technologies such as organic fertilizer and CA and vice versa. It was also noted by Holden (2018) that subsidies tend to lead to complex substitutions suggesting crowding in/out investments in other programs in this context. Given limited resources, there is need for wise investment in FISP without suffocating other programs. Conditioning access to input subsidies on adoption of soil fertility management and climate-smart technologies (Snapp *et al.*, 2014) such as organic fertilizer and CA is potentially a remedy to solve the problem of resource substitution and enhance the impact of the program. In this paper, I discuss the impact of subsidized inorganic fertilizer, integration of inorganic and organic fertilizer and CA. I then discuss suggestions on enhancing the impact of FISP by targeting application of subsidized inorganic fertilizer on soils where organic fertilizer and CA have been adopted.

This review builds on the synthesis of Lunduka *et al.* (2013) who reviewed farm-level impacts of FISP in Malawi. The key findings were that FISP has modestly helped to increase farm-level maize production and productivity. However maize real prices were increasingly high and maize imports continued trekking into the country. Contrary to the program's primary target of resource poor farmers, evidence showed that better-off households had substantial gains from the program than poorer households. Overall, the synthesis showed that while FISP is such a promising policy tool, the program might not be able to reduce food insecurity levels alone. In this current paper, I extend the review of Lunduka (ibid) in two main ways. First, I update the studies reviewed with recent findings. Second, my paper synthesizes the findings on subsidized inorganic fertilizer and CSA technologies.

This review is necessary for Malawi as FISP remains a priority policy tool for the Government (Snapp *et al.*, 2014) at least in foreseeable future. The results are also of policy relevance beyond Malawi given global populace of the current Malawi FISP. Some countries in SSA have used (Messina *et al.*, 2017) or may use the Malawi FISP model to introduce their own farm input subsidies and the conclusions of this paper may be applicable in their settings. Although the evidence of my paper can be applicable in other countries in SSA, a comprehensive review comparing findings from many countries could be more appropriate. I leave that for future reviews.

2. FISP: background and implementation vis-à-vis soil fertility

Farm input subsidies in Malawi have a long history as a strategic agriculture policy instrument for enhancing access to and use of inorganic fertilizer primarily for maize production. "Maize is life" (Smale, 1995) and roughly, 97% of farm households grow maize (Denning *et al.*, 2009). Maize production is however heavily dependent on soil fertility especially availability of nitrogen and soil organic matter (SOM) (Snapp *et al.*, 1998; Marenya & Barrett, 2009; Matsumoto & Yamano, 2009; 2014).

Historically soil fertility was replenished by natural methods such as periodic fallows, crop rotations, animal manure and slash and burn. However with population pressure such methods were no longer feasible and were slowly replaced by continuous cultivation (Kumwenda *et al.*, 1996; Snapp *et al.*, 1998; Mekuria & Siziba, 2003). Gradually nutrient depletion increased resulting in low crop productivity (Kumwenda *et al.*, 1996; Mafongoya *et al.*, 2006). Estimates in early 1990s showed annual nutrient loss of 68 Kg/ha in SSA countries (Stoorvogel *et al.*, 1993) while early 2000s projections indicated annual average loss of 26 Kg/ha nitrogen (N), 7 Kg/ha phosphorous (P) and 23 Kg/ha potassium (K) (Stoorvogel *et al.*, 1993; Drechsel *et al.*, 2001). IFPRI (1999) in Chinsinga and O'Brien (2008) and the World Bank (2004) in Carr (2014) estimated annual average NPK loss of 80-100 Kg/ha in Malawi. Efforts to improve maize production would therefore need heavy investments in integrated soil fertility management (ISFM) (Kumwenda *et al.*, 1996).

Inorganic fertilizer is one guaranteed source of replenishing soil nutrients (Snapp *et al.*, 1998; 2014; Sheahan & Barrett, 2017). However high poverty levels and limited access to credit, mean that access to inorganic fertilizer is difficult among smallholder farmers without help (Chinsinga & O'Brien, 2008). Farm input subsidies come in to help smallholder farmers who cannot afford accessing inorganic fertilizer at commercial price. The first set of farm input subsidies in Malawi were introduced in mid-1970s with the objective of increasing maize production (Wiggins & Brooks, 2010). Through state-run Agricultural Development and Marketing Corporation (ADMARC) and Smallholder Agriculture Credit Administration, government funded a universal fertilizer subsidy in addition to providing cheap credit for smallholders. Such policy instruments were responsible for national food self-sufficiency in non-drought years until early 1990s when economic policy regimes changed. The country adopted economic liberalization and farm input subsidies were removed. Agricultural markets were liberalized, the smallholder agricultural credit system collapsed and the local currency was sharply devalued. Farm inputs eventually became unfordable to most smallholder farmers and resulted in dismal maize production. Exacerbated by an influx of Mozambican refugees and regular droughts, the country shifted from national food self-sufficiency to food deficit and reliance on food imports (Chinsinga, 2008; Chinsinga & Poulton, 2014).

In response, the government introduced Starter Pack Scheme (SPS) in 1998/99 growing season heavily supported by the UK's Department for International Development (DFID) (Chirwa, 2010). SPS consisted of free inputs containing 0.1 ha worth of fertilizer and improved maize and legume seed and covered all rural farming families, estimated at 2.86 million. The aim of the program was to improve food security and substitute maize imports (Crawford *et al.*, 2006). The scheme was repeated in 1999/00 but for the purpose of sustainability and exit strategy, it was scaled down to a Targeted Input Program (TIP) from 2000/01 covering only half of rural farming families. In 2001/02, the country faced severe food crisis affecting 3.2 million people and partly blamed on downscaling of TIP. TIP was then implemented as an extended TIP (ETIP) from 2002/03 reaching 2.8 million farmers (Pauw & Thurlow, 2014). ETIP phased out in 2004/05 following the withdrawal of DFID's financial support (Chinsinga, 2008).

In 2004/05, about four million Malawians were affected by a severe hunger crisis as a result of poor maize harvests (Denning *et al.*, 2009). Government's response was reintroduction of fertilizer input subsidies named Agriculture Input Subsidy Program (AISP), which was later renamed Farm Input Subsidy Program (FISP). The aim was to promote access to and use of inorganic fertilizer primarily for maize production in order to achieve sustainable increase in agricultural productivity and food security (Dorward *et al.*, 2008). The program was to target resource constrained but productive smallholders. Thus, the program was to provide fertilizer not as a safety net but to people who have land and human resource to make effective use of it but would otherwise not afford at commercial prices (Chinsinga, 2008).

Administration of the program is via coupon vouchers given to targeted beneficiaries (Dorward & Chirwa, 2011). Farmers are officially entitled to two coupons of 50-Kg bags of inorganic fertilizer although practically beneficiaries receive less than the intended 100 Kg (Arndt *et al.*, 2015). Other inputs have also been included in some years such as tobacco fertilizer, improved seed for maize, legume and cotton, storage pesticides for maize and cotton chemicals. The first year of implementation in 2005/06, approximately 166000 tons of inorganic fertilizer was subsidized (Figure 2). The highest subsidized inorganic fertilizer was reported in 2007/08 of about 216000 tons but the quantity has been decreasing since then.

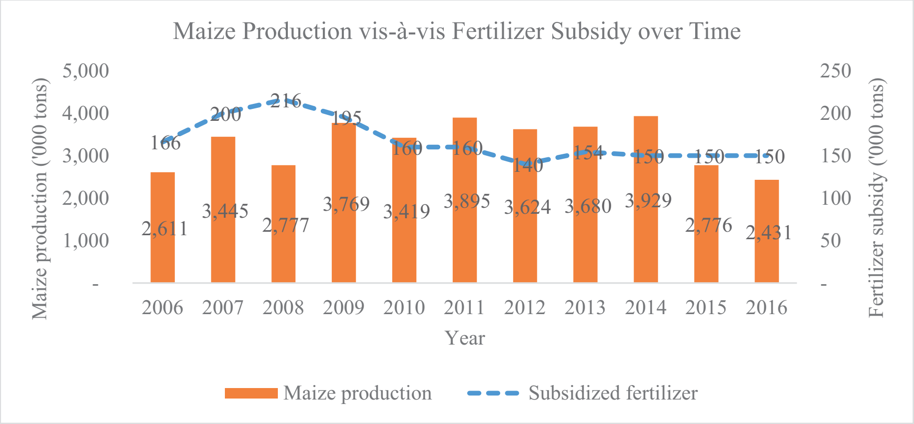

Figure 2: Maize production and fertilizer subsidy over time

Source: Government's annual economic reports (Government of Malawi, 2013, 2014, 2016a) and Chirwa and Dorward (2013).

Farm input subsidies have effectively increased access to and use of inorganic fertilizer (Carr, 2014; Chibwana *et al.*, 2014; Lunduka *et al.*, 2014; Karamba & Winters, 2015) thereby enhancing nitrogen intake. Annual fertilizer application was estimated at 26 Kg/ha approximately 8.6 Kg nitrogen (N) in early 1990s (Stoorvogel *et al.*, 1993; Drechsel *et al.*, 2001) after the removal of input subsides. Crawford *et al.* (2006) reported just over 25 Kg/ha between 1996 and 2002 while the World Bank (2004) estimated nutrient intake of 15.9 Kg/ha. Following the introduction of FISP in 2005/06, Sheahan and Barrett (2017) reported an increase in annual inorganic fertilizer nitrogen intake to 23.1 – 53.1 Kg/ha with total NPK intake of 31.9 – 56.3 Kg/ha. Nonetheless such figures do not offset the 80-100 Kg/ha NPK loss reported by IFPRI (1999) in Chinsinga and O'Brien (2008) and the World Bank (2004) in Carr (2014). This suggests that increasing nutrients intake through inorganic fertilizer without interventions that enhance nutrient maintenance cannot solve the problem of soil fertility.

Organic fertilizer is an alternative and complementary source of soil nitrogen (Snapp *et al.*, 1998). Organic fertilizer as opposed to synthetic fertilizer is an organic-matter based technology originating from organic sources (Snapp *et al.*, 1998; Pavlis, 2013). In Malawi such sources include livestock, compost and green manure, crop residues, household refuse and agroforestry (Snapp *et al.*, 1998; Chilimba *et al.*, 2005; Kabuli & Phiri, 2006; Government of Malawi, 2012a; Holden & Lunduka, 2012). This technology ensures sufficient increase in soil organic matter and essential nutrients such as NPK (Mafongoya *et al.*, 2006; Thierfelder *et al.*, 2015a; 2015b). Other agronomic advantages are increasing nutrient and water use efficiency, nutrient maintenance and soil pH (Heerink, 2005; Mafongoya *et al.*, 2006; Nyasimi *et al.*, 2017). The increase in soil pH is important because increased soil acidity impedes efficient absorption of soil nutrients (Barrett *et al.*, 2017).

A closely related climate-smart technology to organic fertilizer is CA (Ngwira *et al.*, 2013c; Bunderson *et al.*, 2016). CA is a composite of three basic interlinked principles of minimum soil disturbance, permanent organic soil cover and crop diversification involving crop rotation and/or intercropping (FAO, 2015). Full adoption requires use of all the three key principles with 30% as a minimum requirement for permanent organic soil cover (Giller *et al.*, 2009; Government of Malawi, 2012a). CA brings transformation and sustainability in conventional tillage-based agricultural systems by promoting residual retention, enhancing diversification instead of mono-cropping and replacing tillage with no-tillage (Thierfelder *et al.*, 2015b). CA is climate-smart because it improves crop productivity (Ngwira *et al.*, 2012; 2013c; Thierfelder *et al.*, 2015a; Bunderson *et al.*, 2016; Mupangwa *et al.*, 2017); enhances adaptation by increasing soil fertility and organic carbon (Thierfelder *et al.*, 2015a; 2015b) and mitigates against drought and heat shocks (Steward *et al.*, 2018).

However sole reliance on organic fertilizer and /or CA is not sufficient to provide enough soil nutrients for maize production. Organic sources contain unguaranteed and unbalanced quality of nutrients. Experimental evidence reported by Chilimba *et al.* (2005) estimated NPK content in compost manure as 0.21-2.2% N, 0.05-0.75% P and 0.12-2.62% K. Farmyard manure (FYM) contains 1.03-1.55% N, 0.13-0.5% P and 1.26-2.07 K. This suggests that an application of 5000 Kg/ha of compost and FYM would respectively add 10-74 KgN and 23-99 KgN/ha (Chilimba *et al.*, 2005; Mafongoya *et al.*, 2006). Another study by Ngwira *et al.* (2013b) observed that to provide an equivalent of 23 KgN/ha, a farmer would need 15000 Kg/ha of compost manure. Studies have therefore recommended integrating inorganic and organic fertilizer and related CA technology as a sustainable option for improving soil fertility and subsequent crop productivity (Snapp *et al.*, 1998; Mafongoya *et al.*, 2006; Munthali, 2007).

3. Maize productivity impacts

3.1 Impacts of subsidized inorganic fertilizer

Government estimates show a remarkable increase in maize production over the period of FISP implementation (Wiggins & Brooks, 2010; Chirwa & Dorward, 2013; Government of Malawi, 2013, 2014, 2016a). In 2005/06, which is the first year of FISP implementation, maize production more than doubled the 2004/05 harvests of 1.26 million tons to 2.61 million tons. In the second year (2006/07), official estimates were 3.44 million tons of which 300,000 – 600,000 tons was an incremental production due to subsidy program (Jayne *et al.*, 2008; Dorward & Chirwa, 2011; Arndt *et al.*, 2015). Overall maize yield increased by 2.6 times between 2005 and 2007 because of subsidies (Sanchez, 2015). Denning *et al.* (2009) further reported that Malawi moved from 43% national food deficit in 2005 to 53% food surplus in 2007. The positive impact continued in later years as Dorward and Chirwa (2011) reported an increase in FISP-related maize production increment from 406,348 tons in 2006 to 968,900 tons in 2008/09. Production estimates for years 2009/10 – 2015/16 (Figure 2) were well above three million tons except for drought years of 2014/15 and 2015/16.

At household-level, some studies support the macro-level statistics of positive impact of subsidized inorganic fertilizer on maize production and yields while some authors contradict. Holden and Lunduka (2010) used three-waves of panel data from six districts in Central and Southern Malawi and reported a positive and significant impact of FISP on maize production and productivity. Using six years of panel data, Ricker-Gilbert and Jayne (2011) found that an additional kilogram of subsidized fertilizer in the current year and past three seasons, respectively, increases maize yield by 1.82 and 3.16 Kgs. With reference to the standard package of FISP of 100 Kgs fertilizer, these figures suggest an incremental maize production due to FISP of 182 and 316 Kgs. The positive impact of past receipt of subsidized fertilizer could be because of nutrient build-up in the soils due to continuous application of nitrogen. Again, subsidized fertilizer give farmers a learning experience on importance of inorganic fertilizer and may continue using the input in subsequent years. Another possible reason is that FISP generates enough income that enables farmers to invest in other yield enhancing technologies (Lunduka *et al.*, 2013).

In another study, Ricker-Gilbert and Jayne (2012) found that an additional kilogram of subsidized fertilizer contributes 2.43 Kgs of maize for an average farmer, 2.61 and 0.75 Kgs for households at the 75% and 10% percentile of maize production respectively. This suggests that better-off households benefit more from FISP as opposed to poor households. Possible explanation is that fertilizer response is very low on plots for poor households than for rich households. I discuss possible reasons for low fertilizer response in section 3.2. This result however raises questions on the program's ability to generate substantial gains in maize production among the poor. This further threatens the capacity of FISP to reduce productivity and poverty gap between the poor and the rich. Another possible reason is that poor households than better off household are less likely to receive subsidy coupons due to targeting errors and corruption in the program (Holden & Lunduka, 2013).

Evaluating the 2012/13 FISP, Dorward *et al.* (2013) found that access to a full subsidy pack gives an incremental benefit of at least 500 Kgs of maize while a 50-Kg fertilizer access increases maize production by 200-400 Kgs. In Kasungu and Machinga districts, Chibwana *et al.* (2014) reported a maize yield increase of 477 Kg/ha by seed and fertilizer subsidy beneficiaries while it was 249 Kg/ha for fertilizer subsidy beneficiaries only. Using data from the third Integrated Household Survey (IHS3), Karamba and Winters (2015) reported a modest increase in gross output value of 17%/ha due to FISP. The modest impact is possibly due to displacement of commercial inputs, input diversion, and receipt of less than the required amount. The results failed to find significant impact of FISP on reducing gender productivity gap between female-headed (FHHs) and male-headed households (MHHs). The plausible explanation is that FHHs are less likely recipients than men (Holden & Lunduka, 2013). This result cast further doubts of the program's ability to increase overall household maize productivity and end persistent food insecurity.

Using computable general equilibrium (CGE) model calibrated to empirical evidence from household-level evaluations, Arndt *et al.* (2015) reported Malawi FISP as pro-poor. The findings however contradicted Jayne and Rashid (2013) who using partial equilibrium assessments reported FISP as low potential and deeply grounded in political interests. Nonetheless, Arndt *et al.* (2015) observed that FISP generates double-dividends through higher and drought-resilient crop yields. Using the integrated household survey data for 2010 and 2013, Sibande *et al.* (2017) reported that access to FISP increases maize productivity thereby leaving farmers with a surplus for sale. However, the maize supply quantities are too small to affect maize prices. Again, such quantities may not generate enough income to allow participating farmers self-finance input purchase in subsequent years casting doubts on program's long-term impact and sustainability.

Ricker-Gilbert and Jayne (2017) used four-waves of panel data to estimate enduring effects of fertilizer subsidies on maize production and reported a modest positive impact of fertilizer subsidies in a given year. One-kilogram increase in subsidized fertilizer, increases maize yield by 1.00-1.46 Kgs in current year after accounting for contemporaneous crowding out of commercial fertilizer, representing 100-150 Kgs at standard FISP package. However, unlike their previous results of 2011, the 2017 findings by Ricker-Gilbert and Jayne did not find evidence of the impact of lagged access to fertilizer subsidies on maize yield. This suggests that Malawi fertilizer subsidy program has limited long-term impacts on maize production.

Messina *et al.* (2017) used a novel approach to asses yield response to fertilizer through remote sensing to identify spatiotemporal performance of agricultural fields and reported national decline in annual maize productivity trend. The authors (ibid) suggest that the positive evidence reported by some authors could be due to data error on maize production estimates and maize area cultivated. Farm-level data often suffer from respondent measurement errors (Jayne & Rashid, 2013). An evaluation of 2016/17 subsidy by Centre for Development Management (2017) also show that production and productivity has stagnated in recent years. While there was a substantial increase in maize productivity from 1.5 t/ha to 2.4 MT/ha in early years of the program, from 2013/14 productivity has declined to 1.9 t/ha suggesting low maize yield-fertilizer response rate and subsequent reduction to returns from FISP investments.

3.2 Marginal maize productivity impact of subsidized inorganic fertilizer

Finding positive impact of FISP on beneficiaries vis-à-vis non-beneficiaries is not enough as the success of the program depends on marginal return with respect to what is agronomically expected (Pauw & Thurlow, 2014). This is related to nitrogen use efficiency (Vanlauwe *et al.*) defined in this paper as "*amount of additional grain harvested per kilogram of nitrogen applied to the grain crop*" (Snapp *et al.*, 2014: P1). Based on agronomic evidence, NUE is 14-50 Kg/KgN on on-station and on-farm trial plots but it is 2-3 times less on farmer-managed plots (Snapp *et al.*, 2014). On farmer-managed plots, Snapp *et al.* (2014) reported NUE of 17.7 Kg/KgN, Pauw and Thurlow (2014) found an average of 16.8 Kg/KgN while Carr (2014) reported 15.2 Kg/KgN. Variety disaggregation shows 10-12 Kg/KgN for local maize, 15 Kg/KgN for OPV and 18-20 Kg/KgN for hybrid maize varieties (Dorward *et al.*, 2008).

Malawi FISP contains 50 Kg of NPK (with 23% nitrogen i.e. 11.5 KgN) and 50 Kg urea (with 43% nitrogen i.e. 21.5 KgN) giving an average of 33 KgN (Pauw & Thurlow, 2014). Using the average benchmark of 16.8 Kg/KgN, a standard fertilizer subsidy package is expected to increase maize yield by 554 Kg. However evidence from household surveys show less maize-fertilizer response among FISP beneficiaries as shown in Table 1. Ricker-Gilbert and Jayne (2011, 2012) and Jayne and Rashid (2013) reported an overall low NUE of 5.5 – 9.6 Kg/KgN for beneficiaries of subsidized inorganic fertilizer with the poorest households reporting 2.4. Dorward *et al.* (2013) found a relatively higher NUE of 15.2 Kg/KgN while Snapp *et al.* (2014), Pauw and Thurlow (2014), Chibwana *et al.* (2014) and Arndt *et al.* (2015) found maize-fertilizer response of 7 – 14.5 Kg/KgN. Ricker-Gilbert and Jayne (2017) reported the smallest NUE of 3 – 4.4 Kg/KgN. These findings suggest huge inefficient use of subsidized inorganic fertilizer. Jayne and Rashid (2013) indicated that with these inefficiencies the incremental impact of subsidized inorganic fertilizer is insignificant and unprofitable.

Table 1: Nitrogen use efficiency among FISP beneficiaries in Malawi

Authors	Year	NUE (Kg/KgN)
Ricker-Gilbert and Jayne	2011	5.5 for current year and 9.6 for past 3 seasons.
Ricker-Gilbert and Jayne	2012	7.4 for average farmers, 7.9 for rich farmers and 2.3 for poor farmers.
Dorward et al.	2013	15.2
Jayne and Rashid	2013	8.1
Snapp et al.	2014	7.0-14.0
Pauw and Thurlow	2014	9.0-12.0
Chibwana et al.	2014	7.5 - 14.5
Arndt et al.	2015	11.8
Messina et al.	2017	10.0
Ricker-Gilbert and Jayne	2017	3.0 - 4.4

In view of these inefficiencies, one would be tempted to dismiss FISP as an economic failure (Pauw & Thurlow, 2014). It may therefore make no economic sense to continue investing in a program whose marginal benefit is negligible. However history tells otherwise. Minus drought, removal of fertilizer subsidies has been one major reason for recurrent food deficits in the country. In early to mid-1990s, food deficits were rampant after the removal of fertilizer subsidies (Chinsinga, 2008; Chinsinga & Poulton, 2014). In early 2000s, the scaling down of TIP contributed to food deficits (Wiggins & Brooks, 2010). Food deficits in early 2010s have also partly been blamed on downscaling of FISP (Pauw & Thurlow, 2014). There could be several reasons why maize-fertilizer response or nitrogen use efficiency is low for beneficiaries of FISP such that addressing those bottlenecks would be necessary for the success of the program. Jayne and Rashid (2013), Snapp *et al.* (2014), Messina *et al.* (2017) and Ricker-Gilbert and Jayne (2017) show that poor soil fertility, loss of soil organic matter, water stress and poor agronomic practices are among key bottlenecks. Furthermore, poor timing of input delivery, input diversion, recipient of less than the required amount and targeting errors have also limited efficient use of farm input subsidies (Holden & Lunduka, 2013; Lunduka *et al.*, 2013; Lunduka *et al.*, 2014; Centre for Development Management, 2017).

Poor soil fertility

The soils are highly degraded in Malawi as discussed in section 2 due to soil mining resulting in depletion of nitrogen and other essential nutrients. Simply increasing nutrient intake through subsidized inorganic fertilizer without first addressing soil degradation issues does not solve soil fertility problems (Tchale & Sauer, 2007; Ngwira *et al.*, 2013b). The current implementation strategy of FISP where soil conditions are grossly ignored will keep on decreasing its marginal return. Although it is expected that the program would have residual effect in nutrient build up, this expectation is unlikely because of heavy nutrient mining (Branca *et al.*, 2011). Snapp *et al.* (2014) therefore recommended targeting inorganic fertilizer application on plots with sufficient soil quality or encouraging farmers to first adopt soil fertility management technologies. The discussion in section 3.3 provides evidence that maize-fertilizer response is high on good quality soils. Mueller *et al.* (2012) further indicated that maize would increase by 50% if soil nutrient deficiencies are addressed. Thus, if FISP targets the soil, the impact is likely to be consistently high than the current targeting of the farmer who in most cases cultivate on degraded soils.

Loss of soil organic matter (SOM)

Related to soil fertility depletion is the reduction of SOM and related soil organic carbon (SOC) (Chilimba *et al.*, 2005; Snapp *et al.*, 2014). Soils in Malawi are highly depleted of SOM to the extent that cannot effectively support crop productivity (Messina *et al.*, 2017). The responsiveness of maize yield to inorganic fertilizer on farmer-managed plots has decreased by half of what is expected and only 20% of agronomic average because of the decline in SOM (Snapp *et al.*, 2014). Unfortunately, sole reliance on subsidized inorganic fertilizer does not solve the problem of SOM (Mafongoya *et al.*, 2006; Ngwira *et al.*, 2013b). Inorganic fertilizer has high nutrient content with rapid release into the soil but the retention rate is low when soils are deprived of organic matter and its use efficiency is reduced.

The loss of SOM in maize-based farming systems with continuous cropping therefore needs urgent attention if interventions such as FISP are to be effective. Building SOM requires application of organic technologies. Unfortunately, adoption of organic technologies is very low in Malawi (approximately 12.7%) (Snapp *et al.*, 2014). Holden and Lunduka (2012) however reported an increase in organic manure use from 32% in 2006 to 43% in 2009 in six districts in central and southern Malawi. This shows that there is potential to increase organic fertilizer use in Malawi if strategically focused. Conditioning access to subsidized inorganic fertilizer on adoption of organic fertilizer could be a strategic focus.

Water stress

Maize production in many countries in SSA including Malawi rely on rain-fed in a single rainy season that is characterized by frequent dry spells resulting in water stress (Denning *et al.*, 2009). This significantly affect maize-fertilizer response. Evidence has shown that when a drought occurs even fertilizer subsidy does not save millions of Malawians from a hunger crisis due to resulting poor harvests. For example in 2001/02 there was a hunger crisis despite implementation of TIP. Although some critics blamed the scaling down of TIP for the hunger (Wiggins & Brooks, 2010), the associated drought significantly contributed to the crisis. In 2004/05 despite ETIP about four million Malawians were affected by hunger and mainly because of drought (Chabvunguma & Munthali, 2008; Chinsinga, 2008). In 2014/15 and 2015/16 maize production was respectively estimated at 2.8 million tons and 2.4 million tons down from 3.9 million tons in 2013/14 despite

150000 tons of inorganic fertilizer being subsidized in all the three consecutive years (Figure 2). The difference in maize production was mainly due to regular dry spells in 2014/15 and 2015/16 cropping seasons. FEWS NET (2015) also reported that maize harvests in 2014/15 were 25-30% lower than the previous five-year average and a deficit of 500,000 tons was recorded mainly due to late-season droughts.

This means that access to inorganic fertilizer through FISP has insignificant impact on maize production and productivity in the presence of drought because majority of the beneficiaries lack alternative technologies to sustain production (Giller *et al.*, 1997 in Chilimba et al., 2005). Farmers also tend to reduce use of productivity enhancing inputs such as inorganic fertilizer in response to past adverse conditions (Sesmero *et al.*, 2017). Controlling for water stress is fundamental to achieving higher fertilizer response rate. While irrigation is rarely used (Barrett *et al.*, 2017) due to high investment and maintenance costs, integrating inorganic and organic fertilizer would enhance water and inorganic fertilizer use efficiency thereby increasing the impact of subsidized inorganic fertilizer. Addressing both nutrient and water deficiencies can increase maize yield by 75% (Mueller *et al.*, 2012).

3.3 Impact of integrating inorganic and organic fertilizer

Having identified key factors associated with poor maize-fertilizer response, studies have recommended integration of inorganic and organic fertilizer as a remedy (e.g. Chilimba *et al.*, 2005; Mafongoya *et al.*, 2006; Tchale & Sauer, 2007). Integrating inorganic and organic fertilizer can generate multiple benefits to the production of maize and has potential to increase NUE (Holden, 2018). I discuss evidence of maize productivity impact of integrating inorganic and organic fertilizer using on-farm and household survey studies. On-farm studies have compared maize yield on control plots where neither organic nor inorganic fertilizer was used with plots where only inorganic or organic fertilizer was used, and plots where organic and inorganic fertilizer were combined.

Comparing with control plots, Vanlauwe *et al.* (2001b) reported that maize yield was respectively 750, 1000 and 2000 Kg/ha higher in plots with inorganic fertilizer, organic fertilizer and combined inorganic and organic fertilizer. The findings were consistent with Sakala *et al.* (2003) who reported highest maize productivity impact on plots where green manure was integrated with inorganic fertilizer compared with plots with only green manure or with continuous cropping. Fandika *et al.* (2007) reported similar findings where optimum maize yield was found in fields where nitrogen fertilizer (Urea) was mixed with either compost manure or farmyard manure unlike fields with sole application of nitrogen fertilizer or manure. Munthali (2007 citing Chilimba et al. (2004)) showed that sole application of inorganic fertilizer and organic fertilizer, respectively, yielded 6.5 t/ha and 6.9 t/ha. On the other hand, integration of organic and inorganic fertilizer yielded a maximum of 7.5 t/ha.

Using household survey data, Tchale and Sauer (2007) found that use of integrated soil fertility management (ISFM) where organic and inorganic fertilizer were combined had higher levels of technical efficiency (91%) than when inorganic fertilizer was used in isolation (79%). There was a loss of yield of 143 Kg/ha in plots with chemical fertilizer only due to technical inefficiency but it was only 58 Kg/ha for households that used ISFM. In a related on-farm study, Vanlauwe *et al.* (2011) reported nitrogen agronomic use efficiency (Vanlauwe *et al.*) of maize between 17-26 Kg/KgN depending on maize variety. When fertilizer was mixed with organic manure or compost, the result of NUE was 36 Kg/KgN.

A meta-analysis by Chivenge *et al.* (2011) showed that application of organic resources, inorganic nitrogen fertilizer and integration of organic and inorganic fertilizer increased maize yield by 60%, 84% and 114% respectively. The combined effect was due to extra nitrogen available from inorganic fertilizer with organic resources inducing nitrogen use efficiency and water retention (Vanlauwe *et al.*, 2001a). In contrast, an on-farm study by Ngwira *et al.* (2013b) showed that maize yield was higher with sole fertilizer application followed by compost plus fertilizer and compost only relative to no fertilizer no compost. However the impact was highest in areas with long history of compost use, good rainfall and good soils. This is because good soils means all essential nutrients are available including soil organic matter that increases nitrigen use efficiency. With poor soils and low rainfall, the soils require compost manure to increase nitrogen use efficiency thereby increasing maize yield. In a related study Kaczan *et al.* (2013) observed that application of crop residues increased maize yield response by 86-216%.

3.4 Impact of conservation agriculture

Several on-farm studies have examined maize yield on plots with and without CA or its principles separately. Materechera and Mloza-Banda (1997) compared maize yield on convention and minimum tillage for consecutive three seasons and found that at the third season maize yield was significantly less on minimum tillage. The reason was that soil texture was affected with development of hard and compact layer under the soils restricting maize root development. Contrary, in a review paper, Rusinamhodzi *et al.* (2011) observed consistent evidence of maize yield increase under CA over time. However the impact was reduced in high rainfall areas as mulching increased water lodging. In Balaka and Ntcheu districts Ngwira *et al.* (2012) found consistent higher maize yield in CA plots than fields with conventional practices (Brouder & Gomez-Macpherson). The impact was much higher in drier years of 2010 and 2011 where maize yield was 4.4 t/ha on CA and 3.3 t/ha on CP.

In another study, Ngwira *et al.* (2013a) reported that plots with CA treatments were 22.1-23.6% higher in maize yield than convention plots. Wall *et al.* (2013) reviewed 23 studies from Eastern and Southern Africa and only five reported yield decline in CA systems compared to conventional control systems. CA may fail due to lack of crop residues and crop nutrients. Nonetheless, CA systems have no immediate yield advantage, as there is often delay of 2-5 years and that delay is at times interpreted as failure by impatient farmers and researchers. Ngwira *et al.* (2013c) also reported higher maize yield in CA systems than CP in Balaka and Nkhotakota districts in Malawi. The impact was immediate in drier agro-environment in Balaka but there was a delay of five years in an area of high rainfall in Nkhotakota.

Thierfelder *et al.* (2013) also showed that maize yield was 24-40% higher on CA systems than conventional ridge and furrow system. The larger impact is associated with better water infiltration in CA systems that often offset frequent seasonal dry spells. It is worth noting that the yield impact was not immediate but greater after five seasons of consistent practice. Thierfelder *et al.* (2015a) further found that 80% of experimental plots, maize yield was higher on CA than on CP. The decline in yield for the 20% plots was attributed to limited experience of farmers in first years, slow soil fertility build-up, and water lodging in some years. Comparing manual CA systems using dibble stick with sole maize and maize-legume intercropping, maize yield was respectively, 1152

Kg/ha and 1172 Kg/ha higher on CA. Unlike the case with FISP where studies observe no enduring effect, CA impact on maize productivity increases with time of practice. Thierfelder *et al.* (2016) also showed higher yields in manual CA systems than other treatments that included conventional systems.

In another experimental evidence from Malawi, Mozambique, Zambia and Zimbabwe, Thierfelder *et al.* (2017) showed that maize productivity was higher on 80% of the plots with CA than those with conventional practices. Evidence from Malawi showed that under normal rainfall conditions of 2010/11 CA bettered conventional based systems in yield by 12-16% only but the difference was 38-66% when a dry spell of more than 40 days occurred in 2014/15. Steward *et al.* (2018) found that crop yields under CA are in general greater than on CP systems especially in drier areas with a precipitation balance of less than 200 mm. Maize yield was consistently higher on CA systems than CP under any levels of water stress, heat stress and nitrogen application given same conditions.

4. Synthesis of the findings and way forward

The discussion in section 3 provides evidence that the impact of farm input subsidies on maize productivity is modest. While aggregate national maize production appear to have improved in non-drought years due to FISP implementation, marginal maize productivity impact of FISP remains below agronomic average. Furthermore, the long-term impact of the program appears uncertain. The main reason is that the soils are highly degraded of vital nutrients and organic matter. The situation is worsened by regular weather shocks especially droughts and prolonged mid-season dry spells. The combined effect of poor soil fertility, low soil organic matter and water stress due to droughts means that maize-fertilizer response is low. The nutrient and water retention capacity is low resulting in poor maize productivity impact. Increasing nitrogen intake through input subsidies without first addressing soil condition does not solve the problem of poor maize productivity in such instances because the soils are not responsive enough. On the other hand, maize productivity is high and stable with enduring effects on experimental plots where inorganic and organic fertilizer are integrated. The results are equally high on experimental plots with CA compared to convention practices. These technologies enhance nutrient intake, nutrient maintenance and drought-resilience.

The poor maize-fertilizer response among FISP beneficiaries is also because of poor timing of input delivery, receiving less than the required amount of inorganic fertilizer and targeting errors. Often times, subsidized inputs in Malawi are delivered after the onset of the rains. This greatly affects maize-fertilizer response because Malawi receives unimodal type of rainfall that lasts between November and April (DCCMS, 2006) such that any delay in input use result in inefficient use. It is recommended in Malawi to plant maize with the first rains and that any delay of one-two weeks result in 25% yield loss. Furthermore, fertilizer application is supposed to be at planting time or within five-seven days of planting (Government of Malawi, 2012b). Receiving less than the required amount of inorganic fertilizer is another problem that causes poor maize-fertilizer response because farmers tend to use less than the recommended application rates. Agronomically, an acre (approximately 0.4 ha) of maize – a target for Malawi FISP – requires 100 Kg of inorganic fertilizer (Chilimba *et al.*, 2005; Government of Malawi, 2012b; Arndt *et al.*, 2015). When FISP beneficiaries receive less than this amount, they tend to reduce application rates in order to cover a large maize area. This is because most of FISP beneficiaries are too poor to supplement the subsidised inorganic fertilizer with commercially purchased fertilizer. Another challenge as reported by Holden and Lunduka (2013) is targeting errors. An error of inclusion for example where less productive farmers are subsidised, result in inefficient use of the inputs. Often such farmers lack productive resources such as labour and usually cultivate on poor and degraded soils that are less responsive to subsidised inorganic fertilizer. Subsidising better-off farmers is another example of an error of inclusion because such farmers have the capacity to purchase the inputs commercially. Although these farmers use the subsidised inputs efficiently, this error result in displacement of commercial fertilizer.

Recent reforms in Malawi FISP as reported by the Centre for Development Management (2017) shows that the government is working towards minimising targeting errors and on improving timely input delivery by increasing private sector involvement. The government has also intensified means of addressing drought-resilience concerns with the inclusion of drought tolerant (DT) maize seed in FISP packages as well as inclusion of legume seeds (Holden & Fisher, 2015). However soil condition concerns remain unaddressed in FISP implementation strategies. The findings in this literature review show that addressing soil condition issues by integrating subsidized inorganic fertilizer with organic fertilizer and CA has potential to enhance the impact of FISP. There are likely to be multiple benefits of FISP with the inclusion of DT maize seed and potential integration of subsidised inorganic fertilizer with organic fertilizer and CA. The approach has potential to achieve drought-resilience, improved nutrient build-up, and water and nutrient retention, thereby enhancing efficiency with which subsidised inputs are used. Consequently, the impact of FISP on maize production and productivity is likely to be high, consistent and enduring and provide means for exit.

Integration of inorganic and organic fertilizer has been achieved on experimental plots, but achieving the same on farmer-managed plots is still a challenge. There are several implementation hiccups that needs urgent attention. I discuss in sections 4.1 and 4.2 below the key challenges and possible options.

4.1 Policy synchronization

The National Agriculture Policy (NAP) (Government of Malawi, 2016b) recognizes the importance of integrating organic and inorganic fertilizer through ISFM and adoption of CA as a CSA technology. However integration on farmer-managed plots remains low because policy instruments that enhance access to and use of CSA technologies are not well synchronized. FISP as a key policy instrument has successfully increased access to and use of inorganic fertilizer (Lunduka *et al.*, 2014; Karamba & Winters, 2015) but its implementation is not well connected to the promotion of adoption of organic fertilizer and CA. This affects integration process. On the other hand, the government promotes organic fertilizer and CA through agricultural extension services that are often deprived of adequate funding. The two agriculture policy strategies – FISP and agriculture extension services – appear to compete for the meagre government resources thereby affecting operations of one or both. The huge budget requirement for FISP (Branca *et al.*, 2011) for example makes it difficult to increase budget allocation to agricultural extension services (Carr, 2014). Although recent reforms have resulted in reduction in FISP budget (Centre for Development Management, 2017), the savings have not been reallocated to other agricultural programs such as extension services because the government has equally other pressing needs in other sectors other than agriculture. Making adoption of CSA technologies as a prerequisite to accessing FISP would harmonise the operations of FISP and agricultural extension services thereby enhancing integration.

Another challenge to integration of organic and inorganic fertilizer is that the problem of declining soil fertility receives less attention than the problem of low fertilizer use (Jayne & Rashid, 2013). There has been great emphasis on low fertilizer use as a reason for low maize production and hence implementation of FISP but little has been emphasized on declining soil fertility. Policy discussions have been dominated by the problem of market failures of inputs and credit but how soil fertility is declining due to high population densities, continuous cropping and mono-cropping is given little attention. The issues of declining soil fertility and low fertilizer use need equal policy attention.

Furthermore, while subsidized inorganic fertilizer have immediate production benefits, technologies that address declining soil fertility concerns such as organic fertilizer and CA have lagged but long-term benefits (Snapp *et al.*, 1998; Thierfelder *et al.*, 2017). Unfortunately, many smallholder farmers are impatient as they give more weight to immediate gains of the technologies than the future benefits. As a result, they tend to dis-adopt technologies with delayed benefits after one or two seasons. This inconsistent use affects the impact and threatens potential integration of inorganic and organic technologies. Overcoming the risk of delayed production benefits can improve on consistent use of these technologies thereby achieving long-term integration process of organic and inorganic technologies. Following the emphasis in the NAP on the need to increase efficient and timely access to organic and inorganic fertilizer and adoption of CSA technologies such as CA (Government of Malawi, 2016b), policy tools should reflect the same to allow farmers adopt integration.

One option is as proposed by Snapp *et al.* (2014) that FISP should be redesigned in such a way that it is conditioned on adoption of soil fertility enhancing and climate-smart technologies. The authors (ibid) proposed '*conditional universal subsidy*' where farmers will only access subsidized inorganic fertilizer upon adoption of such complementary technologies. Conditioning access to subsidized inorganic fertilizer on adoption of organic fertilizer and CA could efficiently increase adoption of all. Agricultural extension officers would concentrate on core services of training and advising farmers on appropriate agronomic activities such as use of organic fertilizer and CA, and identify FISP beneficiaries from adopters of such CSA technologies. While these technologies have delayed production benefits, the potential access to input subsidies after adoption could be an incentive for the farmers to use the technologies consistently. The result will be high nutrient build-up, an increase in soil organic matter as well as high water and nutrient retention thereby increasing maize-fertilizer response. Potentially, this can provide the government with a sustainable exit strategy from FISP without compromising on sustainable maize production and productivity.

4.2 Integration process

Another way of ensuring integration of organic and inorganic technologies on farmer-managed plots is to have a clear and detailed integration process. There is need to develop appropriate methods of integration as a first step. Certainly different organic sources for organic fertilizer contain different quantities of nutrients (Chilimba *et al.*, 2005; Ngwira *et al.*, 2013b). The appropriate combination rates of inorganic fertilizer with organic inputs such as compost manure, farmyard manure, green manure, agroforestry prunings or other organic sources are not known. Smallholder farmers do not have the required technical knowhow to effectively and efficiently adopt integration of inorganic and organic fertilizer. Snapp *et al.* (2014) therefore recommended investments in agronomy to develop site-specific recommended rates for integration. This should be built on the site-specific inorganic fertilizer application rates developed by the Government of Malawi (2012b). Providing farmers with proper knowledge of preparation and integration is paramount to have good quality of integrated inorganic and organic inputs.

The next phase is to invest in agricultural extension services to train farmers in organic fertilizer preparation and CA process (Ngwira *et al.*, 2013b). In addition farmers should be made aware of potential short-term, medium-term and long-term benefits of these technologies including integration of organic and inorganic fertilizer Munthali (2007). Such vital information should accompany implementation of FISP to allow farmers adopt relevant agronomic technologies besides adopting inorganic fertilizer (Munthali, 2007; Snapp *et al.*, 2014). Agricultural extension services should ensure that farmers appropriately follow agronomic recommendations on applying CA and integration of organic and inorganic fertilizer.

The implementation strategy of FISP should abandon the current farmer-based targeting system and provide the subsidies to all farmers who adopt organic fertilizer and CA. That is, targeting the soil and not the farmer. This targeting will ensure that farmers adopt organic fertilizer and CA first before accessing subsidized inorganic fertilizer. This will allow targeting of inorganic fertilizer application on soils that are of good quality to achieve high nitrogen and water use efficiency and subsequent increase in maize production and productivity. Due to budget constraints, the program should maintain the target of 0.4 ha of land for maize production. Thus, identification of FISP beneficiaries should follow those farmers that have appropriately adopted organic fertilizer and CA for a minimum of 0.4 ha of land. Agricultural extension officers should closely follow up with beneficiaries to allow proper exit from FISP.

5. Conclusion

Farm Input Subsidy Program remains the strategic agriculture policy tool for Malawi in the near future. There is no doubt that the program has increased access to and use of inorganic fertilizer with modest impact on maize productivity. The current implementation strategy where soil fertility issues are grossly ignored and beneficiaries continue cultivating on degraded soils reduces enduring effects of the program and locks farmers into low maize response rates to fertilizer use. The incremental impact of the program is low and the situation is worsened because of frequent dry spells. Addressing soil fertility and drought-resilience issues through adoption of integration of inorganic and organic fertilizer and CA is potentially a magic bullet to increase maize-fertilizer response and achieve sustainable maize productivity gains from FISP. Nonetheless achieving integration on farmer-managed plots is unlikely because policy instruments promoting access to and use of inorganic and organic fertilizer and related CA are not firmly harmonized. I recommend synchronization of policy tools in this paper by conditioning access to FISP on adoption of organic fertilizer and CA. Strategically, the harmonization should involve investment in agronomic research and agricultural extension services and transformation of FISP implementation strategy. This approach can provide the Government of Malawi with an opportunity for a sustainable exit strategy from FISP.

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Samson Pilanazo Katengeza was born in Lilongwe, Malawi. He holds a BSc. Degree in Agriculture (Agricultural Economics) from the University of Malawi, Bunda College obtained in 2006 and an MSc. Degree in Agricultural and Applied Economics from Makerere University, Uganda obtained in 2009. Samson is currently a Senior Lecturer in Agricultural Marketing with Lilongwe University of Agriculture and Natural Resources (LUANAR), Bunda Campus, Malawi.

This thesis examines farmer uptake and opportunities of climate-smart agriculture (CSA) technologies in Malawi using a four-wave household panel data of nine years (2006-2015) merged with daily rainfall data (2003-2015). Specifically, I have tested how exposure to dry spells influences use of CSA technologies and how adoption affects maize productivity in the face of weather shocks. The thesis is a collection of four independent but related papers with an introductory chapter summarising the results from the four the papers.

The results show that farmers build weather expectations from previous weather conditions and respond to weather risks by investing in CSA technologies. The results further indicate that immediate dry spells are more influential in building weather expectations than long-term weather conditions and hence more significant in enhancing use of CSA practices. I have also argued in the papers that CSA technologies have potential to protect farmers from drought-related maize yield losses and provide stable and long-term maize productivity effects.

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