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AGRICULTURAL INPUT INTENSIFICATION, PRODUCTIVITY GROWTH, AND THE TRANSFORMATION OF AFRICAN AGRICULTURE

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AGRICULTURAL INPUT INTENSIFICATION, PRODUCTIVITY GROWTH, AND THE TRANSFORMATION OF AFRICAN AGRICULTURE

DISSERTATION

A dissertation submitted
in partial fulfillment of the requirements for
the degree of Doctor of Philosophy
in the College of Agriculture, Food and Environment
at the University of Kentucky

By

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Lexington, Kentucky

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Lexington, Kentucky 2017

ABSTRACT OF DISSERTATION

AGRICULTURAL INPUT INTENSIFICATION, PRODUCTIVITY GROWTH, AND THE TRANSFORMATION OF AFRICAN AGRICULTURE

This dissertation studies agricultural input intensification, defined as the increased use of modern inputs such as hybrid seeds, mineral fertilizer, herbicide, and pesticide in African agriculture. It also analyses the potential of this intensification to accelerate productivity growth and tests the effectiveness of two policies, input subsidies and land reforms, in promoting it and consequently in increasing crop yield. In the first essay, we argue that to create the conditions for the emergence of a green revolution in Africa, modern agricultural technologies have to be adopted as a package, not in a piecemeal fashion. This argument is consistent with a conceptual framework that we develop to illustrate the importance of harnessing strategic complementarities among agricultural technologies by adopting them simultaneously rather than sequentially. Based on this framework, we propose a methodology to estimate an index to measure agricultural input intensification in its many dimensions. The index provides a simple and intuitive measure to quantify joint adoption of several inputs and compare it across plots, crops, farmers, and regions. Applying this methodology to maize producers in Burkina Faso and Tanzania, we show that our estimated index is a valid measure of joint input adoption and effectively captures the relative importance of each input as well as the number of different inputs adopted. Using the estimated index, we find that simultaneous adoption of modern inputs in Burkina Faso and Tanzania is limited but not rare. Most importantly, we find that the impact of the adoption of individual modern inputs on yield is increasing with the level of intensification for others.

In the subsequent two essays, we assess the effectiveness of government's direct intervention through input subsidies and indirect intervention through land reforms in promoting agricultural input intensification and increasing productivity. Our empirical analyses focus on Burkina Faso, a country that has recently implemented a fertilizer subsidy program and is undertaking profound land reforms to improve land tenure security and land transferability among households. The second essay tests the hypothesis that subsidizing only one input might promote or discourage the use of other inputs. We find that fertilizer subsidy for maize farmers in Burkina Faso crowds in the use of hybrid seeds and crop protection chemicals, but discourages the use of manure. The last essay assesses whether the development of rural land rental markets can facilitate land transferability among farmers and increase input intensification and productivity. The findings suggest that land rental transfers land from less talented or committed farmers to the more able, but it has minimal impact on input intensification. However, our results show that land renters are more productive and better farm managers. These results suggest that the short-term gains from policies that foster the development of land rental markets in Burkina Faso, and more generally Africa, will likely be in terms of efficiency rather than widespread adoption of modern agricultural technologies.

KEYWORDS: Agricultural Intensification, Fertilizer Subsidies, Land Rental, Crop Productivity, Efficiency, Africa

Didier Yélognissè Alia

July 14, 2017

Date

AGRICULTURAL INPUT INTENSIFICATION, PRODUCTIVITY GROWTH, AND THE TRANSFORMATION OF AFRICAN AGRICULTURE

By

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Date: July 14, 2017

To my beautiful wife Katia and my son Joackim

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Chapter 1 Introduction

This dissertation examines the landscape of input use in African agriculture to quantify the extent of input intensification, defined as the increased utilization of modern technologies such as hybrid seeds, mineral fertilizer, herbicide, and pesticide (mainly insecticide but also fungicide, rodenticide, and other chemicals that protect plants again diseases and pests). It also analyses the underlying determinants of such intensification and evaluates the effectiveness of various policy interventions in input and factor markets in stimulating it. This introductory chapter 1 discusses the context of the dissertation, its objectives, research questions, and main contributions.

1.1 Background

Since their independence, African countries face multitudinous development challenges that have resulted in substantially low standards of living (Sachs and Warner, 1997; Easterly and Levine, 1997; Barrios et al., 2010). However, during the past two decades, significant progress in term of macroeconomic performance has occurred and culminated in stable economic growth (Young, 2012; Rodrik, 2016). Since 2000, the Gross Domestic Product (GDP) of the continent has increased at an average annual rate of 5.2%, and as of 2017, six out the 13 fastest-growing economies in the world are in Africa[1]. Despite these macroeconomic performances, poverty in Africa South of the Sahara remains widespread.

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[1] These countries are Rwanda (12th with a growth rate of 7.12%), Tanzania (11th with a growth rate of 7.15%), Mozambique (10th with a growth rate of 7.30%), Cote d'Ivoire (6th with a growth rate of 7.80%), Democratic Republic of the Congo (3rd with a growth rate of 8.62%), and Ethiopia (1st with a growth rate of 9.70%).

Since most poor households are concentrated in rural areas where agriculture is often their main and only source of income (Smale et al., 2016; Diao et al., 2010; Barrett et al., 2001), it is clear that the recent macroeconomic performance in Africa has not been inclusive of the agricultural sector and rural areas. The agricultural sector in African continues to underperform. Crop yields lag behind levels in other regions and productivity growth continues to be sluggish (Sheahan and Barrett, 2017). Between 1961 and 2000, average cereal yields have fluctuated around 0.8 ton/ha and only experienced modest increases afterward to reach 1.3 ton/ha in 2014 (FAOSTAT, 2017). However, this yield represents less than half cereals yield in the rest of developing countries and less than a quarter of yield in high-income countries. These observations led many to conclude that the green revolution of 1970-90 bypassed Africa (Evenson and Gollin, 2003; Estudillo and Otsuka, 2013).

The consequence of a low agricultural productivity is that hundreds of millions of rural households who depend on agriculture for food and income are in chronic food insecurity and poverty. Economic theory and historical experiences have shown that agricultural productivity growth is a prerequisite to clinging on the ladder of economic transformation and economic development (Barrett et al., 2004; Diao et al., 2010). With very few exceptions[2], no country has been able to develop itself without first solving the food problem and releasing resources from agriculture by raising agricultural productivity. Thus, addressing the challenges African farmers are facing in increasing productivity is necessary to ensure the structural transformation and economic development of the continent.

On the premise that agricultural productivity growth is essential for economic development, an abundant literature has developed to understand the causes of low crop yield and labor productivity in developing countries and particularly in Sub-Saharan

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[2] Resource-abundant countries of the Gulf and geographically small but high developed built on a service economy such as Singapore, Hong-Kong, are notable exceptions.

Africa (Feder et al., 1985; Barrett et al., 2004). Crop yields are constrained by a wide array of production-limiting factors. These constraints range from biophysical constraints to agronomic constraints, and to socio-economic and institutional barriers (Diagne et al., 2013). Optimal production under such constraints requires the adoption of modern agricultural technologies such as hybrid seeds, fertilizer, herbicide, insecticide, and other improved soil and water management techniques (Morris, 2007; Evenson and Gollin, 2003). In fact, the green revolution in Asia and subsequently in Latin America was mainly driven by the widespread adoption of these modern agricultural technologies (Pingali, 2012).

However, faced with a multitude of agronomic constraints, smallholder African farmers use fewer modern inputs than their counterparts do in the rest of the world (Sheahan and Barrett, 2017). From the historical experience of countries that realized a green revolution and given the constraints facing African agriculture, it is clear that input intensification in a sustainable manner is the most promising path to increasing crop productivity. This is particularly relevant today with limited available options for land expansion to due increasing population (Muyanga and Jayne, 2014), depleted soils (Marenya and Barrett, 2009), and the adverse effect of climate change (Kurukulasuriya et al., 2006).

Agricultural input intensification is increasingly recognized as critical in African agriculture policy circles and by development partners and important progress has been made in the adoption of modern agricultural input and agricultural productivity growth since the 2000s. FAO data show that, after decades of stagnation, cereal yields in most African countries have started to increase since the mid-1990s. From 1995 to 2014, the average yields of maize for all countries increased from 1.69 ton/ha to 2.1 ton/ha, that is a 25% growth over the 20 years. Rice paddy yield recorded a growth rate of 29% over the same period. Other crops have also been performing relatively well. However, the yield growth rates are far below levels in other regions. Over the same period, Maize yield grew by more than 70% in Asia and 150% in South America. Thus, to accelerate agricultural productivity growth in Africa, a paradigm shift in policy thinking is necessary.

1.2 Motivation and research questions

The motivations underlying this study are to provide a new perspective on how to increase crop productivity and expedite the emergence of the much-needed and long-awaited African green revolution. Given the historical experience in other regions and the constraints African farmers are facing, it is self-evident that traditional farming systems relying exclusively on labor, land, and nature (rainfall) have reached their limit when it comes to increasing yield. Like many others (Sheahan and Barrett, 2017; Evenson and Gollin, 2003), we advocate in this dissertation for more intensive farming systems that take advantage of technological progress and use modern inputs such as hybrid seeds, mineral fertilizer, and crop protection chemicals necessary to increase yield in Sub-Saharan Africa. Agricultural input intensification also holds the potential of transforming African agriculture and rural spaces in order to propel economic development (Denning et al., 2009; Chirwa and Dorward, 2013).

This view on the importance of agricultural input intensification has always been recognized and integrated into agricultural policies. Between 1960 and the late 1980s, nearly all African countries implemented some input subsidy programs with the objective of facilitating smallholder farmer access to critical agricultural inputs, increasing production, and reducing food insecurity and poverty (Ricker-Gilbert et al., 2013). After being phased out in the 1990s due to macroeconomic instabilities and the subsequent implementation of liberalization policies, input subsidies programs resurfaced in the early 2000s (Banful, 2011; Jayne and Rashid, 2013). However, the overall results of intensification policies in Africa have been dissatisfying. Crop yields have marginally increased but at rates far below what could be qualified as a green revolution. This poses the question of the effectiveness of current approaches to input intensification in African countries in delivering on the promises improving agricultural productivity and economic development.

The observation that productivity growth in African agriculture is improving but remains too slow propels us to examine the question of what is the optimal approach to agricultural input intensification that will markedly increase yield and transform African agriculture. To achieve this big and ambitious objective, we address the following three intermediary questions:

i) Which farmers will lead the African green revolution?

ii) Can input subsidies accelerate intensification in a more comprehensive manner to increase productivity?

iii) What will the transformation of African agriculture look like?

Our answers to these questions lead us to make the following three points on agricultural input intensification and productivity. First, we argue that to create the conditions for the emergence of a green revolution in Africa, modern agricultural technologies have to be adopted as a package, not in a piecemeal fashion. An overview of the landscape of modern input use in African agriculture reveals that adoption is incomplete and partial with farmers adopting one or two inputs without using other complementary technologies (Sheahan and Barrett, 2017). For instance, many farmers apply mineral fertilizer on their farms but do not use hybrid seeds. This partial adoption of fertilizer often results in a moderate increase in yield that might not be large enough to offset the cost of acquiring fertilizer. Most hybrid seeds have high yield potential and are specifically selected to be more responsive to mineral fertilizer than traditional seeds. Thus, a package of fertilizer plus hybrid seeds will likely guarantee a relatively higher yield to farmers. Recent studies have also shown that mineral fertilizer needs to be complemented with other non-mineral nutrients, particularly on acid or depleted soil, to improve their effectiveness (Burke et al., 2017; Marenya and Barrett, 2009). In Kenya, Matsumoto and Yamano (2011) find that many farmers are already applying nitrogen at an agronomic optimal level, and further increases in yield can only occur with complementary technologies. Moreover, weeds, diseases, and pests can inflict significant damages to crop if plants are not protected during the vegetative phase of their development (Oerke and Dehne, 2004; Diagne et al., 2013; Kaminski and Christiaensen, 2014). Therefore, the return in terms of productivity gain from the sole application of mineral fertilizer might never materialize, prohibiting adoption in subsequent seasons.

We formulate the hypothesis that to substantially increase crop productivity, farmers need to use a package of technologies that will concurrently address issues with the quality of seeds, soil nutrients problems, and the protection of plants again biotic and abiotic stresses. We test this hypothesis by assessing the impact of agricultural input intensification on productivity. The basic question is: Do households with higher application rates of various modern inputs also have higher crop yields? If so, that provides evidence of the merits for a holistic approach to agricultural input intensification that emphasizes the adoption of a package of complementary inputs. Most importantly, it will suggest that farmers who will adopt a package approach to modern input utilization are the one who will lead Africa toward a green revolution. Given the significant role risk and learning play in village economies, focusing efforts of “innovative farmers” that adopt a package approach to input intensification can set the stage for others to follow and adopt the same technologies.

Having assessed the importance of a package approach to modern input adoption in African agriculture, the second point we made in this dissertation relates to the role of direct government interventions in promoting input intensification through agricultural input subsidies. During the past two decades, dissatisfied with the absence of progress in rural development with market reforms and structural adjustment programs of the 1990s, many African governments have recommitted to increasing support to the agricultural sector (Jayne and Rashid, 2013). A number of large-scale input subsidy programs emerged across the continent with the objective of increasing smallholder farmers' access to modern inputs (Chirwa and Dorward, 2013). However, the effectiveness of these interventions in increasing input utilization and yield is the subject of heated debates (Ricker-Gilbert et al., 2013). We investigate the hypothesis that not only subsidies could increase the adoption of the targeted input but could have spillover effects on the adoption of others complementary inputs not subsidized. For this test, we exploit a unique quasi-experiment in Burkina Faso, in which the government implemented a subsidy program that focuses singularly on mineral fertilizer and provides no support to other inputs. Our study sheds light on overlooked aspects of the potential impact of input subsidy programs in Africa.

Another lever of action for the government is the creation of an enabling environment and market conditions for private agents to increase farm investment. One particular example is to facilitate land transferability among farmers through better securing of land rights. Not everyone has to stay in the farming sector. In fact, an empirical regularity in development is the gradual decrease of the share of agriculture in employment as economies develop. If African agriculture and economies have to transform, land has to be moved from the hands of underproductive, non-innovative, and non-committed individuals to the ones that are more committed, more innovative, and more productive. This is the underlying assumption of land reforms that are becoming popular in Africa. To what extent this hypothesis holds is however not well investigated in the literature. We fill this gap by assessing the impact of land rental on agricultural input intensification, productivity, and production efficiency. This study will shed lights onto how the structural transformation of African agricultural might play out and what role land reforms will play.

1.3 Structure of the dissertation

We structure the dissertation around three essays each addressing specific aspects of agricultural input intensification in African agriculture. The three essays are:

i) Essay 1: Accelerating the realization of a green revolution in Africa: A package approach to agricultural input intensification as an optimal farming system;

ii) Essay 2: Killing many birds with one stone? Spillover Effects of Fertilizer Subsidies on the Adoption of Modern Inputs in Burkina Faso;

iii) Essay 3: Rural transformation in Africa: The role of land rental markets in agricultural input intensification and production efficiency in Burkina Faso

In the first essay (Chapter 2) entitled *"Accelerating the realization of a green revolution in Africa: A package approach to agricultural input intensification as an optimal farming system"*, we study the importance of agricultural input intensification and assess its impacts on productivity. Over the past two decades, crop yields in Africa have increased as the result of the improvement in the use of modern inputs, particularly mineral fertilizer. However, observed productivity growth remains low in comparison to levels experienced in other regions and to the potential achievable on the continent. In this essay, we investigate the potential of agricultural input intensification to increase productivity and accelerate the realization of a green revolution in Africa. To empirically measure input intensification, we develop and estimate an agricultural input intensification index ($A3i$) that accounts for the correlations that exist between farmer's adoption and utilization decisions to use several modern inputs and summarizes these decisions into one variable.

We apply this methodology to nationally representative household surveys for two countries, Burkina Faso and Tanzania, representing two different production environments. Our analysis focuses on maize, the main staple food in both countries and across Africa. First, our descriptive analysis shows that input adoption rates in Burkina Faso and Tanzania are low but are improving over the years. In particular, significant progress has been made in the adoption of mineral fertilizer. However, the adoption of hybrid seeds is still lagging and crop protection chemicals - insecticide and herbicide - are overlooked opportunities (Tamu et al., 2017). We also find that the adoption of modern input is associated with higher maize yield, and the joint adoption of more than one input is associated with a much stronger increase in yield. This suggests that to accelerate agricultural productivity growth in Africa, a greater focus should be placed on promoting and facilitating modern input adoption as a package rather than a narrow focus on only mineral fertilizer.

The second essay (Chapter 3) entitled *"Killing many birds with one stone? Spillover effects of fertilizer subsidies on the adoption of modern inputs in Burkina Faso"* evaluates the spillover effects of the receipt of fertilizer subsidies on the adoption of modern inputs. The empirical analysis exploits a unique experiment in Burkina Faso where the government implemented since 2008 a subsidy program that focused singularly on mineral fertilizer. We exploit this unique feature and use panel data on maize producers covering the period 2010-2012 to test the hypothesis that subsidizing only one input might promote or discourage the use of other inputs. We address three econometric issues as follows: i) the simultaneity in input use decisions, by using seemingly unrelated regressions; ii) unobserved household heterogeneity, by using correlated random effects; and iii) endogeneity of participation in the subsidy program, by using the control function/instrumental variable approach.

We find that the receipt of fertilizer subsidy by maize farmers crowds in the use of hybrid seeds and crop protection chemicals, but crowds out the use of manure. These results suggest that subsidies can be effective in promoting a comprehensive adoption of modern input by relaxing the household budget constraints with respects to the subsidized input. Ignoring theses spillover effects could lead to an underestimation of the impact of the program. However, the crowding out of manure, which is consistent with the hypothesis that farmers view mineral fertilizer and manure as a substitute, is detrimental to productivity, given the beneficial effect of manure on soil fertility. An effective promotion and sustainable intensification in modern input using mineral fertilizer subsidies need to be implemented in conjunction with measures to promote or maintain manure use.

The last essay (Chapter 4) asks the question of how the structural transformation of African agriculture might play out. A key feature of structural transformation is the simultaneous increase in agricultural productivity and decrease in agricultural labor share in total employment. This transformation implies that some individuals will have to be pushed out or pulled out from agriculture. The development of rural land rental markets can facilitate land transferability among farmers. However, such land transfer will enhance productivity only if land markets transfer land from underproductive individuals to the more committed, more innovative, and more productive ones. This essay entitled *"Rural transformation in Africa: The role of land rental markets in agricultural input intensification and production efficiency in Burkina Faso"* aims at testing this hypothesis. It assesses whether land rental markets incentivize farmers to increase input intensification and productivity.

We use a nationally representative household panel data from Burkina Faso to identify the determinants of farmers' participation in land rental markets and assess the resulting impacts on input intensification, productivity, and production efficiency. Using a double hurdle model, we find that households' farming ability and commitment to agriculture positively correlate with their likelihood to rent in land and the amount of land rented in. We look beyond simple correlations by using a multivariable probit regression and the correlated random effects approach to account for unobserved household heterogeneity and potential endogeneity. We find that farmer's participation in land rental markets has a positive effect on the likelihood to use crop protection chemicals. The impact of land rental on mineral fertilizer and manure are positive but weak, and there is no significant effect on the use hybrid seeds or hired labor. However, using stochastic production frontier analysis, we find that land renters are better farm managers and experience fewer inefficiencies in their production processes. Taken together, our findings highlight the mixed effects on input intensification of policies that foster the development of land rental markets in Burkina Faso. Much of the gains from these policies might be in terms of increased efficiency of inputs and not necessarily the use of more inputs.

Chapter 2 Accelerating the realization of a green revolution in Africa: A package approach to agricultural input intensification as an optimal farming system

Following a long period of stagnation, crop yields in African agriculture have recorded a modest growth over the past two decades. However, observed productivity growth remains small in comparison to levels recorded in other regions and to the potential achievable on the continent. In this essay, we argue that a holistic approach to agricultural input intensification through the simultaneous utilization of various modern inputs remains the most promising path for agricultural productivity growth. However, there is a need for a paradigm shift in policy thinking and we advocate for a package approach to modern technologies diffusion and adoption as optimal farming systems to accelerate the emergence of the much-needed and long-awaited green revolution in Africa. We first show that in accordance with agronomic evidence, there are strong complementarities among various inputs in the production process and harnessing such complementarities enhances the marginal productivity of individual inputs and results in higher overall productivity growth. To measure input intensification, we develop a methodology to estimate an agricultural input intensification index ($A3i$) that captures farmer's overall attitude toward the simultaneous adoption of several inputs. Our index also accounts for the complementarities that exist between these inputs. We illustrate the application of this index using national representative surveys for Burkina Faso and Tanzania. After estimating $A3i$, we examine its pattern and determinants. We found that $A3i$ is positively correlated with various factors related to the household access to information through extension services, engagement in the production of cash crops, plot manager education level, and resources as measured by landholding and access to credit during the year prior to the growing season. We also find that the adoption of modern inputs is associated with higher maize yields, and the joint adoption of more than one input is associated with a much stronger increase in yield.

2.1 Introduction

There is a consensus that innovation is a key driver of productivity growth. In agriculture, innovation often simply takes the form of the utilization of modern inputs and farming practices such as hybrid seeds, mineral fertilizer, crop protection chemicals, and integrated soil and water management practices to address a wide range of production-limiting constraints (Feder et al., 1985; Byerlee, 1996). Farmers in Asian and Latin American countries that have adopted these technologies during the 1970s-90s experienced rapid increases in crop yields over a short period - a period termed as "green revolution" (Johnson et al., 2003; Pingali, 2012). However, this "green revolution" bypassed sub-Saharan African countries (Otsuka and Kalirajan, 2006; Toenniessen et al., 2008; Denning et al., 2009) where until the late 1990s crop yields have largely stagnated and remained low in comparison to other regions (Sheahan and Barrett, 2017). Given the importance of agriculture in the household livelihoods and the economy, it has become evident that addressing the challenges facing African farmers in increasing crop productivity is crucial to promote pro-poor economic development and food security (Byerlee et al., 2009).

Over the years, an abundant literature has emerged to analyze the causes of the poor performance of African agriculture (Feder et al., 1985; Foster and Rosenzweig, 2010). The evidence suggests that African farmers face many biophysical, agronomic, socio-economic, institutional constraints that limit productivity (Diagne et al., 2013). In coping with these constraints, input intensification, defined as the utilization of modern inputs and practices such as use of hybrid seeds, mineral fertilizer, crop protection chemicals, and soil and water management practices, is the most promising approach to sustaining yield growth (Feder et al., 1985; Evenson and Gollin, 2003). However, recent evidence shows that African farmers underutilize these inputs particularly on strategic staple crops such as maize, rice, millet, and sorghum[1] (Morris, 2007; Sheahan and Barrett, 2017). This gap in modern input utilization between Africa and the rest of the world explains part of the gap in agricultural productivity. Low adoption of modern agricultural inputs in Africa is due to a confluence factors, among which physical accessibility, resource constraints, incomplete markets (Karlan et al., 2014), risk and uncertainty (Dercon and Christiaensen, 2011; Duflo et al., 2009; Suri, 2011), and insufficient human capital play importand roles (Conley and Udry, 2010). Addressing these challenges holds enormous potential for boosting productivity, and ultimately food security and poverty reduction.

Recognizing the merits of agricultural input intensification, many African governments increasingly invest in programs to increase smallholder farmers' access to and utilization of modern inputs (Byerlee et al., 2009; Ricker-Gilbert et al., 2013). The old recipe of agricultural input subsidies remains the main policy instrument used by many governments (Jayne and Rashid, 2013). However, there are also significant reforms initiated to improve markets and increase investment in infrastructure. As the results of these concerted efforts over the past two decades, the adoption of mineral fertilizer by African farmers is improving and starts to translate into productivity growth observed (Sheahan and Barrett, 2017; Smale et al., 2013; Otsuka and Kalirajan, 2006). From 1995 to 2014, the average yield of maize in Africa increased by 25% from 1.69 ton/ha to 2.1 ton/ha (FAOSTAT, 2017). However, this yield remains low by international standards and a large productivity gap remains between actual yield in farmers' fields and attainable yield as recorded in experimental fields. Thus, it is clear that agricultural productivity growth in Africa remains slow and there is a need to find an optimal approach to accelerate this productivity growth.

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[1] Historically cash crops with well-functioning management organization such as cotton and sugar cane, and export oriented horticultural products tend to received large amount of mineral fertilizer (Jayne et al., 2003).

A snapshot of the agricultural input landscape in African agriculture shows that adoption is partial and imperfect in many aspects (Sheahan and Barrett, 2017). The incompleteness of input adoption manifests in the number of types of inputs used, the rate of application, and the number of fields or crops that received these inputs. In many cases, smallholder farmers tend to use one modern input promoted to them without using others that are also necessary. For instance, it is common for farmers to use subsidized mineral fertilizer on traditional seeds or use hybrid seeds without further amending depleted soil with nutrients (Kijima et al., 2011). In this essay, we argue that in order to create the conditions to accelerate productivity growth and the emergence of a green revolution in Africa, agricultural technologies must be adopted as a package and not in a piecemeal fashion.

Economists have long observed partial adoption of technologies even when they are promoted as a package (Mann, 1978; Feder, 1982; Leathers and Smale, 1991). It has even been argued that such piecewise adoption of innovation might reflect the strategic choice of farmers in the face of various constraints (Ellis, 1992). If this is the case, then farmers will first adopt technologies that provide the highest return, and subsequently, adopt complementary ones. One example ranking of technologies based on complexity, cost, and expected return consists in adopting mineral fertilizer, and when resources permit or the experiment is successful subsequently adopt hybrid seeds, and then crop protection chemicals, farm equipment, and irrigation systems, if possible. Derek and Hesse de Polanco (1986) found evidence that barley farmers in the Mexican Altiplano adopted this strategy and it seems profitable for them.

However, the piecemeal approach to input adoption overlooks the fact that there are important synergies and complementarities among different inputs enhancing their marginal productivities. Furthermore, in many cases, the sole utilization of one type of modern input could be ineffective in increasing productivity enough to offset the cost of investment. For instance, certain hybrid seeds are developed to be responsive to mineral fertilizer in harsh growing conditions (van Bueren et al., 2011). When farmers plant these seeds on depleted soils without further amendment with key nutrients, their performance could be worse than indigenous seeds. In fact, there has been documented evidence of dis-adoption of improved rice seeds in Uganda due to unsatisfying return explained in part by failure to use complementary inputs (Kijima et al., 2011). In many instances, when farmers are given subsidized fertilizer, the increase in yield and revenue are insufficient to sustain fertilizer use at market prices after the subsidy program ends. A recent study by Burke et al. (2017) shows that maize yield response to nitrogen and phosphorus in Zambia are relatively smaller than in Asia discouraging farmers from increasing investment in these nutrients.

The package approach to technology adoption has been the conventional philosophy in developed countries (Leathers and Smale, 1991). Researchers and extension agents, concerned by the large gap between yields on experimental stations and yields recorded by farmers in actual growing conditions, have long advocated and promoted a package approach to agricultural input adoption in developing countries. This approach has proved to be successful in Asian countries that have realized a green revolution (Byerlee and De Polanco, 1986). However, recent policy interventions in African agriculture have not adopted it. Most of the focus has been on mineral fertilizer. All agricultural input subsidy programs since 2000 include mineral fertilizer, but very few include hybrid seeds in the package of inputs. None of these programs have supported the use of manure, soil and water conservation measures, and crop protection chemicals.

We aim at a evaluating the merits of the package approach to agricultural input intensification as an optimal farming system. We empirically show that when farmers take a more holistic approach to input intensification by adopting simultaneously several inputs, yields are much higher and grow much faster. While it is evident that the simultaneous adoption of several modern inputs would be beneficial to yield, beyond experimental evidence, empirical assessments of actual gains from the simultaneous adoption of several modern inputs and practices on the same plot is scant. Such evidence would be important to direct the attention of African governments and their development partners to the importance of a package approach to modern inputs adoption.

Our study aims at filling this gap and contributes to the identification of the optimal approach to input intensification that would accelerate agricultural productivity growth and the emergence of an African green revolution. For instance, to the extent that the adoption of complementary inputs increases the marginal productivity of nitrogen, it might be economically and socially optimal to promote and support the adoption of these other inputs. Our study fits in the literature on agricultural technology adoption and productivity but focuses on the simultaneous adoption of innovations. Previous studies typically estimate the effect of the adoption of one single technology on yield conditional on the use of others types by including them as control variables in regressions. This approach does not inform on the potential impact of joint input use. Others studies interact variables indicating the use of two types of inputs. Despite the appeal, such an approach can be cumbersome and computationally infeasible as the number of technologies studied increases and the number of possible interactions grows exponentially. To circumvent this problem, we propose and estimate an agricultural input intensification index ($A3i$) that summarizes into one variable a farmer's adoption and utilization decisions with respect to several modern inputs while accounting for the correlations that exist between these decisions.

Our empirical analysis uses nationally representative household surveys for two African countries, Burkina Faso and Tanzania, representing two different types of production environments. We first examine the landscape of input adoption to quantify the extent of joint input adoption among farmers focusing on maize, a key staple food crop in most African countries including Burkina Faso and Tanzania. Next, we derive *A*3*i* indices with respect to hybrid seeds, mineral fertilizer, manure, insecticide, and herbicide. Our analysis of the pattern and determinants of our indices shows that joint adoption of modern input remains limited but there is great heterogeneity among farmers in terms of their input use.

Next, we evaluate the impact of agricultural intensification on crop yields. We address threats to identification due to unobserved heterogeneity and selection using correlated random effect methods (CRE) and instrumental variable estimations. The CRE approach allows us to control for household unobserved heterogeneity. To address further endogeneity that results from selection bias when potentially high productivity and wealthy farmers self-select themselves into the adoption of more than one input, we use a control function - instrumental variable. Our instrument is the household membership in an association, which most likely explains access to inputs, thus their adoption, but is likely unrelated to productivity, as long as we control for other commercial inputs. The findings confirm a strong positive effect of agricultural input intensification as measured by our *A*3*i* on crop yield.

We organize the remainder of the paper as follows. In section 2.2, we develop a conceptual framework that highlights the importance of adopting modern input as a package to accelerate productivity growth. We also present our methodology to measure agricultural input intensification using an index that captures intensification in its many dimensions. In section2.3, we present the datasets and document descriptive evidence on the joint adoption of modern input and our estimated agricultural input intensification index. Section 2.4 presents the results of the application of our methodology to estimate an agricultural input intensification index. In section 2.5, we discuss the econometric approach used to evaluate the determinants and impact of agricultural intensification on yields. The results are presented and discussed in section 2.6.

2.2 Conceptual framework

2.2.1 Accounting for complementarities of input in agricultural production function

With an eye toward the construction of an index to measure agricultural input intensification, we develop a simple conceptual framework to illustrate the importance of harnessing strategic complementarities among inputs with simultaneous adoption. Our model builds on the concept of the O-ring production function formalized by Kremer (1993). Standard production functions are typically expressed in term of input levels. The O-ring production function has the particularity that it expresses output as a function of the quality of inputs. In Kremer (1993)'s original formulation, a firm uses a production process that consists of several tasks, each performed by a single worker. Workers are characterized by their quality defined as the likelihood that they will perform a given task with success. The non-execution of a task can result in the total destruction of the final product. Kremer (1993) uses this type of production function model to derive a number of interesting predictions on firm labor demand, firm size, and wage and productivity differentials between developed and developing countries.

To adapt this framework to our analysis, we start by observing that agriculture, like most production processes, consists of n activities carried out by a farmer. Unlike in the original O-ring model, our focus is not on skills but on technologies. We assume that each activity requires one input chosen within a set ranging from the most traditional to the most advanced. For instance, to produce maize, farmers undertake numerous activities related to land preparation, seed selection, soil amendment, crop protection, and harvest. Underperformance, during one activity, due for instance to a low input application rate, can substantially lower the value of output. To illustrate that, let us consider the following two examples. Assume a farmer uses hybrid seed but has failed to apply mineral fertilizer to amend her nutrient-depleted soils. The value of output could be substantially lower than expected. If we assume that the farmer applies the optimal amount of fertilizer but fails to protect the plant during the vegetative phase of development, weed infestation, diseases, or pests can cause important damage to production.

For each input i, farmers choose a level of application q_i. What q_i measures depends on the type of input. For example, if the input considered is seed, q_i takes a value between $0, 1$ with 0 denoting the adoption of traditional seeds and 1 denoting the adoption of hybrid seeds. In the case of fertilizer, manure, insecticide, or herbicide q_i measures a normalized application rate. We normalize by dividing the observed application rate q^{obs} by the optimal application rate q^{max} that would produce the maximum output. Thus, we have $q_i = q^{obs}/q^{max}$. A value $q_i = 0$ implies that the farmer has not used the input; $q_i = 0.50$ implies that the farmer's application rate is half of the optimal level. Let B be the minimum output per hectare if all activities are zero-intensified. Later in our empirical analysis, it will be useful to view $B = B(X_p, X_h, X_v)$ as function of exogenous plot X_p, households X_h, and community X_v characteristics. Consistent with agronomic evidence, we assume that modern inputs increase output beyond the minimum B. Letting farm labor enter the production function in conventional Cobb-Douglas form, we write our modified O-ring production function as follows:

$$y = L^{\alpha}\left(\prod_{i=1}^{n}(1+q_i)\right)B \tag{2.1}$$

Note that there is a fundamental difference between a standard Cobb-Douglas production function and the O-ring production formulated in (2.1). The main difference resides in the choice variables in the of farmer's profit function. The production is formulated both in terms of the observed application rate and how close is such rate to the agronomically optimal rate. Another key difference as noted by Kremer (1993) related to the no substitutability among inputs. Because intensification level enters the production function multiplicatively, it is not possible to increase one input to compensate for foregone yield due to low intensification in other inputs. Another important feature of this production function is that it exhibits an increasing return to the package of input use and not individual input. If we normalize the price of output to one and denote by $p(q_i)$ the cost of choosing a level of intensification q_i and by w labor cost. Farmers profit maximization problem is formulated as follows:

$$\underbrace{Max}_{L,q_i} L^{\alpha}\left(\prod_{i=1}^{n}(1+q_i)\right)B - \sum_{i=1}^{n} p(q_i) - wL \tag{2.2}$$

The first order conditions associated with L and each q_i are:

$$\frac{\partial y}{\partial q_i} = L^{\alpha}\left(\prod_{i\neq 1}^{n}(1+q_i)\right)B = \frac{\partial p(q_i)}{\partial q_i} \tag{2.3}$$

$$\frac{\partial y}{\partial L} = \alpha L^{\alpha-1}\left(\prod_{i=1}^{n}(1+q_i)\right)B = w \tag{2.4}$$

Equation (2.3) implies that in equilibrium, farmers will intensify up to the point that the marginal gain in output due to a slight increase in input i equals the cost associated to that increase. Otherwise, the farmer is better off not making the investment. Similarly, equation (2.4) which equals marginal labor product with labor cost including opportunity cost of family labor translates optimal conditions for labor demand. Together, these equations characterize optimal levels of input intensification and farm labor use.

The first order conditions and the intrinsic properties of the O-ring production function imply that adopting modern technologies as a package is associated with higher productivity and output. To see that, notice that the production function exhibits a positive cross derivative $\partial^2 y/\partial q_i \partial \left(\prod_{i\neq 1}^{n}(1+q_i)\right) = L^\alpha B > 0$. In other words, the marginal productivity with respect to a level of input intensification q_i is increasing in the level of intensification for other inputs taken as a whole. Thus, if farmers with high values of the first $n-1$ inputs choose a similarly higher intensification for the n^{th} input, output will be higher. In other words, having a holistic approach to intensification across all activities will lead to higher productivity[2]. In our empirical analysis, we test this implication by assessing the productivity gains from the simultaneous adoption of several inputs.

2.2.2 Measuring agricultural input intensification

Our empirical analysis seeks to test the hypothesis that input intensification, when inputs are adopted as a package, is the most efficient approach to generating large gains in crop productivity. Previous studies on agricultural input intensification have largely focused on a single input. For instance, there is a large literature on yield response to nitrogen application or the impact of the adoption hybrid seeds on crop productivity (Ricker-Gilbert et al., 2013). However, there is a growing literature that studies joint input use (Levine and Mason; 2014; Holden and Lunduka, 2012). Most

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[2] This result is equivalent to the fundamental finding of Kremer (1993) that firms matching workers with the same skills realize higher production and profit.

studies in this literature focus on understanding the determinants of joint input use. Studies that attempt to account for other technologies in yield regressions generally include variables indicating the adoption of these inputs as additional control variables (Feder et al., 1985; Foster and Rosenzweig, 2010). This approach does not inform on the impact of joint input use. Studies that analyze the impact of joint input use generally limit themselves to two technologies and include interactions of variables measuring farmer's use of these technologies in yield regressions. The issue with this approach in our context is that it produces a very large number of variables to be included in a regression. For instance, for six modern inputs and practices, the corresponding number of interactions is $7! = 7 * 6 * 5 * 4 * 3 * 2 * 1 = 5040$.

To circumvent these problems, we develop and estimate an index of agricultural input intensification that allows us to analyze the simultaneous adoption of several inputs and the resulting impact on crop yield. Our proposed index captures agricultural input intensification in its many dimensions. More precisely, it informs us on the household modern input adoption in terms of the use of improved seeds, application of various mineral nutrients and manure, and the application of insecticide and herbicide for crop protection. Given that these inputs are fundamentally different, denoted in different units, and have different scales, the index approach allows us to combined these measures into a single variable without dropping the underlying information they contain.

Indices have always been prevalent in statistics, economics, and other social sciences. They are useful composite indicators often used to summarize information in a representative group of variables that measure different facets of a complex issue. Indices provide the relative position of individuals in a given area with respect to the issue analyzed. When evaluated over time, they can also provide useful information on the progress made in improving the underlying issues analyzed. Examples of familiar indices are the consumer price index that measures changes in prices for a basket of consumer goods, the human development index that ranks countries in term of human development, the trade openness index that measures countries exposure and openness to international trade (Sachs and Warner, 1997), and the polity score measuring the quality of institution. At micro levels, a number of indices are proposed to measure various aspects of individuals and households life. For instance, there exists an asset index that aggregates the household ownership of various non-durable consumer products in own variables, an index of income diversification that captures households various sources of livelihood, and an index for crop diversification that measure the heterogeneity of farmer crop portfolio. Similar to these indices, we propose an index of agricultural input intensification. To our knowledge, there is no such index despite the importance of agricultural input intensification in agricultural policy and rural development.

There are two approaches for constructing an index: a parametric approach that uses a well-defined functional form to combine observed variables into one single variable and a non-parametric version that uses statistical methods to extract a latent component from a set of observed variables[3] . Each approach has its advantages and weaknesses, and the choice between them depends on conceptual constraint, data availability and quality, and researchers' preferences. However, the two approaches generally produce qualitatively similar results. In this essay, we only discuss the parametric approach[4].

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[3] There is an hybrid approach that uses parametric methods to construct indices for a subset of variables then uses non-parametric methods to aggregate them (see the example of the KOF Index of Globalization (Dreher and Gaston, 2008).

[4] An alternative approach to construct an agricultural input intensification without a functional form is the use of data reduction techniques. In particular, factor analysis (FA) is particularly suitable for the task. FA is a statistical method to describe the variability and correlations among observed variables in order to extract underlying latent variables that create a commonality. In an application of this technique to study input intensification, FA would allow us to extract farmers' intensification attitude toward a set of modern inputs while accounting for interdependencies, relative importance, and measurement errors.

Our parametric approach to estimate $A3i$ is a straightforward application of our conceptual model that suggests a multiplicative aggregation of individual input intensification variables into a single index as follows:

$$A3i = \prod_{i=1}^{n} (1 + q_i) \;\; with \;\; q_i = \frac{q_i^{obs}}{q_i^{max}} \tag{2.5}$$

Where q_i^{obs} is the observed application rate of the input i and q_i^{max} is the application rate that would produce the highest level of output. This index is comparable across plots, households, regions, and countries. It is normalized such that its lowest possible value is one and corresponds to $q_i = 0, \; \forall \; i = 1..n$ and its highest value possible is 2^n when $q_i = 1, \; \forall \; i = 1..n$.

In this formula, we need to estimate q_i^{max} independently from households to minimize risks of endogeneity in yield regression. Ideally, information on q_i^{max} should come from agronomic recommendations on the optimal rate of application suitable to local growing conditions. For seeds, the optimal recommendation is straightforward: use of hybrid varieties that have high yield potential and are bred to perform relatively well under various unfavorable cultivation conditions such as drought and flood (Evenson and Gollin, 2003). However, agronomic research on experimental stations or in the field are the main source of information on optimal application rates. A recent study on fertilizer use in Africa by Wortmann and Sones (2017) calibrate agronomic models with experimental data to derive optimal mineral fertilizer application rates for selected African countries. Their findings for Burkina Faso recommend 50 kg/ha of urea and 39 kg/ha of DAP for maize. However, these recommendations might not reflect necessarily optimal rates in the uncontrolled environment of the household production. In addition, the study has not covered other inputs such as manure, insecticide, and herbicide.

In absence of relevant data, we estimate agronomic optima q_i^{max} using the observational data we have and regression-based methods. We follow the same approaches as in Sheahan et al. (2014), Koussoubé and Nauges (2017), and Theriault et al. (2017) to estimate the unconditional yield response functions to various inputs. We adopt the following quadratic response function:

$$y_{pht} = \alpha_0 + \alpha_1 q_{pht} + \alpha_2 q_{pht}^2 + \beta_1 W_{pt} + \beta_2 X_{ht} + U_{pht} \tag{2.6}$$

Where y_{pth} indicates yield for the plot p belonging the household h during the crop season t; q_{pth} represents the input application rate and q_{pth}^2 is the squared term; W_{pt} and X_{th} represent respectively plot and household level variables that explain crop yield, U_{pth} is a composite term that contains unobserved plot heterogeneity u_p, unobserved household heterogeneity v_h, time fixed effect γ_t, and random errors ϵ_{pt}.

The quality of the estimated optimal input application rates depends on the quality of the estimated coefficients in the yield response function. By including detailed plots level and household level characteristics, we control for various factors that explain jointly input use and yield. However, there are plausible reasons to believe that there might still be unobserved factors such as farmers' ability that affect both input use and yield. If this is the case, our coefficients, and consequently the optimal application rates, will be biased. To address the threat of endogeneity, we combine the Correlated Random Effect (CRE) method developed by Mundlak (1978) and Chamberlain (1984) with a control function instrumental variable method estimate yield response functions.

The CRE approach helps us address unobserved plot and household level heterogeneity and their correlation with observables by modeling them as a function of the average of time-varying variables. More formally, the CRE consists in substituting u_p

with $u_p = \gamma_0 + \gamma_1 \bar{W}_p + e_p$ and v_h with $v_h = \delta_0 + \delta_1 \bar{X}_h + \varsigma_h$. We address endogeneity due to selection in input adoption using an instrumental variable. An ideal instrument in our context needs to explain the household adoption decision of each input but has to remain unrelated to yield (Greene, 2008). Following previous studies, we use variables measuring farmers' access to inputs such as distance to markets, membership in farmer organizations, and prices, as instruments. Since our focus is on commercial inputs and input markets in most African countries are underdeveloped, closeness to markets and membership in a farmer organization remain the most important factors that explain the availability of these inputs to smallholder farmers. Conditional on plot, managers, and the household characteristics, these variables will likely satisfy the exclusion-restriction criteria for good instruments. The CF approach allows a direct test of the validity of the instruments to confirm or reject the threat of endogeneity.

Once, we estimate equation (2.6) separately for each type of input, we can derive unconditional agronomically optimal input application rates by setting the first derivative of the yield function with respect to q to zero. It follows that the optimal rate is:

$$\frac{\partial y}{\partial q_i} = \hat{\alpha}_1 + 2\hat{\alpha}_2 q_i = 0 \Rightarrow \hat{q}_i^{max} = \frac{\hat{\alpha}_1}{2\hat{\alpha}_2} \tag{2.7}$$

The estimated $\hat{q}_i^{max}$ are subsequently used to compute our agricultural input intensification index as follows:

$$A3i = \prod_{i=1}^{n} (1 + q_i) \text{ with } \; q_i = \frac{q_i^{obs}}{q_i^{max}} \; \text{ and } \; \hat{q}_i^{max} = \frac{\hat{\alpha}_1}{2\hat{\alpha}_2} \tag{2.8}$$

While indices are useful constructs in economics and other social sciences to analyze various issues, they have a number of drawbacks that need to be recognized.

First, the choice of set of inputs over which to compute the index is often arbitrary. We limit our analysis to variable inputs for which decisions must be made every growing season. As such, our index does not capture all the farmers' production and investment decisions. Also, we compute the index on the set of inputs comprising both yield-enhancing inputs (hybrid seeds and nutrients) and loss-limiting inputs (insecticide and herbicide). Both types of inputs result in higher crop yields but through distinct mechanisms. It is possible to compute two separate sub-indices for each category of input, but in this application, we only estimate the combined index. Second, indices often suffer from the 'index number problem' that refers to their inadequacy in measuring change over time when several underlying factors change. While it generally applies to indices that use prices and quantities, the index number problem is also relevant to this analysis. In our case, we assume the agronomically optimal application rates are constant. However, it is possible that as the same plot is farmed repeatedly, the optimal application rates of the different inputs also change. Finally, because, indices are unit-less, their interpretation is often difficult. In our context, a unite change in the value of the index could be the result of various scenarios of changes in the application rate of individual inputs. Nonetheless, the index allows for a consistent ranking of plots and farmers with a defined population within a country.

2.2.3 Aggregation

The initial unit of estimation of the agricultural input intensification described in equations (2.5) and (2.8) is the plot level. For practical and policy purposes, and for various other reasons, it is interesting to learn how a household as a farm enterprise is adopting agricultural technologies as a package. It can also be instructive to investigate how a particular administrative region, relative to others, is performing in terms of input intensification. In this section, we discuss some simple aggregation procedures to aggregate $A3i$ estimated at the plot level into various higher levels of aggregation.

Household level $A3i$ for a particular crop. Although farms in Africa are in general small, they are highly fragmented with farmers engaging in the production of a crop on several contiguous or distant small plots (Blarel et al., 1992). We use weighted averages to aggregate plot level $A3i$ for a given crop c into household level $A3i$ with the weights being the area share of each plot. More formally, if a household h produces a crop c on n_c different plots of size $a_{p,c}$ each, then the household level $A3i_c^h$ for this household with respect to this crop is:

$$A3i_c^h = \sum_{p=1}^{n_c} A3i_{p,c} * \frac{a_{p,c}}{\sum_{j=1}^{n_c} a_{j,c}} \tag{2.9}$$

Where $A3i_{p,c}$ is the plot p agricultural input intensification index for crop the crop c.

Household level $A3i$ for all crops. For various reasons including diversification and risk management, smallholder farmers also engage in the production of various crops. Although input decision are plot and crop specific, understanding farmer input adoption with respect to all crops produced is informative of their global attitude toward agricultural technology adoption. We can also use weighted averages to aggregate crop level $A3i_c^h$ into household level $A3i^h$ irrespective of the crop produced, with the weight being the relative importance of each crop in the household farm enterprise. The aggregation formula is:

$$A3i^h = \sum_{c=1}^{C} A3i_c^h * \frac{\sum_{j=1}^{n_c} a_{j,c}}{\sum_{c=1}^{C} \sum_{j=1}^{n_c} a_{j,c}} \tag{2.10}$$

Where is C is total number of crops produced by the household h, $\sum_{j=1}^{n_c} a_{j,c}$ the total area devoted to the plot c (summed area over all plots of crop c), and $\sum_{c=1}^{C} \sum_{j=1}^{n_c} a_{j,c}$ the total farm size (summed over all plot and all crops).

Further aggregation at the villages, district, region, and country levels are possible for household-crop level $A3i$ using either simple average or weighted averages with various weighting schemes.

2.3 Data and descriptive results

2.3.1 Data sources and variables

Our empirical analysis focuses on two countries, Burkina Faso and Tanzania. The dataset for Burkina Faso is drawn from the Continuous Farm Household Survey (Enquête Permanente Agricole (EPA). The survey has been implemented since 1995 by the General Research and Sectoral Statistics Department (Direction Générale des Études et des Statistiques Sectorielles (DGESS)) of the Ministry of Agriculture and Food Security (Ministère de l'Agriculture et de la Sécurité Alimentaire (MASA)). We focus on the waves 2009/10, 2010/11 and 2011/12 which represent the latest years fully cleaned and made available by DGESS[5] . The Tanzanian dataset comes from the Living Standards Measurement Study - Integrated Surveys on Agriculture (LSMS-ISA implemented by the National Bureau of Statistics (NBS) with the assistance of the Word Bank. We use all three waves, 2008/2009, 2010/2010, and 2011/2012 that are publicly available. Certain regions of Tanzania have two growing seasons: one long rainy season and one short rainy season. For our analysis, and to have a national sample, we focus only on the long rainy season.

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[5] We omit surveys prior to 2009 since the sample is different from the one uses for the years 2008-2012.

We restrict our analysis to maize plots and maize cultivating households. Our focus on maize is motivated by the strategic importance it has as a staple food consumed across Africa, and especially in Burkina Faso and Tanzania. After keeping only maize plots and removing plots with missing information on the size, the type of crop, and the value of harvest, our final sample for the three years consists of 8,021 plots (cultivated by 4,112 households) in Burkina Faso and 6,942 plots (cultivated by 3,231 households) in Tanzania[6] . For each country, we identify and select four categories of variables: input use and production, plot characteristics, plot manager characteristics, and household characteristics including selected variables at the village and region level. As much as possible we compile the same variables for the two countries, and wherever definitions differ, we mention it and explain the equivalence.

Input use and production are our main variables. We focus on inputs for which decisions need to be made during each cropping season. We exclude long-term farm investment such as irrigation, equipment, soil and water conservation structures. We also exclude farm and water management practices, such as sowing methods, land preparation methods, and the timing of fertilizer application that can have important effects on yield. That leaves us with the following inputs: hybrid seeds, mineral fertilizer, manure, herbicide, and insecticide. For each of these inputs, we have data on the quantity used by plot. We estimate input prices directly from the data using information from farmers that have purchased them. Prices were obtained by dividing the value of purchased input by the quantity. These household level unit prices are then averaged across farmers within the same region to obtain the prices facing all households, including those who did not use any input.

Since the type of mineral fertilizer available to, and used by, farmers vary considerably across locations and in terms of nutrient content, we follow the standard

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[6] Our panel data are not balanced, thus there are farmers entering and exiting the sample over years.

practices in the literature to convert fertilizer quantity q_F into the main macronutrients, Nitrogen, Phosphorus, and Potassium , using the given proportion of $N(s_f^N)$, $P(s_f^P)$, and $K(s_f^K)$. In both Burkina Faso and Tanzania, farmers generally apply both basal fertilizer in the form of composite $N-P-K$ and top-dressing fertilizer in the form of Nitrogen (urea) (Wortmann and Sones, 2017). Previous studies either do not distinguish between the types of nutrient or focus exclusively on nitrogen. Studies have shown that phosphorus, potassium, and other nutrients are important for plant growth and for the efficiency of nitrogen intake. Our analysis includes both N, P, and K. To obtain the prices of these nutrients , we follow the same approach as in Xu et al. (2009) and Theriault et al. (2017) to compute the prices of different nutrients using the computed prices of the different type of fertilizer and the information on their nutrient contents. More formally, if there are F types of fertilizer indexed $f, f = 1..F$, each sold at the price p_f and has the nutrient content (s_f^N, s_f^P, s_f^K), then the vector of price for (N, P, K) is $(\sum_{f=1}^{F} p_f / \sum_{f=1}^{F} s_f^N \ ,\sum_{f=1}^{F} p_f / \sum_{f=1}^{F} s_f^P \ ,\sum_{f=1}^{F} p_f / \sum_{f=1}^{F} s_f^K)$[7].

At the plot level, the variables used are the location of the plot, whether it is located within or outside the compound. In the case of Tanzania, we have a more precise measure for plot location in term of distances from the household compound. We also use a variable indicating the mode of acquisition for the plot (rented or fully owned), type of management (individual or collective), history of use (fallow, intercropping), and various measures of soil quality (farmers' perception of quality as good or poor) and soil slope (steep or not). A number of studies have demonstrated that soil characteristics are key determinants of crop yield and input use decision (Marenya and Barrett, 2009; Theriault et al., 2017). Controlling for these characteristics is important to minimize risks of endogeneity.

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[7] The intuition behind the calculation of these prices is the following. Assume the farmer purchases 1 kg of each of the F types of fertilizer at the unit price of p_f each. Then total quantity of N purchased is $\sum_{f=1}^{F} s_f^N$ and the amount spend to acquire such quantity is $\sum_{f=1}^{F} p_f$. It follows that the unit price of N is $\sum_{f=1}^{F} p_f \sum_{f=1}^{F} s_f^N)$. The same logic applies to other nutrients.

Following Theriault et al. (2017), we control for plot manager characteristics as his skills and strategic choices are important in determining input use and yield. We also control for various household characteristics such household size, as a proxy for family labor, off-farm income and access to credit, as proxies for cash resources, total landholding and number of tropical livestock units, as a proxies for assets, and contact with extension services and membership in an association, as proxies for access to information. Finally, we include in our analysis rainfall, agro-ecological zones, and regional dummies to control for external village level condition environments that might explain farmers input use decisions and yield response to various inputs.

2.3.2 Descriptive analysis

Summary statistics on modern input use

We present basic descriptive statistics on input use and other variables in our analysis in this section . Table 2.1 presents summary statistics on the use of modern input for maize plots and maize farmers in both Burkina Faso and Tanzania. The summary statistics are pooled across the survey years. Consistent with our expectations, we find that the utilization of modern input use in both countries is limited. About 10.4% of maize cultivating households in Burkina Faso use some form of hybrid seeds and about 8.7% of maize plots, representing 8.6% of the total area devoted to maize, received these seeds. In Tanzania, hybrid seeds adoption rates are much higher[8]. Almost a quarter of farmers cultivating maize use hybrid seeds and the number of maize plots receiving these seeds represents 22.6% of all plots. Although these adoption rates are low, it worth noting that they are much higher than adoption rates observed a decade ago, suggesting that the spread of hybrid seeds in Africa is grad-

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[8] In Tanzania, the exact definition use for of hybrid is commercialized seeds. In some instance, farmers specify whether the seeds are hybrid. However, in many cases it was not clear whether the seeds are hybrid or traditional. We assume that all purchased seeds are improved. However, this could actually overestimate adoption rates.

ually improving (Sheahan and Barrett, 2017). However, it should be noted that one of the challenges facing farmers is the access to certified seeds that meet high-quality requirements. In Tanzania where the data permit, we find that about 30% of farmers reported using non-certified hybrid seeds or hybrid seeds from their previous harvest. In general, these types of seeds are not reusable or perform poorly (van Bueren et al., 2011).

Unlike hybrid seeds, we find that mineral fertilizer is more common in maize farming systems in Burkina Faso but less in Tanzania. In Burkina Faso, over half of the maize plots received all three mineral macronutrients (N, P, and K). The percentage of farmers applying these nutrients ranges between 51.2% for K to 53.3% for N. Average application rates are however low by international standards. We estimate the unconditional average application rates as 25.5kg/ha for N, 6.3 kg/ha for P and 2.8 kg/ha for K. However, when we compute the averages over plots that actually received these nutrients, application rates are much higher. It is important to mention that these application rates mask important heterogeneities across farmers, plots, and years with the minimum N application rate as low as 0.15 kg/ha and the maximum as high as 99.1 kg/ha. In Tanzania, only 13.8% of maize plot received mineral fertilizer and the application rates are even lower than in Burkina Faso[9].

Manure is another source of nutrients for plant growth, particularly micronutrients and organic matter necessary to maintain and replenish soils. Our analysis finds that respectively, 30.8% and 18.0% of maize farmers in Burkina Faso and Tanzania use manure on their plots. The average application rates range between 1,137 kg/ha in Tanzania to 2,168 kg/ha in Burkina Faso. Manure and compost are typically home produced from crop residues left on the plot, green manure consisting of leguminous

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[9] Both Burkina Faso and Tanzania have recently implemented fertilizer subsidy program. The share differences in fertilizer adoption between the two countries might reflect differences in policies but also growing conditions. Our analysis is not aimed at understanding these macro differences.

plants cultivated from fallowed plots and plowed back into the soil, and human and animal waste (Jama et al., 2000; Becker et al., 1995). Its usage is not often generally well tracked by farmers and the statistics reported might largely underestimate adoption and application rates.

Agricultural inputs in agricultural policies in Africa often neglect crop protection chemicals, pesticide , and herbicide. None of the agricultural input subsidy programs implemented in Africa address the issues of crop protection using agrochemicals. Traditionally used for cash crops such as cotton, sugar cane, and tobacco, insecticide and herbicide are increasingly being used for food crops (Williamson et al., 2008; Kaminski and Christiaensen, 2014). Consistent with this observation, we find that a sizable proportion of farmers in Burkina Faso use these agrochemicals on maize plots. In Tanzania, crop protection agrochemicals are not widely used in food crop production. However, recent evidence shows that their adoption by smallholder food crop producers is rapidly increasing (Haggblade et al., 2017a). A number of factors explain the rise in the use of insecticide and herbicide for food crops in Africa. The most important factors are the increased scarcity of labor and higher rural wage rates, the changing perception about chemicals in food production, and global supply shocks due to the flood of off-patent formulations since 2000 and substantial drop in prices (Haggblade et al., 2017b). While the increase in agrochemical' use is fast increasing, it should be noted that there are legitimate concerns related to their environmental and human health effects that should be taken into account in the promotion of these inputs to smallholder farmers in Africa (Sheahan et al., 2016).

Summary statistics on joint input use

In line with our argument in favor of the adoption of agricultural inputs as a package, we also present summary statistics on joint input use. Figures 2.1 and 2.2 show for Burkina Faso, the proportion of plots and farmers by the number of modern inputs used. The number of different types of input used ranges from zero for no inputs to seven indicating that all the main inputs we listed above have been used. Figures 2.3 and 2.4 present the same information for Tanzania. The main observation from both figures is that joint input use is limited but not rare. In Burkina Faso, less than a third of plots received no input. The same observation applied for households. Over the years, we also observed a slight decrease in the proportion farmers using no input and an increase in the proportion of farmers using four and more inputs.

To further analyze joint input use with a focus on the type of input, we present in Table 2.1, the proportion plots, land, and farmers for various combination of modern inputs. As before, the summary statistics are pooled across the three years. The proportions of joint input use are small and vary with types of input. In Burkina Faso and Tanzania, nearly zero plot received at the same time hybrid seeds, mineral fertilizer, manure, insecticide, and herbicide. In other parts of world, using simultaneously all these inputs on the same plot is the norm.

Summary statistics on yield and modern input use

How does yield respond to input use, and more importantly to joint input use? To start answering this question, we present basic descriptive statistics on the difference in plot yield by the type of input use combinations. We present a number of mean comparison tests in Table 2.3. Consistent with our expectations, we find that maize yields in Burkina Faso and Tanzania are low. However, plots receiving modern inputs have significantly higher yields than those with no modern inputs. For instance, maize plots with hybrid seeds have yields that are 129 kg higher than those with traditional seed varieties. With the exception of manure, utilization of modern inputs is associated with significantly higher maize yields. The results are qualitatively consistent across countries with small differences in the magnitudes of the yield gains associated with modern input use.

We also report various conditional means comparison tests in panel B of Table 2.3. We find that in the group of plots with hybrid seeds, additional application of mineral fertilizer results in higher yields. The increase in yield as the result of the joint adoption of hybrid seeds and fertilizer (+163 kg/ha in Burkina Faso) is much higher than the sole adoption of hybrid seeds (+129 kg/ha also in Burkina Faso). Similar results are obtained when other modern inputs are adopted on top of hybrid seeds or fertilizer. These results provide descriptive evidence on the yield growth-accelerating effect of the simultaneous adoption of several modern inputs. As we discussed in the previous sections, including all the possible interactions between the different inputs in a regression is computational difficult due to sample size and high correlations. In the following section, we discuss the results of the application of our methodology to derive an agricultural input intensification index that will combine intensification with respects to several inputs into one single variable.

2.4 Application of the *A3i* methodology

2.4.1 Results

The first step is this analysis is to estimate the the agronomic optimum for each of the inputs considered. In the series of Figures 2.5 to 2.10, we present graphically the relationship between maize yield and observed input application rates using Kernel-weighted local polynomial[10] smoothing for Burkina Faso. We run a similar analysis for Tanzania and present the results in Figures 2.11 to 2.16. An interesting appeal of this nonparametric approach is that it makes no assumptions about the functional form of the relationship between the two variables and allows us to get insights into the functional form of the yield response to each input (Fan and Gijbels, 1996) . The shape of the non-parametric smoothing functions confirms the non-linearity of yield response to nutrient, manure, insecticide, and herbicide.

Based on these observations, we estimate a set of quadratic regressions of maize yield on inputs to determine agronomically optimal application rates. We first estimate the models using OLS with the correlated random effect methods to address unobserved heterogeneity. Tables 2.4 and 2.5 present the estimations results for Burkina Faso and Tanzania, respectively. As found by previous studies in different contexts (Theriault et al; 2017; Burke et al., 2017, Sheahan et al., 2013, Xu et al., 2009), our OLS-CRE regressions indicate that yield response to nitrogen is quadratic in Burkina Faso and Tanzania. Our results show that this quadratic relationship also holds for a wide range of agricultural inputs other than nitrogen (N). Most of these nutrients, phosphorus (P), and potassium (K), manure, and crop protection chemicals, have not been well investigated in past.

We attempt to address endogeneity due to time-varying unobserved factors using instrumental variables. Our instrument is household membership in an agricultural association. This variable was available only for Burkina Faso. Given the context of agricultural farming in this country, membership in an agricultural association is the

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[10] The kernel regression considers the scatter plot of yield and each input $(y_1, q_1), \ldots, (y_n, q_n)$ and the model: $y_h = m(q_h) + \sigma(q_h)\epsilon_(h)$ where $m(.)$ is an unknown mean with no assumption about its functional form, $\sigma(.)$ is an unknown variance, and ϵ_h are symmetric errors with $E(\epsilon_h) = 0$ and $Var(\epsilon_h) = 1$. The Kernel-weighted local polynomial regression proceeds by estimating for each smoothing point $q_0 m(y_0) = E[y|q]$ as the intercept of regressions weighted by a kernel function of y on $(y - y_0), (y - y_0)^2, \ldots, (y - y_0)^r$. The choice of the kernel function or weighting scheme is the popularly-used Epanechnikov kernel function; a rule-of-thumb bandwidth estimator as defined in Fan and Gijbels (1996) is used.

main channel used by households to access agricultural inputs through either subsidies or credit. To minimize the risk that membership in an agricultural association might be determined by expected productivity, we use a variable indicating whether at least one member of the household holds a management position within an association. This variable is a proxy for household status within the village. Using a control function approach and this instrument, we were unable to confirm endogeneity. The residuals from the first stage of the control function approach were not significant in most of the regressions despite our instrument being a powerful predictor of access to input (the coefficient of the instrument is positive and significant at 1% in all the first data regressions). Thus, we restrict our analysis to the OLS-CRE estimate with the understanding they are imperfects.

The optimal application rates estimated are summarized in Tables 2.4 and reftable25. For Burkina Faso, we estimate that optimal input application rates for maize are 138.70 kg/ha of N, 94.29 kg/ha of P, 93.40 kg/ha of K, 8322.73 kg/ha of manure, 4.05 L/ha of insecticide, and 10.40 L/ha of herbicide. Optimal rates estimated for Tanzania are 247.2 kg/ha of N, 140.5kg/ha of P, 108.9kg/ha of K, 1050.8kg/ha of manure, 3.6 L/ha of insecticide, and 9.6 L/ha of herbicide.

Our estimates for optimal nitrogen application rates are in line with the recent estimates reported in the literature. Agronomic research by Holtzman et al. (2013) based on experimental field recommend 50 kg/ha of urea and between 150 and 200 kg/ha of NPK on maize in Burkina Faso. Using the same conversion factors from fertilizer to nutrients, we use in our analysis, we estimate that these recommendations correspond to 54.4 kg/ha of N, 36 kg/ha of P, and 36 kg/ha of K. It is important to mention that these recommendations might not reflect farmers' actual growing conditions. Our estimates are larger than those suggested by Holtzman et al. (2013) but have the advantage that they are based on farmer practices and growing conditions.

Two recent studies in Burkina Faso by Koussoube and Nauges (2017) and Theriault et al. (2017) also report agronomically optimal nitrogen application rates for maize cultivation in Burkina Faso. The first authors calculated optima ranging from 77 to 106 kg/ha. Theriault et al. (2017) find optimal nitrogen application rates in the range of 612-722 kg/ha. Our estimates are backeted by these two extremes. However, neither of these studies, nor those on others regions of Africa, report optimal application rates for P, K, and other inputs. For the purpose of our analysis and the estimation of an index, we need to estimate these optima. Based on the ranges of our estimates and evidence from previous agronomic research, the optima we estimate for these other inputs seem quite reasonable.

Once we estimate the q-max, the next step is to apply the formula in equation 2.5 to compute our agricultural input intensification index ($A3i$). One immediate observation is that all the optima are outside the range of observed inputs used both in Burkina Faso and in Tanzania. This suggests that there is ample room for expanding modern input utilization in Africa. The index provides insight into how close are farmers to these optimal rates.

2.4.2 Descriptive statistics on $A3i$ and validation

We use the estimated q-max and the formula in equation 2.5 to calculate plot level $A3is$ for maize plots. The index ranges between 1 and 16.1 in Burkina Faso and between 1 and 10.4 in Tanzania. In this section, we examine the pattern of the index and document its relation to observed input use. We expect the index to have strong correlations with individual input use, and capture joint input use. In Figures 2.17 and 2.18, we present the distribution of the indices across farmers and by year for Burkina Faso and Tanzania respectively. The distribution of the index is right skewed with long tails. This distribution is consistent with the low incidence of joint input use observed in the data.

We also compute the correlations between the index and individual levels of input. We expect these correlations to be positive. The strength of the correlations indicates the relative contribution of the input level to the overall index. Table 2.6 summarizes these correlations. In Burkina Faso, the correlations range between 0.15 for insecticide to 0.71 for N, P, and K. This suggests that mineral fertilizer followed by hybrid seeds drives the value of the index. This is consistent with the descriptive evidence on input use that shows that mineral fertilizer is the most frequently used input. In Tanzania, as expected, the adoption of hybrid seeds has the stronger correlation with the estimated index. The index should also be increasing in the number of modern inputs adopted. A higher number of modern inputs implies a greater intensification. To check this, we plot the relationship between $A3i$ and the number of inputs adopted. The resulting graphs in Figures 2.19 and 2.20 clearly shows an upward trend with strong positive correlations both in Burkina Faso and Tanzania. These simple checks ensure that our estimated index truly captures agricultural input intensification. Changes in the index reflect at the same time the number of modern inputs used, the prevalence of each input, and the rate of application.

2.5 Determinants and impact of $A3i$ of crop productivity

Having estimated and validated our index of agricultural input intensification, we now turn to an analyze the determinants of agricultural input intensification and its impact on crop yield. In this section, we present the empirical models used for these analyses and discuss the results.

2.5.1 Determinants of agricultural input intensification

In this section, we explore the determinants of agricultural input intensification as measured by our index. The purpose of this analysis is to identify the observable factors that explain the level of input intensification. Without attempting to be comprehensive, we limit our analysis to selected factors that are typically investigated in the literature as determinants of individual modern input use. Our aim is to test the relevance of these factors in explaining joint input adoption, including applications rates as measured by our index. We categorize these factors into four groups: resource constraints, cost and mode of access to inputs, preferences and skills, and access to information.

As proxies for farmers resources and assets, we use total owned land and total tropical livestock units. We also use off-farm income and access to credit as additional measures of resources, particularly liquid resources. In both Burkina Faso and Tanzania, the cotton sector has a well functioning input supply system (Theriault and Serra, 2014; Kaminski, 2011; Poulton, 2009), and in Tanzania horticulture is considered as a cash crop that is very input intensive (Lynch, 1999). For these reasons, being involved in cotton or horticulture production could facilitate farmers access to inputs that could potentially be diverted to maize production. To test this possibility, we also include dummy variables indicating whether farmers are engaged in the production of cotton or horticulture.

It is well known that access to information plays an important role in farmers' awareness of the existence of new technologies. Farmers get information through various formal and informal channels through. Our data allow us to control only for farmers' contact with extension services to test the role of access to information on agricultural input intensification. The fourth group of variables we include in the analysis are related to farmers preferences and skills as reflected in production practices, plot level characteristics, and plot managers and household socio-demographics characteristics. Finally, we control for year and region fixed effects.

Our empirical strategy consists in regressing the estimated $A3i$ on the set of explanatory variables using OLS regression. We further control for unobserved heterogeneity using CRE. The results are presented in column (1) of Table 2.7 for Burkina Faso and Table 2.8 for Tanzania. The estimated coefficients represent measures of association and have causal interpretation only under the assumption that they are no time-varying unobserved factors that are correlated with both our dependent variables and the independent variables. This a plausible assumption for demographic and plot characteristics that physical. It is also plausible for variables that are predetermined to input decision. However, it is likely that this assumption will fail for income and credit as well as crop choice variables.

Overall, our results identify key variables that are significantly correlated with agricultural input intensification with signs confirming with our expectations. However, many other variables are surprisingly not significant or have counter-intuitive signs and merit further explanations.

One of the key variables of interest is household status in the community measured by the binary variables indicating whether a member of the household holds a management position in a community agricultural association. Consistent with our expectation, having a higher status in the village is associated with greater input intensification in Burkina Faso. The mechanism is that farmers with high social status have more access to productive inputs distributed either by the government or other non-governmental organization. This observation has been consistently found in previous studies in countries where input subsidy programs have been implemented in the recent years (Ricker-Gilbert et al., 2013).

Another variable that is positively correlated with input intensification in Burkina Faso is farmer engagement in cotton production. The positive effect of cotton in Burkina Faso is intuitive since the cotton sector has a well-functioning input supply system based essentially on input credit by the government. As such, being a cotton producer almost guarantee access to mineral fertilizer and insecticide. However, cotton does assure access to seeds and herbicide. Nonetheless, our results indicate that being a cotton producer in Burkina Faso is strongly correlated with the overall input intensification index. This result is in line with the finding by Theriault et al. (2017) that being a member of a cotton cooperative is associated with higher nitrogen application in Burkina Faso. Surprisingly however, we observed the opposite result in Tanzania. This is perhaps related to the deregulation in the Tanzanian cotton sector undertaken during the 2007-2010 and difficulties of transition from a state control sector to a liberalized sector. However, we find that being a producer of horticultural products in Tanzania is associated with greater input intensification.

In both Burkina Faso and Tanzania, we find that access to information through the extension service is associated with greater input intensification. Similarly, the plot manager's education level and household access to credit increase level input intensification. We also find that farm size is inversely related to input intensification, and the relationship is U-shaped. In fact, on a tiny plot it likely that input application rates are higher. However, farmers with very large plots and more wealth adopt more modern inputs and have higher intensification level.

2.5.2 Impact of agricultural input intensification on crop productivity

In our descriptive analyses, we show evidence from t-tests that the adoption of individual modern inputs is associated with higher maize yield. We also show that combining two of these input further increases yield. In this section, we document the positive correlation between joint input use as measured by the $A3i$ and crop productivity. We use regressions to estimate the change in yield resulting from a change in intensification level conditional on a set of factors also affecting yield. We estimate an OLS regression with plot level maize yield as dependent variable and $A3i$ as our treatment variable. We control for various determinants of $A3i$ that also explain yield. We further control for unobserved heterogeneity using the correlated random effects approach. Finally, we use IV with control function combined with the CRE method to estimate the causal effect of $A3i$ on maize yield. The index captures the relative importance of the adoption of each individual input. However, its use in a regression cannot identify the additive effect for the combination of several inputs.

The results of both the OLS and IV estimation for Burkina Faso are presented in columns 2 and 3 of Table 2.7. The results for Tanzania are in column (2) of Table 2.8. In both countries, the OLS estimates suggest a strong positive effect of agricultural input intensification as measured by the index on maize yield. The magnitude of the OLS effect is 42 kg/ha in Burkina Faso and 130 kg/ha in Tanzania. The effect of $A3i$ on yield is much larger in Tanzania than in Burkina Faso. This difference in the effect of input intensification in yield between the two countries stems from two effects. First, maize yields are lower in Tanzania than in Burkina Faso, thus the potential for increase in yield is higher in Tanzania. Second, input intensification as measured by the index is higher in Burkina Faso than in Tanzania. Thus, the marginal productivity of input intensification should be lower.

The OLS-CRE estimates are likely biased due to endogeneity of the input intensification index. The Burkina Faso data allow us to address this issue using instrumental variable methods with household's social status measured (at least one member holding a management position in an association) as an instrument. We adopt a control function approach and the results are presented in column 3 of Table 2.7. A direct empirical test of the presence of endogeneity consists in examining the significance of the first stage residuals. We find that the coefficient for the first-stage residuals is statistically significant. This result indicates that $A3i$ is likely endogenous and the OLS estimate of its effect on yield is biased. The point estimate for the effect of agricultural input intensification on yield increases from 42 kg/ha to 347.2 kg/ha. The data for Tanzania does not permit the use of the same instrument to address endogeneity using IV regression. Nonetheless, given the directional change of the estimated coefficient for Burkina Faso when endogeneity is accounted for, we can argue that the OLS estimate for Tanzania represents the lower bound of the effect of $A3i$ on maize yield.

To illustrate the importance of simultaneous adoption of input to accelerate productivity growth, let's consider the following example with two hypothetical farmers A and B. Both farmers apply half of the optimal application rate of N, P, K, manure, insecticide and herbicide. However, farmer A adopts a hybrid seed and farmer B uses a traditional seed. Using the formula for $A3i$, we have $A3i^A = 2 * 1.5 * 1.5 * .15 * 1.5 * 1.5 * 1.5 = 2.27$ which translates into a yield gain of 788.1 kg/ha. However, farmer B has an index $A3i^A = 1 * 1.5 * 1.5 * .15 * 1.5 * 1.5 * 1.5 = 1.14$ for a yield gain of 392.3 kg/ha. Similar counterfactual exercises can be performed for other inputs to show that the joint adoption of more than one input is associated with a much stronger increase in yield. This suggests that in order to accelerate agricultural productivity growth in Africa, the great focus needs to put on promoting and facilitating modern input adoption as a package rather narrow focus on only mineral fertilizer.

2.6 Conclusion

After a long period of stagnation, crop productivity in sub-Saharan Africa has recorded modest growth over the past two decades. The recent performance of African agriculture is the result of a combination of several factors including the increasing support to the sector in public policies and investment, improvements in the economic environment and incentive in the sector, and the increased availability and adoption of modern technologies. However, the growth rate of yield remains too slow and the continent continues to lag other regions in term of productivity. Much of the recent effort has focused on the promotion and adoption of mineral fertilizer through input subsidy programs. An analysis of input use by African smallholder farmers also shows a partial adoption with farmers experimenting one or two inputs without using other equally important complementary technologies. In this essay, we argue that in order to accelerate crop productivity growth, technologies need to be adopted as a package, rather than in a piecemeal fashion.

We start the analysis, by developing a simple conceptual framework to illustrate the importance of harnessing strategic complementarities among inputs with simultaneous adoption. The model adapts the O-ring model to show adopting modern technologies as a package is associated with higher productivity and output. To empirically test this implication, we use household panel data for maize producers in two countries, Burkina Faso and Tanzania. Descriptive analyses confirm that modern input use in both countries is limited. Joint adoption of input is also low but not rare. In Burkina Faso, more than half of maize plots receive mineral fertilizer but only a tenth are sowed with an improved seed variety. In Tanzania, hybrid seeds are more prevalent with about a quarter of farmers reporting using some improved certified or non-certified cultivars. However, mineral fertilizer is used by less than 15% of farmers. In both countries, application rates of mineral fertilizer are low by international standards. Moreover, the use of manure which is another important source of micronutrients essential to maintain and replenish soils, and crop protection chemicals such as insecticide and herbicide, is low.

We also found that the adoption of individual modern input is associated with higher maize yields. More importantly, our descriptive analyses show evidence of the yield growth-accelerating effect of the simultaneous adoption of several modern inputs. The joint adoption of improved seeds and fertilizer is associated with an increase in yield larger than the sole adoption of them individually. Moreover , whenever farmers use other modern inputs on top of hybrid seeds or fertilizer, the yield increase is even higher.

To further, examine the impact of joint input use on yield, we develop an agricultural input intensification index ($A3i$) that captures agricultural input intensification in its many dimensions. The formula of the index is a straightforward application of our conceptual framework and allows us to measure modern input adoption in terms of the use of improved seeds, application of various mineral nutrients and manure, and the application of insecticide and herbicide for crop protection. Previous studies are often unable to analyze joint input adoption due to fundamental differences among inputs in term of nature, scale, and units. The index circumvents this problem by rescaling and combining all input adoption variables into on single variable without losing the underlying information they contain. Our index measures how close observed input application rates are to agronomically optimal rates . We estimated these optimal rates that reflect farmers growing conditions using the available data and regression methods.

We illustrate the application of this index using national representative surveys for Burkina Faso and Tanzania. As expected, the index is strongly correlated with observed levels of input application and the number of inputs adopted. More importantly, it also captures the relative importance of each input in the set of inputs adopted by farmers. Consistent with the descriptive evidence, the index confirms that modern input adoption by smallholder farmers are limited and application rates are far from optimal levels. Next, we use the estimated index to examine the determinants of agricultural input intensification and its impact on yield. In both Burkina Faso and Tanzania, we find that higher input intensification lead to higher maize yields. Thus, the adoption of modern input is associated with higher maize yield, and the simultaneous adoption of several inputs is associated with a much stronger increase in yield.

The index provides useful information on modern input adoption in concert. However, its use in a regression model does not allow us to distinguish between the effect of higher levels of inputs and the simultaneous adoption of several inputs. In fact, a change in the index could result from either a large increase in the application rates of one input or a small increase in the application rates of all inputs. Given the formulation of the index, the former will likely result in a higher value of the index, and consequently a higher increase in yield. There are various approaches to separate the effect of an increase in the application rates of one input from the effect of adopting several inputs in concert. One could possibly estimate a translog production function allowing specific inputs of interest to be interacted and estimate their additive effect on yield. This approach could become non-parsimonious as the number of inputs and potential interactions increases. An alternative approach exploiting the idea of the index proposed in this essay consists in estimating a partial $A3i$ for all other inputs except the one that is being considered and interacting this partial index with the application rate of the specific input considered. For instance, if we are interested in how nitrogen affects yield in the presence of the joint adoption of all other modern inputs, we will estimate an $A3i$ for all these inputs except nitrogen and include the interaction term between nitrogen application rate and the partial $A3i$ in the yield regression. The coefficient of this interaction term provides insights into the effect of nitrogen on yield when combined with all other inputs.

2.7 Tables and figures for chapter 2

Table 2.1: Summary statistics on modern input use in Burkina Faso and Tanzania

	Burkina Faso							Tanzania					
	# plot	% plot	% of farmers	% of land	Unconditional Rate (kg/ha or L/ha)	Conditional Rate (kg/ha or L/ha)		# plot	% plot	% of farmers	% of land	Unconditional Rate (kg/ha or L/ha)	Conditional Rate (kg/ha or L/ha)
Hybrid seeds	698	8.7	10.4	8.6	.	.		1572	22.6	24.6	23.5	.	.
Fertilizer	4264	53.2	53.4	50.2	25.5	128.8		958	13.8	14.4	13.0	15.0	123.0
N	4253	53.0	53.3	50.0	6.3	31.9		941	13.6	14.0	12.8	5.1	43.0
P	4056	50.6	51.2	47.8	2.8	15.3		173	2.5	2.9	2.4	0.5	19.6
K	4071	50.8	51.3	47.9	2.8	15.1		197	2.8	3.3	2.7	0.3	11.4
Manure	1916	23.9	30.8	26.9	309.6	2167.5		994	14.3	18.0	14.6	161.2	1136.6
Insecticide	752	9.4	10.5	9.1	0.04	0.3		125	1.8	2.0	1.7	0.1	2.3
Herbicide	2960	36.9	37.0	33.7	0.09	0.5		554	8.0	9.2	8.1	0.2	1.7

Note: Unconditional rate is the average for all plots including plots with zero application rates while conditional rate is the average for all plots excluding plots with zero application rates. Measurement units for fertilizer, N, P, K, and manure are kg/ha; Measurement units for insecticide and herbicide are L/ha.

Table 2.2: Summary statistics on joint use of modern inputs in Burkina Faso and Tanzania

	Burkina Faso					Tanzania			
	# plot	% plot	% of farmers	% of land		# plot	% plot	% of farmers	% of land
Hybrid seeds x Fertilizer	557	6.9	8.0	6.6		285	4.1	4.6	4.1
Hybrid seeds x Manure	211	2.6	3.3	2.7		333	4.8	6.2	5.0
Hybrid seeds x Insecticide	120	1.5	1.7	1.3		54	0.8	1.0	0.8
Hybrid seeds x Herbicide	26	0.3	0.4	0.2		183	2.6	3.1	2.7
Fertilizer x Manure	1004	12.5	15.9	13.1		222	3.2	3.9	3.1
Fertilizer x Insecticide	557	6.9	7.7	6.4		59	0.8	1.0	0.7
Fertilizer x Herbicide	2442	30.4	30.9	27.7		202	2.9	3.3	2.9
Insecticide x Herbicide	445	5.6	6.1	5.1		0	0.0	0.0	0.0
Hybrid seeds x Fertilizer x Manure	168	6.9	2.5	2.0		81	4.1	1.6	1.2
Hybrid seeds x Fertilizer x Insecticide	111	6.9	1.6	1.2		28	4.1	0.5	0.3
Hybrid seeds x Fertilizer x Herbicide	354	6.9	5.1	4.0		72	4.1	1.3	1.1
Hybrid seeds x Fertilizer x Manure x Insecticide x Herbicide	26	0.3	0.4	0.2		0	0.0	0.0	0.0

Table 2.3: T-test of mean comparison of maize yield by modern input adoption status

	Burkina Faso				Tanzania		
	(1)	(2)	(3)		(4)	(5)	(6)
	Yes (sd)	No (sd)	Diff [t-stat]		Yes (sd)	No (sd)	Diff [t-stat]
Unconditional difference							
Use Hybrid Seeds	1545 (831.3)	1416 (761.2)	129 [4.2]***		830 (901.3)	705 (800.8)	125 [5.3] ***
Use Fertilizer	1564 (791.5)	1272 (710.2)	292 [17.3] ***		919 (909.2)	703 (808.3)	216 [7.5] ***
Use Manure	1430 (773.9)	1426 (766.7)	5 [0.2]		784 (876.6)	724 (817.2)	60 [2.1] **
Use Insecticide	1568 (780.3)	1412 (765.7)	155 [5.3] ***		1117 (929.1)	726 (822.6)	391 [5.2] ***
Use Herbicide	1650 (817.1)	1296 (706.4)	354 [20.4] ***		869 (901.8)	721 (818.3)	147 [4.0] ***
Conditional difference							
Use Seed + Fertilizer	1578 (825.9)	1415 (842.8)	163 [2.1] **		721 (822.3)	425 (500.2)	296 [7.9] ***
Use Seed + Insecticide	1785 (877.1)	1495 (813.4)	290 [3.5] ***		1021 (858.9)	460 (561.7)	561 [7.1] ***
Use Seed + Herbicide	1722 (871.2)	1339 (731.7)	383 [6.2] ***		526 (856.9)	473 (536.9)	54 [1.2]
Use Fertilizer + Manure	1565 (796.8)	1563 (789.9)	2 [0.1]		522 (515.4)	608 (661.7)	-86 [-1.8] *
Use Fertilizer + Insecticide	1632 (783.2)	1553 (792.3)	78 [2.2] **		975 (827.5)	563 (608.7)	412 [4.9] ***
Use Fertilizer + Herbicide	1671 (817.9)	1420 (730.4)	252 [10.4] ***		685 (890.9)	562 (539.7)	123 [2.5] **
Use Insecticide+ Herbicide	1677 (792.3)	1409 (735.4)	268 [4.7] ***				

Notes: sd denotes standard deviation, Diff is the difference between column (1) and (2) or columns (4) and (5). Conditional difference refers to the means comparison test in the sub-group of plot with already on input. For instance for Use Seed + Fertilizer, we are comparing yields between plots with fertilizer and no fertilizer in the sub-group of plot with already hybrid seed.

Table 2.4: Regression results for the estimation of agronomically optimal input application rates for Burkina Faso

	N OLS CRE (1)	N IV-CF CRE (2)	P OLS CRE (3)	P IV-CF CRE (4)	K OLS CRE (5)	K IV-CF CRE (6)	Manure OLS CRE (7)	Manure IV-CF CRE (8)	Insecticide OLS CRE (9)	Insecticide IV-CF CRE (10)	Herbicide OLS CRE (11)	Herbicide IV-CF CRE (12)
q_{pht}	4.789***	6.203*	7.510***	13.343	7.274***	13.357	0.030*	0.188	116.616	1,660.203	162.078***	477.257
	(0.95)	(3.45)	(2.1515)	(9.46)	(2.23)	(9.56)	(0.02)	(0.14)	(106.63)	(1,325.28)	(54.92)	(370.39)
q_{pht}^2	-0.035***	-0.034***	-0.080	-0.078	-0.078	-0.076	-0.000	-0.000	-29.138	-27.885	-15.574	-14.786
	(0.01)	(0.01)	(0.058)	(0.06)	(0.06)	(0.06)	(0.00)	(0.00)	(27.45)	(27.51)	(24.63)	(24.69)
$\hat{q}^{max} = \frac{\hat{\alpha}_1}{2\hat{\alpha}_2}$	138.70***	138.70*	94.29**	171.45	93.40*	176.06	8322.73***	52606.79	4.05**	59.53	10.40***	32.27
	(20.6)	(106.57)	(44.96)	(163.37)	(49.77)	(177.75)	(1969)	(51744.77)	(1.78)	(74.38)	(3.14)	(56.7)
First stage residuals	Not Included	Included	Not Included	Included	Not Included	Included	Not Included	Included	Not Included	Included	Not Included	Included
First stage residuals significant		Yes		No		No		No		No		No
Observations	7,951	7,926	7,951	7,926	7,951	7,926	7,951	7,926	7,951	7,926	7,951	7,926
R-squared	0.147	0.147	0.146	0.146	0.146	0.146	0.143	0.142	0.142	0.142	0.149	0.148

Notes: Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. All regressions plot characteristics, plot manager characteristics, and household characteristics defined listed in the text.

Table 2.5: Regression results for the estimation of agronomically optimal input application rates for Tanzania

	N OLS CRE (1)	P OLS CRE (3)	K OLS CRE (5)	Manure OLS CRE (7)	Insecticide OLS CRE (9)	Herbicide OLS CRE (11)
q_{pht}	13.344***	21.895***	36.887***	0.121***	669.921***	195.658***
	(1.313)	(4.105)	(5.369)	(0.162)	(155.179)	(32.373)
q_{pht}^2	-0.054***	-0.156***	-0.338***	-0.000	-185.823***	-20.057***
	(0.009)	(0.051)	(0.071)	(0.000)	(58.995)	(3.959)
$\hat{q}^{max} = \frac{\hat{\alpha}_1}{2\hat{\alpha}_2}$	247.2***	140.5***	108.9***	1050.8	3.6***	9.6***
	(19.5)	(23.8)	(10.4)	(796.5)	(0.41)	(0.7)
First stage residuals	Not Included	Not Included	Not Included	Not Included	Not Included	Not Included
First stage residuals significant						
Observations	6,928	6,928	6,928	6,928	6,928	6,928
R-squared	0.069	0.054	0.055	0.056	0.051	0.052

Notes: Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. All regressions plot characteristics, plot manager characteristics, and household characteristics defined listed in the text.

Table 2.6: Correlations between $A3i$ and individual input application rates

	Burkina Faso	Tanzania
Hybrid Seeds	0.631	0.8395
Nitrogen	0.6964	0.4454
Phosphorus	0.7091	0.3297
Potassium	0.7087	0.33
Manure	0.3479	0.3079
Insecticide	0.159	0.2641
Herbicide	0.2821	0.0656

Table 2.7: Determinants and Impact of $A3i$ of maize yield in Burkina Faso

	(1) Determinant A3i	(2) Impact of A3i on yield OLS-CRE	(3) Impact of A3i on yield IV-CF-CRE
A3i		42.3497***	347.1452**
		(8.5798)	(143.9554)
First Stage residuals			390.8823***
			(144.2116)
Member of association	0.1439***		
at management level	(0.0273)		
Contact with extension service	0.1288***	38.1664	96.8942**
	(0.0471)	(35.6973)	(41.7458)
Grow cotton	0.2176***	115.6509***	205.0557***
	(0.0293)	(22.2716)	(39.7948)
Grow horticulture	0.0224	-29.0891	-22.2895
	(0.0417)	(31.6928)	(31.7791)
Plot manager age	-0.0001	-1.9101***	-1.9825***
	(0.0008)	(0.6231)	(0.6234)
Plot manager gender	-0.0293	-18.9486	-29.3712
	(0.0264)	(20.0546)	(20.4119)
Plot manager education	0.0819**	-115.4120***	-79.9486***
	(0.0322)	(24.4504)	(27.7223)
Household size	-0.0024	5.6189*	4.7470
	(0.0040)	(3.0553)	(3.0709)
Plot has anti-erosion and	-0.0027	46.3011	45.1897
water conservation structure	(0.0481)	(36.5630)	(36.5505)
Steep slope	-0.0417	-33.5772	-49.4712
	(0.0504)	(38.3249)	(38.7555)
Lowland	-0.0819	7.0629	-24.7045
	(0.0540)	(41.0072)	(42.6332)
Collective management	-0.0801**	21.9805	-10.8208
	(0.0381)	(28.9431)	(31.3603)
Year since last fallow	0.0008	0.2359	0.6037
	(0.0011)	(0.8467)	(0.8572)
Intercropping	-0.1022**	-54.2977	-94.6131**
	(0.0480)	(36.4923)	(39.3934)
Rented plot	-0.0020	21.7323	21.3331
	(0.0424)	(32.2066)	(32.1939)
Use hired labor	0.0028***	2.5711***	3.6477***
	(0.0009)	(0.6549)	(0.7658)

Table 2.7: Determinants and Impact of $A3i$ of maize yield in Burkina Faso (continued)

Plot area	-0.1186***	172.2718***	127.3760***
	(0.0230)	(17.4730)	(24.0711)
Plot area square	0.0096***	-13.9348***	-10.2751***
	(0.0026)	(1.9448)	(2.3669)
Non-farm income	0.0000	0.0177	0.0186
	(0.0000)	(0.0228)	(0.0228)
Total tropical livestock units	0.0011	2.0277**	2.4353***
	(0.0011)	(0.8187)	(0.8320)
Total farm size	-0.0195***	-8.9414**	-16.4818***
	(0.0054)	(4.1158)	(4.9664)
Access to credit	0.1039***	16.9046	63.5963**
	(0.0314)	(23.7694)	(29.3475)
Observations	7,866	7,866	7,866
R-squared	0.162	0.158	0.159

Table 2.8: Determinants and Impact of $A3i$ of maize yield in Tanzania

	(1) Determinant A3i	(2) Impact of A3i on yield OLS-CRE
A3i		129.5599***
		(13.2560)
Contact with extension service	0.1611***	66.8549**
	(0.0294)	(32.3557)
Grow cotton	-0.1193**	-1.4224
	(0.0464)	(51.0341)
Grow horticulture	0.1307***	26.3773
	(0.0365)	(40.1526)
Plot manager age	0.0001	1.4313**
	(0.0006)	(0.6386)
Plot manager gender	-0.0401***	-8.5984
	(0.0110)	(12.0514)
Plot manager education	0.0115***	1.7854
	(0.0013)	(1.4680)
Household size	-0.0045	17.5322**
	(0.0077)	(8.5013)
Plot has anti-erosion	0.1156***	69.7243
and water conservation structure	(0.0391)	(42.9290)
Steep slope	0.0108	36.0996***
	(0.0120)	(13.2309)
Collective management	-0.0162	36.5355*
	(0.0184)	(20.1732)
Year since last fallow	0.0000	0.0460
	(0.0001)	(0.0573)
Rented plot	-0.0539	-14.8189
	(0.0368)	(40.3833)
Use hired labor	0.0002	2.8654***
	(0.0006)	(0.6957)

Plot area	-0.0337***	-77.8892***
	(0.0088)	(9.7189)
Plot area square	0.0006**	1.8373***
	(0.0003)	(0.3172)
Non-farm income	-0.0000	0.0005
	(0.0000)	(0.0007)
Total tropical livestock units	0.0043	1.8029
	(0.0028)	(3.0256)
Total farm size	0.0021	-10.1901***
	(0.0025)	(2.7507)
Access to credit	0.0637	26.0268
	(0.0481)	(52.7938)
Observations	6,925	6,925
R-squared	0.168	0.062

Figure 2.1: Percentage of plots using a given number of input in Burkina Faso

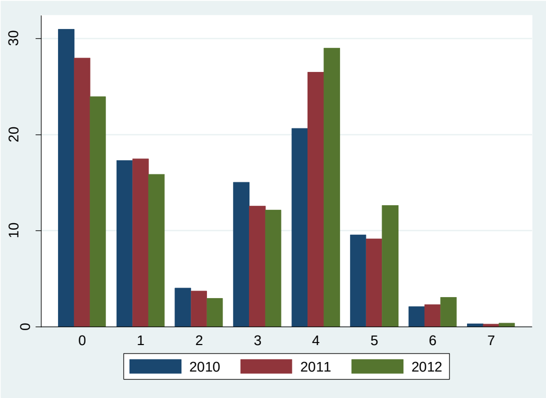


Figure 2.2: Percentage of households using a given number of input in Burkina Faso

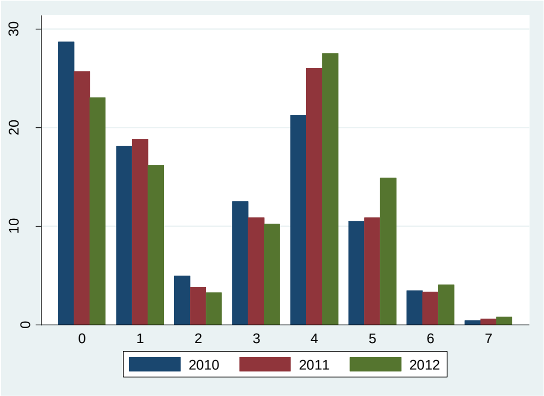


Figure 2.3: Percentage of plots using a given number of input in Tanzania

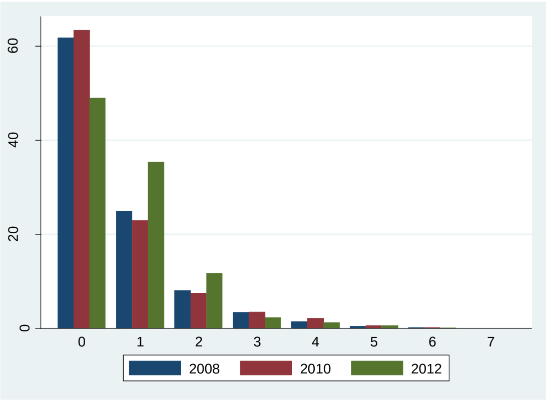


Figure 2.4: Percentage of households using a given number of input in Tanzania

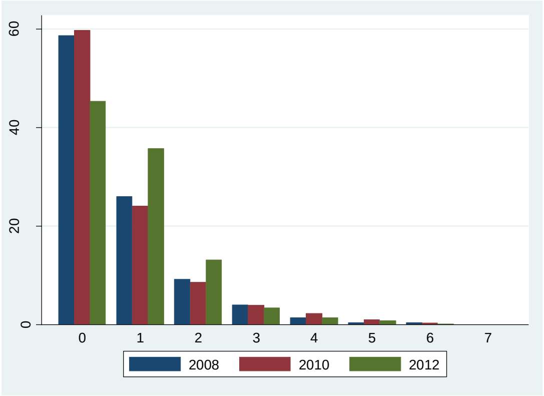


Figure 2.5: Local polynomial regression of maize yield on nitrogen use in Burkina Faso

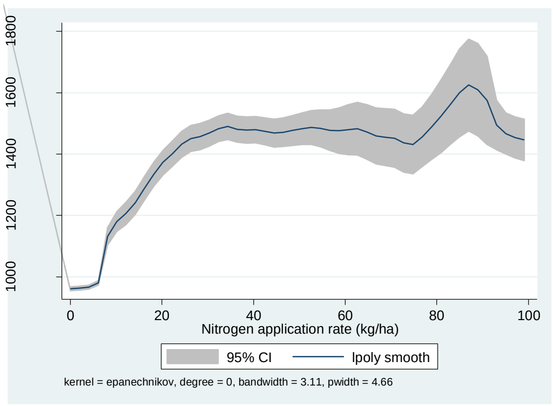


Figure 2.6: Local polynomial regression of maize yield on phosphorous use in Burkina Faso

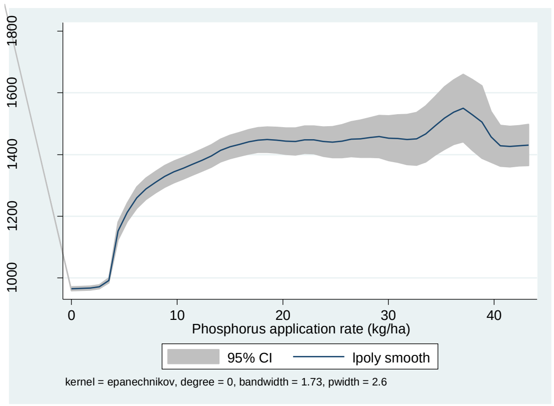


Figure 2.7: Local polynomial regression of maize yield on potassium use in Burkina Faso

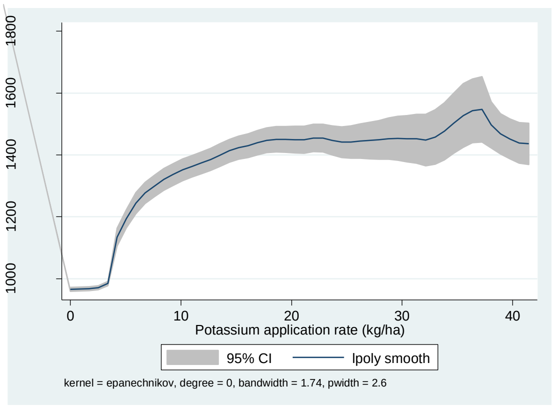


Figure 2.8: Local polynomial regression of maize yield on manure use in Burkina Faso

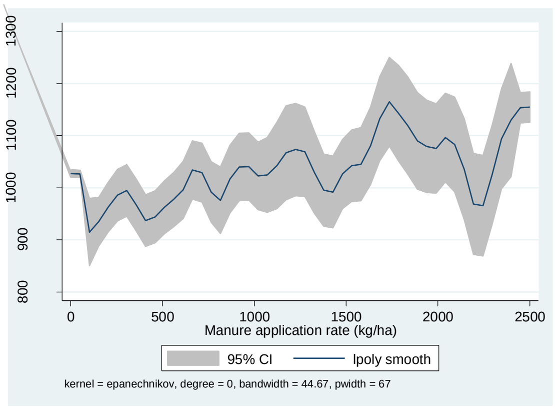


Figure 2.9: Local polynomial regression of maize yield on insecticide use in Burkina Faso

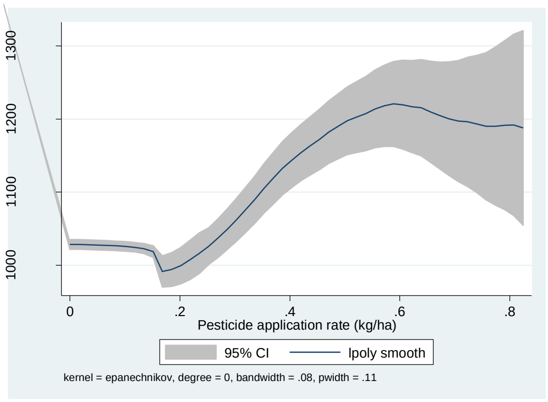


Figure 2.10: Local polynomial regression of maize yield on herbicide use in Burkina Faso

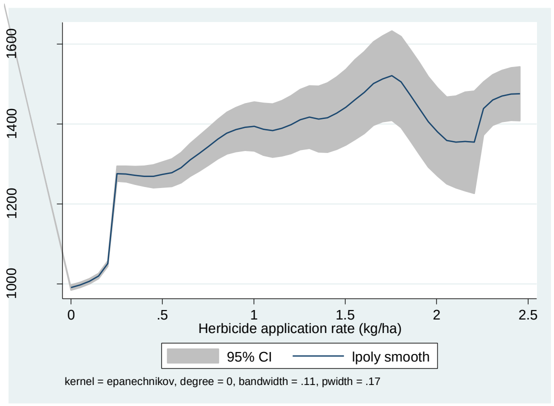


Figure 2.11: Local polynomial regression of maize yield on nitrogen use in Tanzania

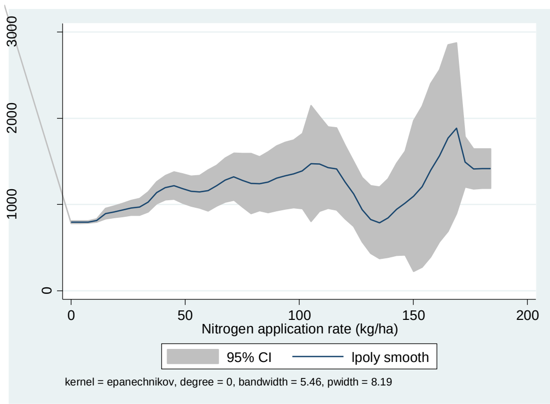


Figure 2.12: Local polynomial regression of maize yield on phosphorous use in Tanzania

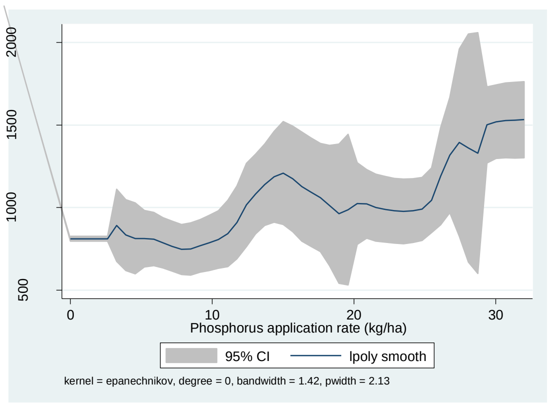


Figure 2.13: Local polynomial regression of maize yield on potassium use in Tanzania

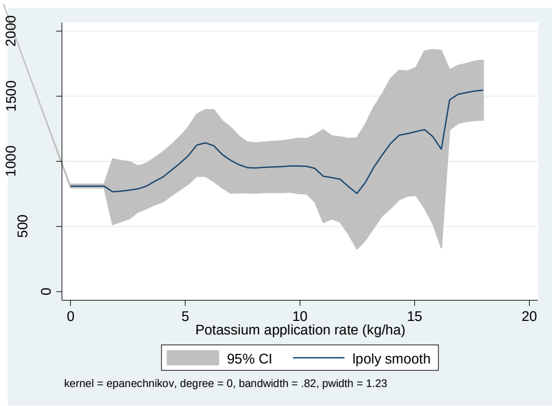


Figure 2.14: Local polynomial regression of maize yield on manure use in Tanzania

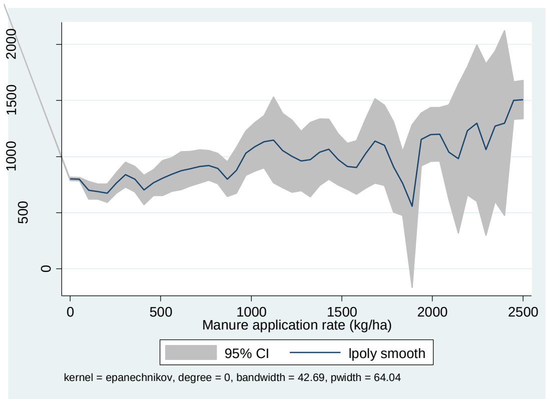


Figure 2.15: Local polynomial regression of maize yield on insecticide use in Tanzania

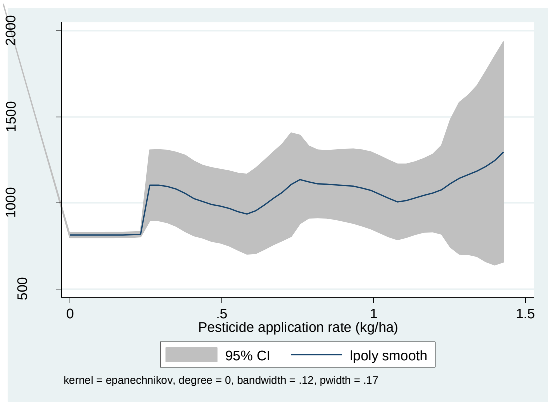


Figure 2.16: Local polynomial regression of maize yield on herbicide use in Tanzania

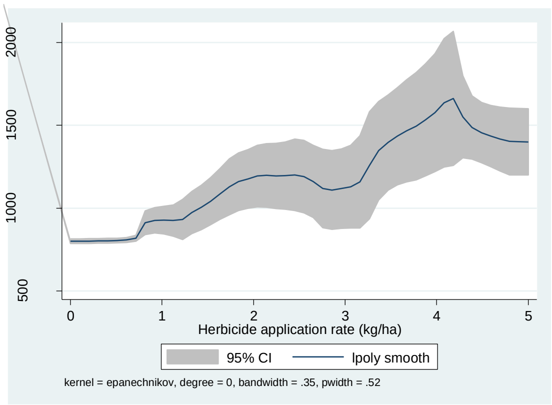


Figure 2.17: Density of the distribution of $A3i$ by year in Burkina Faso

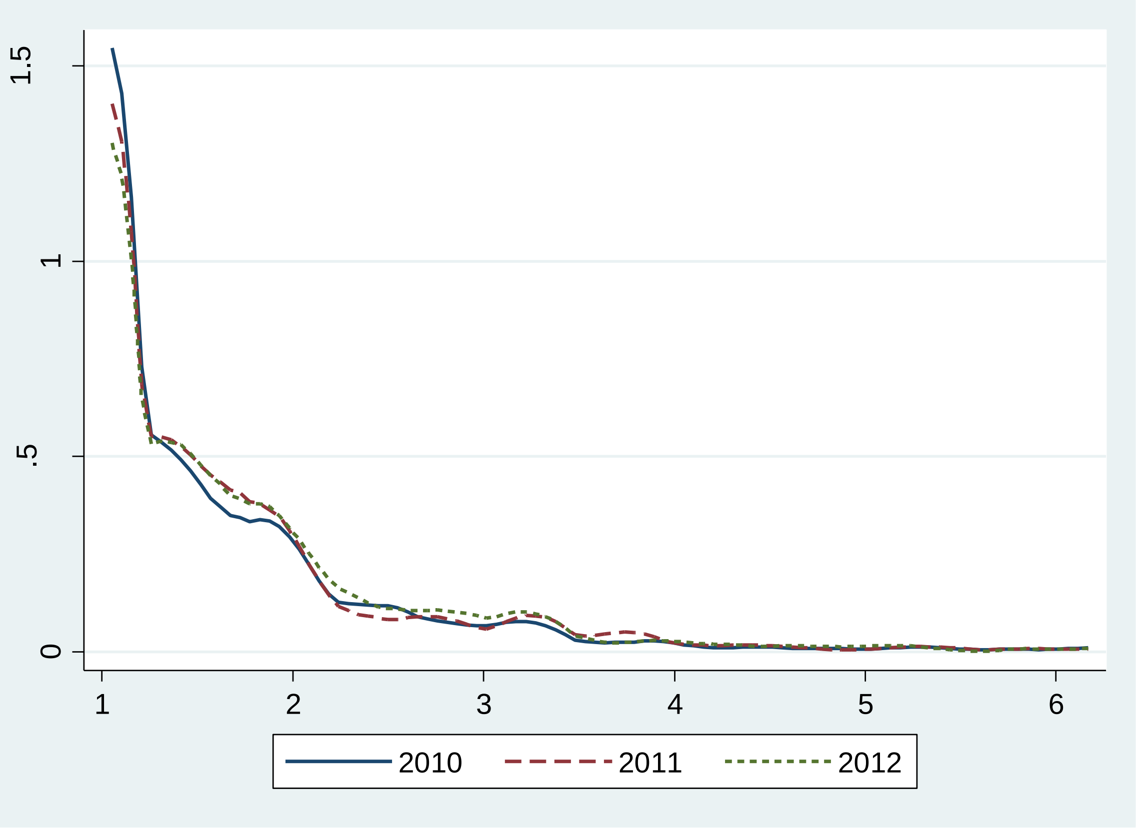


Figure 2.18: Density of the distribution of $A3i$ by year in Tanzania

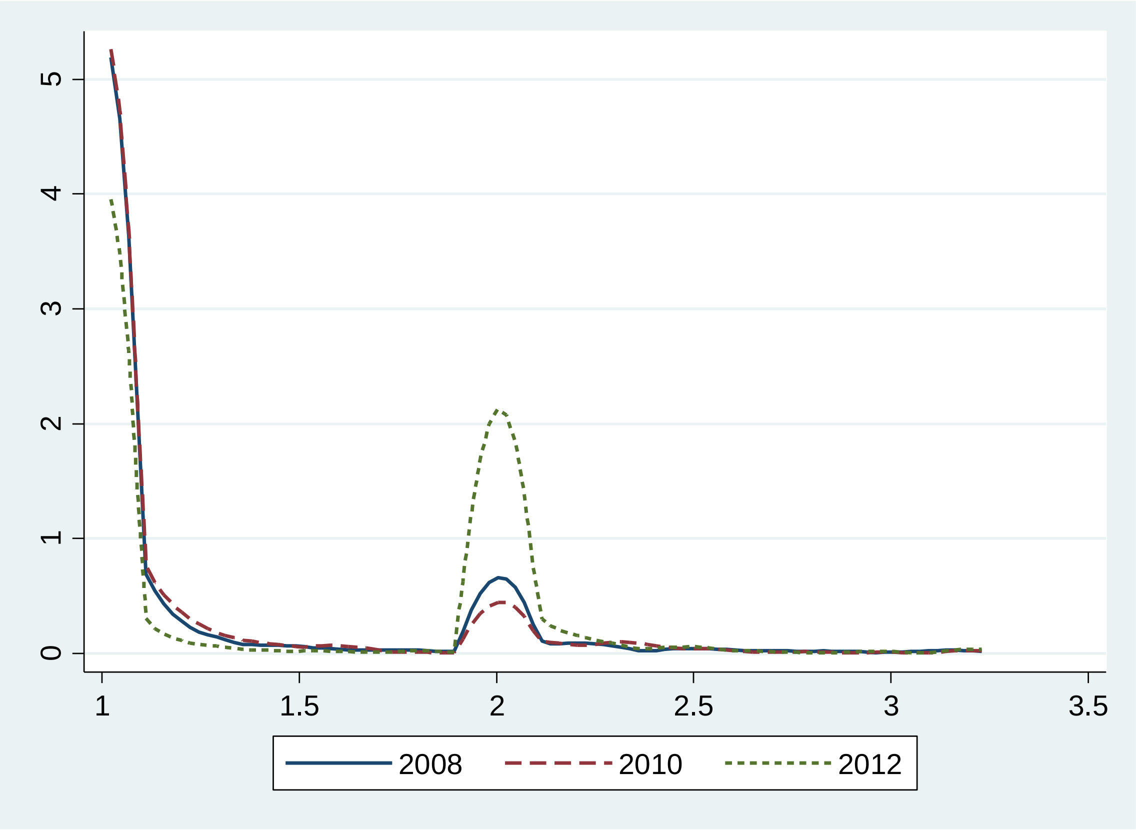


Figure 2.19: Relation between $A3i$ and the number of modern input adopted in Burkina Faso

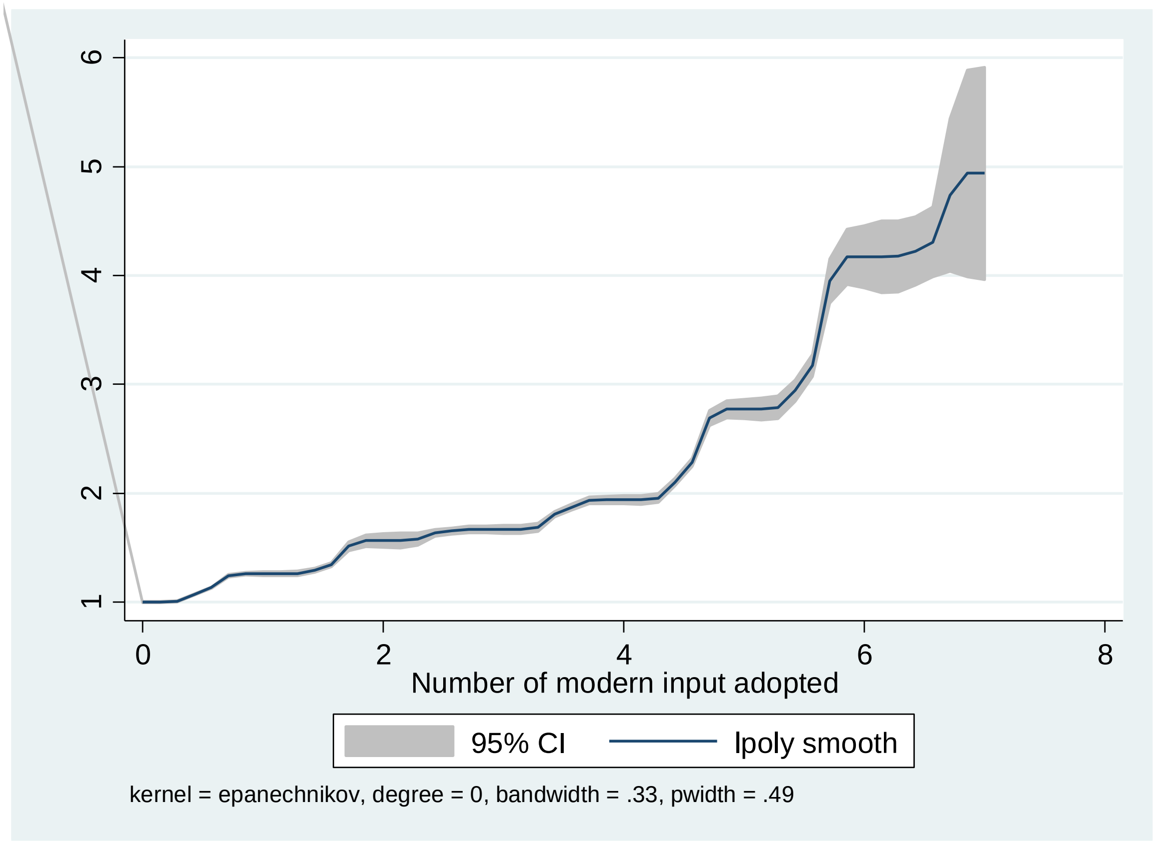
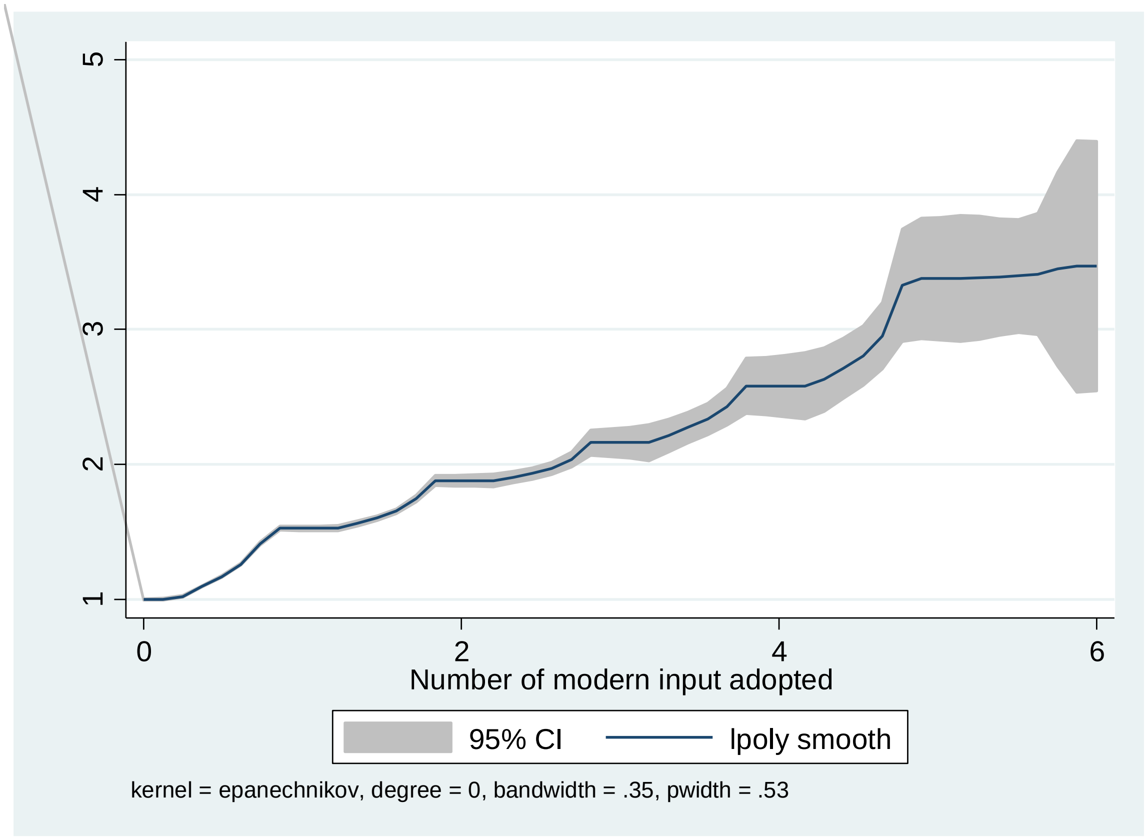


Figure 2.20: Relation between $A3i$ and the number of modern input adopted in Tanzania



Chapter 3 Killing many birds with one stone? Spillover effects of fertilizer subsidies on the adoption of modern inputs in Burkina Faso

In the aftermath of the 2007-2008 food crises, the Government of Burkina Faso launched an input subsidy program to provide mineral fertilizer to small farmers at a 15%-50% discounted price. Unlike similar programs in other countries, the Burkina Faso's program has the particularity that it subsidizes only mineral fertilizer. We exploit this unique feature and use panel data on maize producers covering the period 2010-2012 to assess the impact of subsidizing only one input on households' decisions to use other inputs. The empirical analysis addresses three econometric issues, with the following methods: 1) the simultaneity in input use decisions, by using multivariate probit; 2) unobserved heterogeneity among households, by using correlated random effects; and 3) endogeneity of participation in the subsidy program, by using the control function/instrumental variable approach. We find that fertilizer subsidies increase mineral fertilizer use, crowd in the use of hybrid seeds and crop protection chemicals, but crowd out the use of manure. Given the beneficial effects of manure on soil fertility, the results suggest that -for sustainable input intensification- mineral fertilizer subsidies need to be implemented in conjunction with measures to promote or maintain manure use.

3.1 Introduction

The low utilization of modern inputs has been consistently identified as the most important factor for low productivity in Africa agriculture. Many studies have shown that smallholder African farmers face substantial physical and economic barriers to access and adopt modern inputs such as hybrid seeds, fertilizer, herbicide, and insecticide. Physical constraints relate to the physical availability of these technologies to farmers (Chianu et al., 2012). Even when these inputs are imported, poor infrastructure and inefficient institutional environments - all of which push up transaction costs - make their distribution to production zones difficult. Economic barriers concern the affordability of inputs to resource-poor farmers. The widespread and high poverty combined with incomplete credit and input markets imply that smallholder farmers have limited resources to invest in productive inputs. To help farmers overcome these barriers, many African governments often recourse to subsidy programs to import and distribute agricultural inputs to farmers below market prices (Druilhe and Barreiro-Hurlé, 2012).

During the 1970s and 1980s, most African countries implemented various forms of subsidy programs. These government interventions in markets faced fierce criticisms for being inefficient and thus were completely phased out during the 1990s due to the structural adjustment programs and market liberalization reforms (Ricker-Gilbert et al., 2013; Morris, 2007). However, since 2000, Input Subsidy Programs have resurfaced in the African agricultural policy landscape (Jayne and Rashid, 2013). This re-emergence received a high-level support with the 2006 African Union's Abuja Declaration on Fertilizer that urged African countries to improve farmers' access to fertilizers by adopting concrete policy measures including subsidy programs. Following this call and the successful experience in Malawi in the early 2000s, several African countries including Burkina Faso designed and implemented various input subsidy programs with the objective of boosting agricultural production and reducing food insecurity and poverty (Denning et al., 2009; Dorward, 2009; Minde et al., 2008). Assessing the effectiveness of these programs is important to justify their existence or to reform them to serve better their intended purpose.

Most subsidy programs focus primarily on mineral fertilizer, and to a lesser extent on hybrid seeds (Denning et al. 2009; Dorward 2009; Minde et al., 2008). Assessments of programs rolled out in the 1970s and 1980s find that they were successful in increasing fertilizer utilization, but the resulting increases in yield were insignificant (Holden and Lunduka, 2012). The lessons learned from these experiences have been instrumental in designing 'smarter' subsidy programs that resurfaced in the early 2000s. However, the effectiveness of fertilizer subsidy programs in increasing yield depends on a wide range of factors. In this essay, we evaluate the potential for fertilizer subsidies in increasing modern input utilization in a more comprehensive manner.

In the aftermath of the 2007-2008 food crisis, the Government of Burkina Faso designed and implemented a program to provide mineral fertilizer to small farmers at below market prices with the objective of boosting fertilizer use and agricultural production. Unlike similar programs in other countries that provide subsidies for a package of agricultural technologies, the Burkina Faso program has the particularity that it focuses singularly on mineral fertilizer. We exploit this unique feature of Burkina Faso's fertilizer subsidy program to evaluate the impact of subsidizing only one input on a household's decisions to use non-subsidized inputs. The aim of the empirical analysis is to test the hypothesis that farmers may be using fertilizer as a substitute for - rather than a complement to - other technologies such as manure.

The importance of balancing agricultural inputs to increase productivity cannot be overstated in the context of Africa where soils and nutrient depletion is a fundamental biophysical problem (Chianu et al., 2012). There is a strong agronomic argument for combining mineral and organic matter to increase soil fertility (Chivenge et al., 2011; Vanlauwe et al., 2010). Also, hybrid seeds perform better in production environments vulnerable to various biotic and abiotic stresses and are shown to be more responsive to mineral fertilizer (van Bueren et al., 2011). Moreover, protecting plants at various stage of the growth process using herbicide, insecticide, and other protection chemicals, could minimize production and post-harvest damages and increase yield (Oerke and Dehne, 2004; Kaminski and Christiaensen, 2014). Thus, assessing the spillover effects of fertilizer subsidies on farmers' adoption of hybrid seeds, organic materials, and crop protection chemicals is essential to unpack the impact of the program on crop yield.

The nature of the spillover effects of the fertilizer subsidy also has important implications for the efficiency of the program. Previous assessments of fertilizer programs in Africa have largely ignored these spillover effects. In the particular context of Burkina Faso, if subsidizing only mineral fertilizer crowds in the use of manure and other soil improvement practices, the adoption of hybrid seeds, and the use of crop protectant, the program would have been very effective. However, it is also possible that a fertilizer subsidy sends the wrong signal for farmers that only mineral fertiliser matters and lead them to crowd out other input. In this case, it might be more efficient to subsidize concurrently those inputs or practices, or to provide training to farmers on the importance of adopting other technologies in conjunction to mineral fertilizer.

The resurgence of input subsidies in Africa generates a second wave of empirical studies that places greater focus on identifying the causal effects (Ricker-Gilbert et al., 2013; Jayne and Rashid, 2013; Lunduka et al., 2013; Morris, 2007). However, most of the existing studies concentrate on prominent programs implemented in Malawi, Zambia, Tanzania, Kenya, and Nigeria (Jayne and Rashid, 2013; Ricker-Gilbert, et al., 2013). To date, little is known about the impacts of the input subsidy programs in other African countries particularly in Burkina Faso. Our study aims at filling this gap in the growing literature on the assessment of fertilizer subsidy programs in Africa by providing empirical evidence unique to the particular context of Burkina Faso.

Another particularity of the new wave of studies on input subsidies is the recognition that their impacts are not confined to fertilizer use and yield. To understand why aggregate production and productivity have only marginally responded to fertilizer subsidies, a small but growing set of studies captures the effects of these programs on a broader set of outcome variables. Many studies suggest that subsidized fertilizer displaces non-subsidized commercial fertilizer demand to the point that the aggregate increase in fertilizer use is much smaller (Ricker-Gilbert et al., 2011; Xu et al., 2009; Mason et al., 2017).

More recently, some studies analyze the relationship between fertilizer subsidies and farm input mix with the goal of quantifying the spillover effect of fertilizer subsidies on the use of modern varieties and the adoption of agricultural management practices. An earlier attempt in this direction made by Holden and Lunduka (2012) finds that fertilizer subsidies crowd in manure in Malawi, but the magnitude of the effect is small. Levine and Mason (2014) also find that, in Zambia, the receipt of a fertilizer subsidy crowds in the use of most soil fertility management practices except fallow. Liverpool-Tasie and Salau (2013) analyzing the effect of fertilizer subsidies on the adoption of hybrid seeds in Nigeria find that farmers who received subsidized fertilizer are more likely to adopt improved seed varieties.

Our study is related to these papers but differs in many aspects. First, our assessment concerns the fertilizer program in Burkina Faso with its distinguishing feature of universal access and singular focus on mineral fertilizer. Also, all the previous studies consider either manure, soil conservation practice or improved seeds, but not all together. Our paper is more comprehensive as it analyzes all the main modern inputs, including crop protection chemicals simultaneously.

Our empirical analysis uses three waves of panel data from the Permanent Agricultural Survey (Enquête Permanente Agricole) to assess the impact of the fertilizer subsidy program on farmers' demand for mineral fertilizer, hybrid seeds, crop protection chemicals, and manure. We address numerous empirical challenges. We use the correlated random effects approach to control for unobserved heterogeneity, system estimation using seemingly unrelated regression to account for the interdependence in input demands, and instrumental variables methods to address the endogeneity of fertilizer subsidies. We use household head's status in the village proxied by his membership and status in an association in the village as an instrumental variable to identify the effect of the receipt of the subsidy on input demand. In an alternative specification, and for robustness checks, we use the amount of subsidized fertilizer supplied to the village as an instrument.

Overall, we find evidence that input demands are made simultaneously and the access to the fertilizer subsidy is endogenous. Our analysis suggests that the receipt of fertilizer subsidy increases the likelihood of maize farmers in Burkina Faso to use mineral fertilizer and crowds in the use of hybrid seeds and crop protection chemicals such as insecticide, herbicide, rodenticide, and fungicide. However, the fertilizer subsidy program crowds out the use of manure. The result is robust to alternative treatment variables and instruments. Our explanation of these results is that the receipt of a fertilizer subsidy relaxes household budgetary constraints to allow them to adopt money-intensive inputs such as fertilizer, seeds, and crop protection chemicals. The crowding out effect on the use of manure is the result of the perceived substitutability between mineral fertilizer and manure as a source of nutrient, and the labor-intensive nature of home manure production .

The remainder of the paper is organized as follows. In section 3.2, we provide a brief background on design and implementation of the Burkina Faso fertilizer subsidy program. In section 3.3, we present the conceptual model that guides our empirical analysis. Section 3.4 discusses the empirical models and identification strategy. Section 3.5 introduces the data and section 3.6 presents and discusses the empirical findings.

3.2 Background on the Burkina Faso's fertilizer subsidy program

The Burkina Faso fertilizer subsidy program, like similar programs in many African countries, was precipitated by the 2007-2008 food crisis. The economic and social impacts of the crisis prompted policy makers in Burkina Faso and across the continent to recognize the urgent necessity to increase domestic food production and reduce reliance on imports (Sabo et al., 2010; Holtzman et al., 2013; Berazneva and Lee, 2013). Among the measures taken, input subsidy programs were the most prominent with medium and long-term goal of improving crop productivity and food production.

The Burkina Faso program targeted strategic food crops - maize and rice - of great importance for food security. However, the quantity of fertilizer supplied the government was limited. Therefore, only a small proportion of farmers received subsidized fertilizer. In the first year of the program, a total of 23, 375 tons of fertilizer comprising 14,250 tons of NPK and 9,124 tons of urea was purchased for a total cost of 8, 218 millions of FCFA ($US 18.3 million) (Sabo et al., 2010). Information about the total number of beneficiaries of the program are rarely available, but our data suggest that about 7.7% of maize farmers benefited from the subsidy program receiving on average

8.9 kg of fertilizer. The percentage of farmers receiving fertilizer subsidies dropped during the year 2010-11 to 5.1% with an average subsidized fertilizer amount of 7.4 kg before slightly rising in 2011-12 to 7.3% with an average subsidized fertilizer of 7.9 kg. The decrease in the subsidy program in 2010-2011 partially reflects the decline in the price of mineral fertilizer due to the appreciation of the Burkina Faso's currency (FCFA) relative to the US dollar, as well as a cut in the subsidy program budget.

The Burkina Faso program also has some particularities that make it an interesting case to study. The program is closer to the first-generation of input subsidy programs of the 1970s and 1980s but also shares some commonalities with the newer generation designs. The program is entirely funded by the government offers discounted prices amounting to 15-30% depending on the year and budget allocation. It extensively involves government agencies from the importation to the distribution of the subsidized fertilizer. The government, through the Ministry of Agriculture, imports a certain quantity of mineral fertilizer based on estimated needs and budgetary constraints. The fertilizer is then dispatched physically to farmers using the administrative structure of the Ministry from the national level to the regions, communes, and villages. Unlike the celebrated Malawian program, the Burkina Faso's program has not used a voucher system or a targeting system for the distribution. It is also universal in the sense that all producers are eligible, but the limited quantity of the stock fertilizer clearly implies that a small proportion of farmers benefited.

Most importantly, the Burkina Faso program has the particularity that it focuses singularly on mineral fertilizer. Often, agricultural technologies are introduced as a package of several complementary technologies (Feder, Just, and Zilberman, 1985). In these settings, it is hard to separate the impact of the programs by type of input. Burkina Faso's subsidy program neither directly supports nor discourages the use of other inputs, although other government channels and programs do promote other inputs (Druilhe and Barreiro-Hurlé, 2012; Sabo et al., 2010). This feature provides a unique setting for assessing the spillover effects of subsidizing only one agricultural input on the use of other inputs.

Finally, few studies are based on the Burkina Faso's program. To our best knowledge Sabo et al. (2010) is the only exception. The authors use computable general equilibrium model to assess the economy-wide impact of the Burkina Faso fertilizer program. The paper makes various assumptions to model the inter-linkages of the cereal sectors to the rest of the agricultural sectors and the rest of economy. Multiple simulations show that the fertilizer program has increased maize and rice production, and has resulted in a moderate increase in household's income thus contributing to poverty reduction. The assessment also shows that the program has led to a slight drop in aggregate economic growth due to the diversion of resources from other sectors, and warns that excessive subsidies would be inefficient. Our studies use microeconometrics approaches to quantify the impact of the program on input use, crop productivity, and production efficiency.

3.3 Conceptual framework

To assess the impact of the fertilizer subsidy on fertilizer use and the use of other inputs, we use the framework of the agricultural household model proposed by Singh et al. (1986). The purpose of the model is to provide testable predictions on how the receipt of fertilizer subsidies affect household input use decisions. For simplicity of exposition, we focus the analysis on the production of a single crop - maize and assume that small subsistence farmers make production and consumption choices to maximize their consumption utility under budget constraints. Following Carter et al. (2014), we assume that an agricultural household can produce maize using a traditional technology getting a fixed output x ? or he can adopt modern inputs to add soil nutrients N with a production gain rN. Thus, the amount of output q takes the form:

$$q = N(M, F) + r\bar{x} \tag{3.1}$$

Additionally, we assume that farmers get nutrients from two sources: mineral fertilizer F and manure M. The total nutrient intake on the farm is expressed by the aggregation function $N(F, M)$ assumed to be quasi-concave. This function is such that the non-use of one particular source of nutrient does not nullify the return on the other; that is $N(M, F) \neq 0$ and $N(M, F) \neq 0$. We also assume that both sources of nutrient are important in increasing production $\partial N/\partial F > 0$ and $\partial N/\partial M > 0$. However, we allow the two inputs to be either complements or substitutes letting the sign of the second order cross partial derivatives to be undetermined. If the farmer perceives the two inputs as complements, then we have $\partial^2 N/\partial F \partial M = \partial^2 N)/\partial M \partial F > 0$. In the case that the farmers perceives that the two inputs are substitutes, we have $\partial^2 N/\partial F \partial M = \partial^2 N)/\partial M \partial F < 0$..

Farmers are small-scale producers, take price as given, and are risk neutral; thus, we can assume that they maximize total consumption. Households have a fixed labor endowment $\bar{L}$ and an initial income y_0. Additional resources are from the value of production and income from off-farm work paid at the fixed wage w. Manure is not available on the market and has to be home-produced using labor according to the production function $M = L_M$. We implicitly set aside the choice of land, irrigation, equipment and long-term inputs treating them as quasi-fixed inputs $\bar{A}$ that also affect production. The assumption of such quasi inputs is common in the literature on agricultural households and is valid in the short run (Feder, Just, and Zilberman, 1985). Finally, for simplicity, we consider a static model.

The household problem is written as follows:

$$\begin{aligned} \underbrace{Max}_{C,F,M} U(c) &= C \\ C + p_F F &\leq y_0 + p_q(N + r\bar{x}) + w(\bar{L} - M) \end{aligned} \tag{3.2}$$

Where C is household's consumption, F denotes the demand for mineral fertilizer, M denotes the demand for manure, p_q is the price of output, p_F is the price of mineral fertilizer, w is the agricultural wage rate and also captures the shadow price of manure, and y_0 is household's non-agricultural and non-labor income.

Taking the first order conditions of the maximization problem, we have the following set of first order equations:

$$\begin{aligned} p_q r N_F - p_F &= 0 \\ p_q r N_M - w &= 0 \end{aligned} \tag{3.3}$$

Assuming that the second order conditions for maximization holds, we can use these equations for comparative statics analysis. Applying the implicit theorem function, we have:

$$\begin{aligned} \tfrac{dF^*}{dp_F} &= \tfrac{p_q r N_{MM}}{|H|} \leq 0 \\ \tfrac{dM^*}{dp_F} &= \tfrac{-p_q r N_{MF}}{|H|} \leq \; or \; \geq 0 \end{aligned} \tag{3.4}$$

The quasi-concavity assumption of the function N assures that the second order conditions hold and that the determinant of the hessian matrix $|H|$ is positive. From the first line of equation 3.4, we have $dF^*/dp_F \leq 0$ since $N_{MM} \leq 0$ and $|H| > 0$. This inequality indicates that a decrease in the price of fertilizer unambiguously increases the amount of fertilizer demanded. The effect of the receipt of a fertilizer subsidy on the demand for manure depends on whether the manure is perceived as a substitute or a complement to mineral fertilizer. The second line of equation 3.4 becomes $dM^*/dp_F \geq 0$ if $N_{MF} \leq 0$ indicating manure and mineral fertilizer are substitute. In this case, a decrease in the price of mineral fertilizer or alternatively the receipt of subsidies decreases the use of manure demanded.

Similarly, we can incorporate improved seeds and crop protection chemicals in this framework by assuming that they enhance productivity but do not add soil nutrients. For the purpose of our analysis, we assume that these inputs are more likely to enhance the marginal productivity of mineral fertilizer. This assumption stems from the observation that more than 95% of hybrid crop varieties are bred to be responsive to mineral fertilizer and to resist to disease, insects, and weeds competition (van Bueren et al., 2011). This assumption implies that the increase in fertilizer demand resulting from farmers' access to subsidies would likely translate into an increase in the likelihood to adopt hybrid seeds or use crop protection chemicals. Our empirical analysis seeks to identify and quantify these effects using household panel data from Burkina Faso.

3.4 Empirical models

3.4.1 Methods for fertilizer subsidies and farmers' decision to use modern inputs

To estimate the impact of fertilizer subsidies on the farmer's decision to use fertilizer, hybrid seeds, crop protection chemicals, and manure, we consider latent class models that link observed household decisions to latent variables capturing the perceived net benefit (Maddala, 1986). More specifically, we consider the following equation describing the demand for the modern input i.

$$D_{kht} = \begin{cases} 1 & \text{if } Z^*_{hkt} > 0, \\ 0 & \text{Otherwise} \end{cases} \tag{3.5}$$

with $Z^*_{kht} = \alpha R_{Fht} + X_{kht}\beta + \epsilon_{kht}$, $k \in (F, V, P, M)$

Where F stands for mineral fertilizer, V stands for hybrid seeds, M stands for manure, and P stands for crop protection chemicals. In this equation, D_{kht} is a binary variable indicating whether a household h has used any amount of a particular input k in the year t. This variable takes the value 1 if a certain latent variable Z^*_{kht} measuring the net benefit of the use the input k is greater than 0. We assume that this latent variable is a linear function of household's observed demographic and economic characteristics and other factors affecting production, and most importantly a variable RS_{Fht} denoting whether a farmer has received subsidized mineral fertilizer or not. In an alternative specification, we use a variable AS_{Fht} representing the amount of subsidized fertilized received to measure the extent of farmer participation in the program. The term ϵ_{kht} represents unobserved factors affecting Z^*_{kht} and can be decomposed in two components as follows: $\epsilon_{kht} = u_{kh} + e_{kht}$. The first component u_{kh} is the household's unobserved heterogeneity that is time invariant and the second component e_{kht} is the error term which measures the unobserved time-varying shocks affecting input use (Cameron and Trivedi, 2005; Greene, 2008).

3.4.2 Estimation methods and identification issues

In estimating the models formulated above, we can exploit variation in farmer demographic and production characteristics X and the selection on observable framework to identify the parameter α. Under this assumption, equation 3.5 can be estimated using a probit or linear probability model. However, there are a number of identification problems with this setting, and we discuss various strategies in this sub-section to address them.

Simultaneity in input demand. The first issue with the estimation of input demand functions is related to simultaneity and interdependence. The household utility maximization problem suggests that decisions to use modern inputs are inter-linked. Therefore, we begin the estimation by assuming that the error terms in demand equations are correlated and follow a multivariate normal distribution. This assumption allows us to estimate multivariate probit regressions when the outcome variables are the binary variables indicating whether the household has used modern inputs. The multivariate probit model is an extension of the bivariate probit model with a structure similar to the seemingly unrelated regression. This model captures the underlying simultaneity and interdependence in the decisions to use mineral fertilizer and other modern inputs. We model this inter-dependence by taking into account the correlation between the residuals of the different input demand equations. The identification in the models relies on the assumption that the error terms ϵ_{kht} follow a join multivariate normal distribution and the existence of sufficient variation in the data (Wilde, 2000). The identification also requires that each equation include an exogenous shifter that does not directly affect the dependent variable in the other equations (we discuss this in detail below). The estimation is based on simulated maximum likelihood using the Geweke-Hajivassiliou-Keane simulator to evaluate the 4-dimensional normal integrals in the likelihood function (Greene, 2008).

Endogeneity of fertilizer subsidies and instrumental variable approach. While the multivariate probit regression addresses issues related to the simultaneity of input demands, it still relies largely on the assumption of selection on observable to identify the causal impact of fertilizer subsidies on the outcome of interest. Two main problems remain and introduce serious bias in the estimations: the presence of unobserved household heterogeneity u_{kh} and the potential endogeneity of the receipt of fertilizer subsidies due to time varying unobservable. Given the non-linear nature of the models , we use the correlated random effects (CRE) approach to control for the unobserved heterogeneity (Mundlak, 1978; Chamberlain, 1984). The CRE method provides a consistent estimation of panel models when traditional fixed effects are not feasible particularly when the number of time periods are small. The CRE methods allows the unobserved household heterogeneity to be determined by time averages of covariates.

The receipt of fertilizer subsidies can be endogenous for a number of reasons. The main source of endogeneity is the non-randomness of the distribution of the fertilizer subsidy to farmers. In fact, the program is, by design, universal, but only certain farmers can obtain the subsidized fertilizer given the limited amount provided by the government. Thus, government and local leaders allocate subsidized fertilizer to households based on household characteristics, many of which are unobservable to us. It is also likely that unobserved factors explaining input demand also affect farmers' likelihood of receiving subsidized fertilizer. For instance, the need to ease financial constraints and purchase other inputs may push some farmers to proactively seek ways to obtain subsidized fertilizer. These unobserved factors, if not accounted for, introduce bias in the estimation.

As a second defense against endogeneity, we instrument the receipt of subsidized fertilizer. Finding a valid instrument is essential but challenging. In the related literature, researchers have used a variety of instruments, usually drawing from the institutional setting of the subsidy program. Ricker-Gilbert (2013) provides a review of these instruments. Chibwana et al. (2011), Ricker-Gilbert et al. (2011) uses the number of years of residence in the village as an instrument for fertilizer subsidy in their evaluation of the fertilizer subsidy program in Malawi. Other studies use village-level variables such as the total amount of subsidized fertilizer allocated to a village (Mason and Ricker-Gilbert 2013), the political connection of the village to the ruling president or party (Mather and Jayne 2013; Mason et al., 2017).

We follow this literature and derive our instrumental variable from the institutional setting of the Burkina Faso's fertilizer program. The fertilizer subsidy program in Burkina Faso uses a top-down approach to allocate and dispatch subsidized fertilizer to farmers. Once the government determines the total quantity of subsidies fertilizer, the program then allocates a certain amount to each region, and then to each commune and each village based on estimated needs. At the village level, local authorities are responsible for the selection and the distribution to eligible farmers. Given this institutional setting, household's status in the village is a strong predictor of the likelihood of receiving the subsidy. A good proxy for a household's status in the village is the household head's membership and status in an agricultural association. Given the institutional setting of the Burkina Faso fertilizer subsidy program, households with some form of formal or informal connections with local authorities are more likely to acquire the subsidized fertilizer. Being involved in local organizations, especially in a managing position, places a household in a better position to develop strong connections with local authorities. After controlling for various time varying and time-constant variables related to household demographics, production technologies, and practices, it is unlikely that household status in local associations would be correlated with unobserved time-varying factors in the error terms of the system of input demand equations. For robustness check, we also use the total amount of subsidized fertilizer supplied at village-level as an instrument.

Given the non-linearity of the multivariate probit model, we use the control function (CF) approach proposed by Smith and Blundell (1986) to incorporate the IV into the model. The control function approach consists of estimating a first stage reduced-form regression using a probit model for the binary variable indicating the receipt of the subsidized fertilizer. For the specification in which the endogenous treatment variable is the amount of subsidized fertilizer, the first stage consists of a Tobit. In the second stage of the CF approach, residuals from the first stage are included as an explanatory variable in the system of input demand functions. When the first stage regression is non-linear, we use generalized residuals computed as the derivative of the log-density function with respect to the constant at the maximum (Gourieroux, Monfort, Renault, and Trognon, 1987; Chesher and Irish, 1987; Greene, 2008).

For the case of a binary treatment variable RS_{Fht} indicating the receipt of fertilizer subsidy, we first estimate the following equation using probit regression.

$$R_{Fht} = \begin{cases} 1 & \text{if } R^*_{Fht} > 0, \\ 0 & \text{Otherwise} \end{cases} \tag{3.6}$$

with $\mathrm{R}^*_{Fht} > 0 = \delta I_{ht} + X_{kht}\beta + \nu_{ht}$

Where RS_{Fht} is a latent variable that determines the participation in the fertilizer subsidy program, I_{ht} is the instrumental variable, X_{kht} is a vector of household characteristics, and ν_{ht} is the error term.

Next, we obtain the generalized residual $g\hat{r}\nu_{ht}$ for probit as follows:

$$g\hat{r}\nu_{ht} = \frac{\phi(w\hat{\theta})[-\Phi(w\hat{\theta})}{\Phi(w\hat{\theta}[1 - \Phi(w\hat{\theta})]} \tag{3.7}$$

With $w\hat{\theta} = \delta I_{ht} + X_{kht}\beta$ and ϕ and Φ are respectively the *pdf* and *cdf* of the standard normal distribution.

When the measure of fertilizer subsidies used is the total amount of subsidized fertilizer received AS_{Fht}, the first stage of the CF approach consists in estimating a Tobit regression and the generalized first stage residual takes the following form:

$$g\hat{r}\nu_{ht} = RS_{Fht}(AS_{Fht} - w\hat{\theta}) + (1 - RS_{Fht})\hat{\sigma}\frac{\phi(w\hat{\theta}}{1 - \Phi(w\hat{\theta})} \tag{3.8}$$

Finally, the second step of the CF approach consists in estimating the different models with the generalized first stage residual $g\hat{r}\nu_{ht}$ as additional explanatory variable. The test of the significance of the coefficient of this generalized residual in the second stage regression provides a direct test for endogeneity.

3.5 Data and descriptive statistics

3.5.1 Data source and variables description

The data used in the empirical analysis are from the Continuous Agricultural Survey (Enquête Permanente Agricole - EPA) conducted by the Ministry of Agriculture and Food Security of Burkina Faso. The EPA is a household level panel survey conducted every year since 1994-95 with the objective to estimate crop areas and yields and provide early warning for food shortage and food insecurity in the country. The panel of households has significantly evolved over the year and in 2007/08 an entirely new panel was selected. For this reason, and in order to focus the analysis on the years during which the fertilizer subsidy program was being implemented, we only use the last three waves of data available corresponding to the years 2009/10, 2010/11, and 2011/12.

The initial sample size of the EPA survey consists of 4,130 households per year but has fluctuated over time due to households entering or leaving the panel. Given the strategic focus of the fertilizer program on food crops such as maize and rice, we limit our analysis to maize producers, who represent between 72% and 76% of all farmers, and are located in all regions. For comparison, rice which is the second crop targeted by the program is produced by less than 20% of farmers (predominantly those located in the southern regions of the country). However, in all models, we control for whether the farmer produces rice in addition to maize since the joint production of maize and rice increases the likelihood of receiving fertilizer subsidies.

The survey collects detailed information on household socio-demographic and economic characteristics, plot characteristics, input acquisition and use (including the receipt of subsidized fertilizer), farm and nonfarm labor, crop production and commercialization, etc. As discussed in the methodology, we consider various measures of input use, namely binary variables indicating whether a given input has been used, a continuous variable indicating the total amount of land in which a given input has been used, and the intensity of use of the input in kilograms per hectare of land.

Our key explanatory variable is a self-reported binary variable of whether a farmer participate in the fertilizer subsidy program or not. We also extend the analysis using the amount of subsidized fertilizer received. The other explanatory variables are carefully identified and selected based on previous studies and economic theory to address selection bias to heterogeneity in observables. We include households socio-demographic characteristics such as the age of household head, the age and gender composition of households, and proxy variables for household wealth like total farm size and non-farm income. We also control for rainfall and input prices measured by as the average village-level price of commercialized input.

In general, the empirical estimation of a system of equations requires the inclusion of equation-specific exogenous shifters. For this reason, we also include in each equation variables that are not included in other equations. Thus, for the equation with mineral fertilizer as the dependent variable, we include a binary variable indicating whether the household grows cotton such households have easy access to fertilizer credit. In the equation with the use of hybrid seeds as a dependent variable, the excluded exogenous shifter is a binary variable indicating whether the farmer has any contact with extension services or NGOs since these organizations are the main promoters of modern varieties. The exogenous shifter in the use of manure equation is a variable indicating the number of tropical livestock units possessed by the households. Finally, noting that weed, disease and pest controls in the absence of crop protection chemicals are labor intensive, we include in the crop protection equation the quantity of available family labor proxied by the total number of members between 12 and 65 years old. The final set of control variables consists of year dummies to control for time-varying, household constant unobserved factors and region fixed effect.

3.5.2 Descriptive analysis

We start the analysis by presenting and discussing some basic descriptive statistics on the adoption rate of fertilizer, improved seeds, crop protection chemicals, and manure by maize farmers. Table 3.1 presents the summary statistics on input use disaggregated by the receipt of fertilizer subsidy. Overall modern input use on maize farms in Burkina Faso remain extremely low. Over the period 2010-2012, just 10% of maize farmers have cultivated improved (hybrid) varieties. About one of three farmers use liquid or solid herbicide, insecticide, rodenticide, disease, or weed control. Fertilizer and manure are more frequently used, but the adoption rates remain much lower than the levels observed for farmers outside sub-Saharan Africa. Approximately 50% of maize farmers use mineral fertilizer, and the same proportion uses manure to enrich the nutrient contents of their soil. We also find that joint input use is limited suggesting that farmers often make trade-offs among the various types of modern inputs to adopt.

Table 3.1 compares the proportion of maize farmers using a particular input and that input in conjunction with mineral fertilizer among the group of farmers benefiting from the fertilizer subsidies and those who do not. The results of the comparison tests show that the proportions of farmers using hybrid seeds, mineral fertilizer, and crop protection chemicals are significantly higher among the farmers in the fertilizer subsidy program. However, we observe a reversed for manure. This finding is evidence of the complementary between fertilizer and hybrid seeds and crop protection chemicals on the one hand, and the substitutability between fertilizer and manure on the other hand. However, these descriptive results do not account for confounding factors and the unobserved heterogeneity among farmers. Thus, we use various econometric methods to investigate more rigorously the spillover effects of fertilizer subsidies on the use of modern inputs.

Table 3.2 presents standard summary statistics over the period 2010-2012 for the main variables used in the econometric analysis. The means for the binary variables indicating the use of modern inputs and the receipt of fertilizer subsidy are consistent with the descriptive results above. The total quantity of subsided fertilizer supplied to a village in the sample varies between 0 kg for villages with no households participating in the fertilizer program to 500 kg with an average of 7.9 kg. We also present summary statistics on input price, household socio-demographic and economic variables, and livestock holdings. The size of the standard deviations, the panel nature of the data, and the high sample size are evidence that we have enough variation in the data.

3.6 Empirical findings

3.6.1 Multivariate probit regression of fertilizer subsidy on inputs use

We start the econometric analysis with the assessment of the receipt of fertilizer subsidies on the probability to use various types of modern agricultural inputs on maize farms. Despite the concerns over the potential endogeneity of fertilizer subsidies discussed at length in the method section, it is always useful to present the benchmark results which rely on the selection on observable assumption. We estimate multivariate probit regressions accounting for the simultaneity of input demands. The model is estimated using simulated maximum likelihood and the GHK simulator to evaluate the M-dimensional Normal integrals in the likelihood function (Cappellari and Jenkins, 2003; Greene, 2008). The results of the estimation are presented in Table 3.3 below.

Panel A of Table 3.3 presents the estimated coefficients and panel B presents the estimation of the correlations between the error terms of the input demand equations. These statistically significant correlations are important to justify the use of the multivariate probit model to account for the simultaneity in farmers' input use decisions. As we argue in the conceptual model and the methods sections, we find that nearly all the bivariate correlations are statistically different from zero. The likelihood test strongly suggests that the full multivariate probit model better fits the data than the univariate probit models. These results suggest that input demands are inter-linked and ignoring this interdependency would biase the estimations.

Overall, the multivariate probit regression of fertilizer subsidy on input use suggests that the access to fertilizer subsidies increases the likelihood of farmers to use fertilizer on maize farms. Most importantly, we also find that the receipt of fertilizer subsidies increases the likelihood to adopt hybrid maize seeds - including farmer home-produced hybrid varieties- and use crop protection chemicals such as insecticide, herbicide, fungicide, and rodenticide. However, we find that the likelihood to use manure decreases with the receipt of subsidized fertilizer , bu, the coefficient estimate is not statistically significant at conventional levels.

As we argue in the method section, the results from the multivariate probit regressions are subject to potential bias due to the endogeneity of the receipt of fertilizer subsidies and the observational nature of the data. For this reason, we will not over stress and interpret the findings or the magnitude of the effects. In the following sections, we present the results of our instrumental variable approach that attempts to address the endogeneity problem and substantially reduce the bias in the estimation.

3.6.2 Addressing the endogeneity of fertilizer subsidy

We address the issue endogeneity of the fertilizer subsidy program by using an instrumental variable approach. Given the non-linearity of the multivariate probit regression, we use the control function approach combined with the correlated random effects device to account for unobserved heterogeneity. Our instrument is a binary variable indicating whether anyone in the household is a member of a farmer group or an association involved in agriculture and holds a management position. Membership in an association is not time constant and exhibits spatial variation across region and village. The descriptive analysis shows that between 27% and 32% of households have at least one member participating in the activities of a farmer group or an association of producers. Also, between 11% and 12% of households have one or more of their members in the management team of a farmer group.

The control function is a two-step procedure wherein the first stage we estimate the probability of receiving the fertilizer subsidy conditional to household membership in an agricultural association and observed socio-demographic and economic characteristics. The results of the first stage are presented in Table 3.4. The overall quality of the model is good with a pseudo r-squared of 0.09 with about 93% of household correctly classified in the fertilizer receipt status. The result shows that households whose members hold a management position in a farmer group are more likely to benefit from the subsidy program. The Figure 3.1 shows graphically the density function of the probability of receiving subsidized fertilizer. The graph for households with at least member holding a management position in a farmer group is clearly more located at the right and right-skewed compared to the other group. Other determinants of the participation in the fertilizer subsidy program include being a male-headed household, having a large farm, earning off-farm income, and being a rice producer.

In the second stage of the control function approach, we add the generalized residuals from the first stage probit regression as an additional control variable and estimate a multivariate probit regression of input use. The results are presented in Table 3.5. For all demand equations except the equation for hybrid seeds, the coefficient of the generalized probit residuals is statistically different from zero providing an evidence of the endogeneity of the receipt of fertilizer subsidy. As before, most of the elements of the correlation matrix are significant confirming the simultaneity of input use decisions. The effect of fertilizer subsidies on input use, after addressing the issue of endogeneity, is qualitatively similar to the previous finding. We still find that the access to fertilizer subsidies increases the likelihood to use mineral fertilizer, crowds in the use of hybrid seeds and crop protection chemicals, but significantly crowds out the use of manure.

Our finding that fertilizer subsidies increase the probability of using fertilizer on maize farms is in line with the literature on a fertilizer subsidy that consistently finds a positive effect of fertilizer subsidy on fertilizer use (Carter et al., 2014; Jayne and

Rashid, 2013; Duflo et al., 2011). This result also provides evidence that subsidized fertilizer for food crop is not entirely diverted to other cash crops or sold on the black market for cash. Most importantly, we find that the receipt of fertilizer subsidies increases the likelihood to adopt hybrid maize seeds - including farmer home produced hybrid varieties- and use crop protection chemicals (mainly insecticide, but also fungicide and rodenticide). Our results confirm the finding by Liverpool-Tasie and Salau (2013) that targeted fertilizer subsidies promotes the adoption of improved seeds in Kano state in Nigeria. We provide the additional evidence that the fertilizer subsidy also promotes the adoption of crop protection chemicals in Burkina Faso. Our results support the hypothesis that access to cheaper fertilizer relaxes the household's cash constraints and allows them to invest more money in purchasing hybrid seeds and crop protection chemicals.

3.6.3 Robustness checks

We perform two main robustness checks to confirm our findings. First, following Mason and Ricker-Gilbert (2013), we use the aggregated subsidized fertilizer at village level as an alternative instrumental variable. Next, we consider the total amount of subsidized fertilizer received as an alternative treatment variable. In this case, given the continuous nature of the nature of this variable, we use a Tobit regression in the first stage of the control function estimation. The combination of the these checks yields four regressions presented in Table 3.5. In all regressions, we find strong support for the simultaneity of input demand and the endogeneity of fertilizer subsidy. All the estimations qualitatively confirm the findings that fertilizer subsidies crowd in the adoption of hybrid seeds and crop protection chemical but crowd out the use of manure.

3.7 Conclusion

Modern input use in Africa is less prevalent than in any other parts of the world, and there is a consensus that these low adoption rates largely explain low crop yields. African governments often intervene in the markets using subsidy programs to facilitate the physical and economic access to inputs by small farmers. The Government of Burkina Faso, with the objective to increase food production and reduce food insecurity, responded to the 2006 Abuja Declaration on fertilizer, initiated a subsidy program in 2008 to provide mineral fertilizers to farmers at fertilizer at a 15%-30% discounted price. This study provides an empirical evaluation of the program focusing on how it affects input demand by maize farmers. It assesses the spillover effects of subsidizing only one agricultural input on the use of other inputs to test the hypothesis that farmers may be using mineral fertilizer as a substitute for -rather than a complement to- other technologies.

Our empirical analysis uses a panel data from the continuous agricultural survey for the years 2009/10, 2010/11, and 2011/12. We address issues of simultaneity in inputs use decisions, unobserved household heterogeneity, and endogeneity of the receipt and amount of subsidized mineral fertilizer using multivariate probit and control function - instrumental variable with correlated random effects. Following the practices in the literature, we derive our instrument exploiting the institutional setting of the program which relies on local government's structures for the dispatching of the subsidized fertilizer. We use a variable indicating whether a household member holds a management position in an agricultural association. In alternative specifications, we also use total subsidized fertilizer received at village level as an instrument.

The results confirm that modern input use in Burkina Faso is limited and the fertilizer subsidy programs substantially increases the proportion of farmer applying mineral fertilizer on their maize farms. The regression results also confirm the endogeneity of fertilizer receipt due to non-randomization of the distribution and the heavy implication of government-decentralized structures. The results also confirm the simultaneity in input use decisions. We find that fertilizer subsidies crowds in the use of hybrid seeds and crop protection chemical, but crowd out the use of manure. We can then infer that hybrids seeds and protection chemicals are perceived as complements to fertilizer while manure is perceived as a substitute. The results are robust to various alternative specifications of the treatment variable and instrumental variable. Our results are consistent with a number of previous studies and expand the literature with new evidence specific to the Burkina Faso context. Our finding suggests that subsidizing mineral fertilizer should be accompanied by measures to promote manure to achieve a sustainable input intensification which minimizes the adverse effect on the environment of mineral fertilizer.

3.8 Tables and figures for chapter 3

Table 3.1: Proportion of farmers using various types of inputs and jointly with mineral fertilizer by participation status in the fertilizer subsidy program over the period 2009-2012

	All farmers (1)	Farmers with fertilizer subsidy (2)	Farmers without fertilizer subsidy (3)	Difference (4)=(2)-(3)
Fertilizer	0.47	0.84	0.45	0.40***
	(0.50)	(0.36)	(0.5)	[17.8]
Hybrid seeds	0.10	0.17	0.10	0.07***
	(0.30)	(0.38)	(0.30)	[5.37]
Manure	0.51	0.43	0.51	-0.08***
	(0.50)	(0.50)	(0.5)	[-3.63]
Protection chemicals	0.34	0.57	0.33	0.24***
	(0.47)	(0.5)	(0.47)	[11.41]
Fertilizer & hybrid seeds	0.08	0.16	0.07	0.09***
	(0.27)	(0.37)	(0.26)	[7.65]
Fertilizer & Manure	0.20	0.36	0.19	0.17***
	(0.40)	(0.48)	(0.39)	[9.16]
Fertilizer & protection chemicals	0.27	0.54	0.26	0.28***
	(0.45)	(0.50)	(0.44)	[14.17]

Notes: Numbers in parenthesis () are standard deviation; the numbers in bracket [] are t-statistics of the proportion comparison test. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.2: Summary statistics

	Min	Max	Mean	Std Dev
Outcome variables				
Use fertilizer (0/1)	0	1	0.47	0.50
Use hybrid seeds (0/1)	0	1	0.10	0.30
Use manure (0/1)	0	1	0.51	0.50
Use crop protection chemicals (0/1)	0	1	0.34	0.47
Treatment variables				
Receive fertilizer subsidy (0/1)	0	1	0.07	0.25
Quantity of subsidized fertilizer (Kg)	0	500	7.9	48.5
Instrumental variables				
Member of an association a management level (0/1)	0	1	0.11	0.32
Quantity of subsidized fertilizer at village level (Kg)	0	3,113	65.0	254.8
Control variables				
Price of fertilizer (Log FCFA/Kg)	3	8	6.1	0.6
Price of seeds (Log FCFA/Kg)	3	8	5.6	1.2
Price of protection chemicals (Log FCFA/Kg)	2	8	7.5	0.8
Female headed household (0/1)	0	1	0.03	0.2
Age of the head of household (Years)	0	99	49.8	14.5
Total farm size (Log Ha)	-3	4	1.1	0.9
Off-farm income (Log FCFA)	0	17	6.5	5.4
Cotton producer (0/1)	0	1	0.2	0.4
Has a contact with extension service/NGO (0/1)	0	1	0.2	0.4
Number of tropical livestock units (count)	0	987	56.6	62.5
Number of adult male in the household (count)	0	25	2.5	1.7
Number of adult female in the household (count)	0	26	3.0	2.1

Table 3.3: Multivariate probit regression of fertilizer subsidy on inputs use

	Mineral Fertilizer	Hybrid Seeds	Manure	Protection Chemicals
Panel A : Coefficient				
Receive fertilizer subsidy	0.547***	0.234***	-0.022	0.110*
	(0.07)	(0.07)	(0.06)	(0.07)
Marginal Effect	[0.155]	[0.036]	[-0.007]	[0.026]
Female headed household	-0.103	-1.013**	-0.232	-0.246
	(0.30)	(0.43)	(0.26)	(0.34)
Household head education	0.048	0.011	-0.018	0.096
	(0.09)	(0.11)	(0.08)	(0.09)
Age of the head of household	-0.002	-0.001	-0.002	0.001
	(0.00)	(0.00)	(0.00)	(0.00)
Household size	0.013	0.000	0.006	0.009
	(0.01)	(0.01)	(0.01)	(0.02)
Log total farm size	0.076	0.079	0.046	0.024
	(0.05)	(0.07)	(0.05)	(0.06)
Log of off-farm income	0.002	-0.010	0.005	0.009
	(0.01)	(0.01)	(0.01)	(0.01)
Access to credit	0.150	-0.013	0.048	0.084
	(0.10)	(0.10)	(0.08)	(0.09)
Log of price of fertilizer	-0.037	-0.031	0.165***	-0.015
	(0.04)	(0.05)	(0.04)	(0.04)
Log of price of seeds	0.010	-0.006	0.012	0.058***
	(0.02)	(0.02)	(0.02)	(0.02)
Log of price of protection chemicals	-0.010	0.005	0.013	0.012
	(0.03)	(0.04)	(0.03)	(0.03)
Cotton producer	0.337***			
	(0.10)			
Contact with extension service/NGO		-0.032		
		(0.08)		
Number of tropical livestock units			0.001	
			(0.00)	
Number of adult male				0.006
				(0.03)
Number of adult female				-0.047
				(0.03)
Observations	9,409	9,409	9,409	9,409
Panel B: Correlation matrix				
Mineral Fertilizer		0.283***	-0.037*	0.468***
		(0.03)	(0.02)	(0.02)
Hybrid seeds			0.080***	0.180***
			(0.02)	(0.02)
Manure				0.009
				(0.02)

Figure 3.1: Density of the probability of receiving fertilizer subsidies

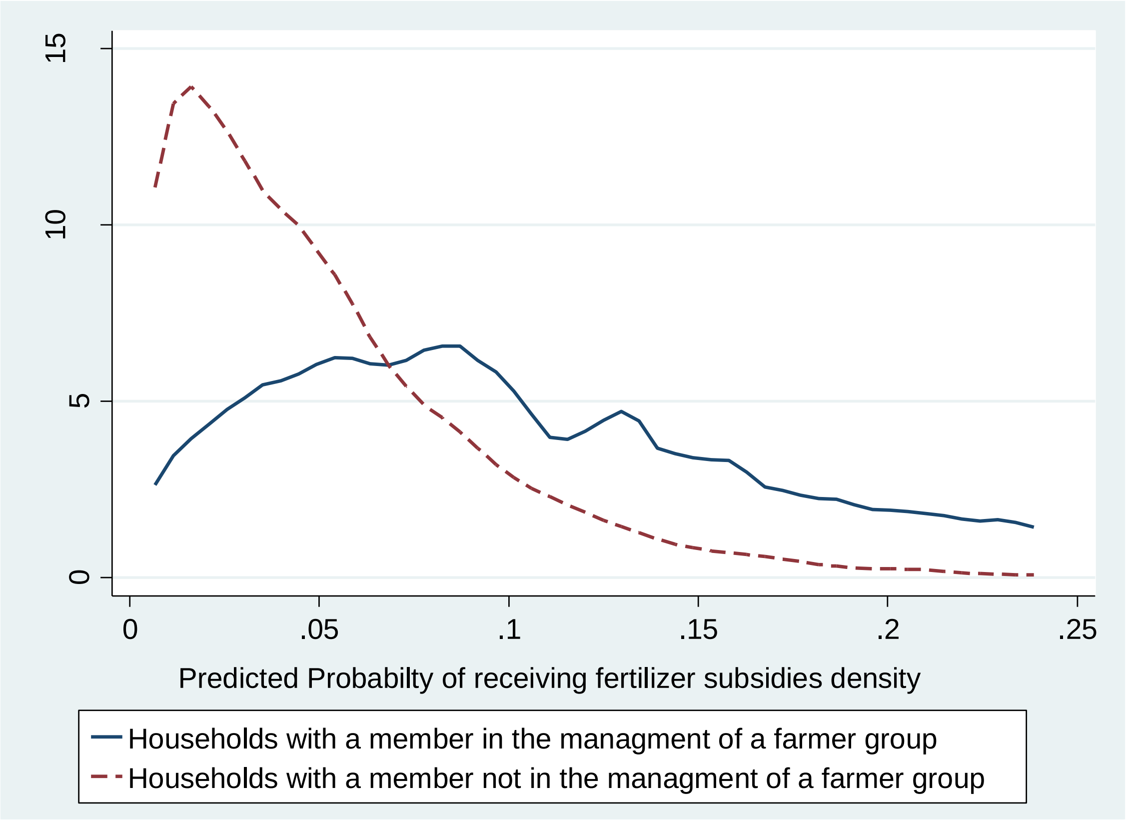


Table 3.4: First stage probit regression of receipt of fertilizer subsidy

	Has received fertilizer subsidy
Member of an association a management level	0.264***
	(0.06)
Female-headed household	-0.264
	(0.17)
Age of the head of household	-0.006***
	(0.00)
Log total farm size	0.259***
	(0.03)
Log of off-farm income	0.012***
	(0.00)
Rice producer	0.229***
	(0.05)
Constant	-1.408***
	(0.11)
Observations	9,405

Notes: All regressions include region and time fixed effects and account for unobserved heterogeneity using correlated random effects. *** p<0.01, ** p<0.05, * p<0.1.

Table 3.5: Instrumental Variable - Control function multivariate probit regression of fertilizer subsidy on inputs

	Mineral Fertilizer	Hybrid Seeds	Manure	Protection Chemicals
Panel A: Coefficient				
Receive fertilizer subsidy	**1.431*** **	**0.968** **	**-0.862** **	**1.307*** **
	(0.47)	**(0.49)**	**(0.41)**	**(0.44)**
Marginal Effect	**[0.408]**	**[0.149]**	**[-0.293]**	**[0.328]**
First stage Generalized probit residuals	**-0.427***	**-0.365**	**0.416** **	**-0.592*** **
	(0.22)	(0.24)	(0.20)	(0.22)
Female headed household	-0.095	-1.012**	-0.244	-0.236
	(0.30)	(0.43)	(0.27)	(0.34)
Household head education	0.044	0.006	-0.012	0.089
	(0.09)	(0.11)	(0.08)	(0.09)
Age of the head of household	-0.002	-0.001	-0.003	0.002
	(0.00)	(0.00)	(0.00)	(0.00)
Household size	0.013	-0.000	0.005	0.010
	(0.01)	(0.01)	(0.01)	(0.02)
Log total farm size	0.058	0.058	0.072	-0.018
	(0.06)	(0.07)	(0.05)	(0.06)
Log of off-farm income	0.000	-0.011	0.006	0.008
	(0.01)	(0.01)	(0.01)	(0.01)
Access to credit	0.142	-0.018	0.056	0.071
	(0.10)	(0.10)	(0.08)	(0.09)
Log of price of fertilizer	-0.038	-0.032	0.167***	-0.019
	(0.04)	(0.05)	(0.04)	(0.04)
Log of price of seeds	0.012	-0.005	0.010	0.062***
	(0.02)	(0.02)	(0.02)	(0.02)
Log of price of protection chemicals	-0.010	0.004	0.014	0.009
	(0.03)	(0.04)	(0.03)	(0.03)
Cotton producer	0.335***			
	(0.10)			
Contact with extension service/NGO		-0.033		
		(0.08)		
Number of tropical livestock units			0.001	
			(0.00)	
Number of adult male				0.004
				(0.03)
Number of adult females				-0.047
				(0.03)
Observations	9,409	9,409	9,409	9,409
Panel B: Correlation matrix				
Mineral Fertilizer		0.347***	-0.011	0.531***
		(0.03)	(0.02)	(0.02)
Hybrid seeds			0.115***	0.172***
			(0.03)	(0.03)
Manure				0.037*
				(0.02)

Table 3.6: Robustness check of the effect of fertilizer subsidies on inputs use (partial reporting)

	Mineral Fertilizer	Hybrid Seeds	Manure	Protection Chemicals
Treatment: Receipt of subsidized fertilizer [a]				
Control function multivariate probit	2.280***	1.710***	-1.036**	2.534***
IV – member of farmer group	(0.50)	(0.50)	(0.41)	(0.45)
Control function multivariate probit	0.753***	0.213*	-0.350***	0.480***
IV – village-level subsidized fertilizer	(0.14)	(0.13)	(0.11)	(0.11)
Treatment: Amount of subsidized fertilizer [b]				
Control function multivariate probit	0.703**	0.584**	0.047	0.191
IV – member of farmer group	(0.28)	(0.24)	(0.21)	(0.21)
Control function multivariate probit	0.780***	0.390**	-0.156	0.773***
IV – village-level subsidized fertilizer	(0.24)	(0.18)	(0.17)	(0.19)

Notes:All regressions include the same control variable as in the benchmark analysis. They also include region and time fixed effects and account for unobserved heterogeneity using correlated random effects. *** p<0.01, ** p<0.05, * p<0.1. a The first stage regressions use probit. b The first stage regressions use tobit. We report only the coefficients of fertilizer subsidy.

Chapter 4 Rural transformation in Africa: The role of land rental markets in agricultural input intensification and production E=efficiency in Burkina Faso

Rural land rental markets are fast developing and increasingly used as a medium to transfer land among households in Sub-Saharan Africa. This paper uses a nationally representative household panel to identify the determinants of farmer's participation in these markets in Burkina Faso and assesses its impact on farm investment and production efficiency. Using a double hurdle model, we find that household's farming ability and commitment to agriculture is positively correlated with the likelihood to rent in land and the amount of land rented. This result corroborates previous findings, in both Africa and outside, that land rental markets transfer land resources from less talented and committed farmers to the more able or wealthier ones. We extend the analysis using a multivariable probit regression and the correlated random effects approach to account for unobserved household heterogeneity and potential endogeneity. We find that input use decisions are made jointly, and farmer's participation in land rental markets has a positive effect on the likelihood to use crop protection chemicals. The effect on the use of mineral fertilizer and manure are positive but marginal, and there is no significant effect on the use hybrid seeds or hired labor. Using stochastic production frontier analysis, we find that land renters are better farm managers and experience fewer inefficiencies in their production processes. Our findings highlight the mixed effects of policies that foster the development of land rental markets in Burkina Faso on input intensification. Much of the gains from these policies are in terms of efficiency and not widespread adoption of modern agricultural inputs.?

4.1 Introduction

The historical experiences of developed countries and emerging economies in Asia and Latin America during the green revolution exemplify the importance of improving agricultural productivity to promote agricultural growth and structural transformation (Johnston, 1970; Duarte and Restuccia, 2010). Unlocking the potential of agriculture to generate economic growth and reduce poverty requires substantial improvement in productivity which, by international standards, remains extremely low in Africa South of the Sahara (Dethier and Effenberger, 2012; Gollin et al., 2002). Policies aimed at improving crop productivity have largely focused on input intensification. However, smallholder farmers who dominate African agriculture also face important barriers to access farmland (Barrett et al., 2001; Muyanga and Jayne, 2014). Land constraints not only prevent farmers from expanding farm operations, but also have important adverse effects on their incentives to invest in modern inputs and on productivity (Headey et al., 2014; Deininger et al., 2003). Recognizing the importance of land as a key factor of production, African governments have engaged in a number of reforms over the past two decades to improve agricultural productivity (Peters, 2009; Place, 2009).

The recent surge in land policy reforms across Africa is a welcome development (Toulmin and Quan, 2000). The implemented policies generally seek to address two main issues. The first issue concerns the strengthening of land rights and tenure security which have been historically weak in most developing countries (Place, 2009; Colin and Ayouz, 2006). In recent years, several countries in Africa initiated land reforms with the aim to formalize property rights and improve tenure security (Deininger and Feder, 2009; Benjaminsen et al., 2009). The rationale behind these increased interests in land reforms is that improving and securing households' access to land will provide them with sufficient incentives to increase farm investment and stimulate productivity (Feder and Feeny, 1991; Abdulai et al., 2011; Besley, 1995; Place, 2009). This hypothesis has been widely explored theoretically and tested empirically (Feder and Feeny, 1991; Fenske, 2011). While there are conflicting findings (Brasselle et al., 2002), the body of evidence tends to support the argument that secure access to land enhances farm investment and productivity (Deininger and Feder, 2009; Abdulai et al., 2011).

The second issue of land policy reforms relates to creation and strengthening land markets that were nearly nonexistent until the 1990s (Colin and Ayouz, 2006; Holden et al., 2010). Land, as a natural resource, typically has a skewed distribution with some households having large endowments of land and others are landless (Deininger et al., 2008). In African countries, farm size is typically small raising the concern of lack of scale effect in agricultural production although it is generally shown that small farms are more productive (Ali and Deininger, 2015). Many farmers desire to expand their farm but face significant constraints in accessing agricultural land. These constraints are heightened with increasing population density, urbanization, and climate change (Holden et al., 2010; Muyanga and Jayne, 2014). Even though Africa is generally perceived as a land abundant continents, the cost of converting unexploited land to agriculture is generally prohibitive for most smallholder farmers who do not use machinery for land preparation.

Over the years, landless and land-constrained farmers have relied on a variety of approaches to gain access to land. These include: gifts from land-abundant households or the community, inheritance, purchase, sharecropping, and rental. In Burkina Faso, land rental markets, including informal markets, have emerged as important modes of land transfer among households. Over the past 20 years, due to the gradual liberalization policies of land markets implemented, the government of Burkina Faso is increasingly addressing land tenure security to improve land transferability (Platteau, 2000; Brasselle et al., 2002; Koussoubé, 2015). Although still largely informal, circulations of land rights through leasing in Burkina Faso is increasing rapidly. However, the implications of this rapid development of land rental markets remain largely unassessed and ununderstood. In this study, we aim to fill this gap by quantifying the extent of smallholder farmers' participation in land rental markets in Burkina Faso and the resulting impact on agricultural input intensification, farm productivity, and production efficiency.

An analysis of the functioning of land rental markets and their implications for agricultural development is essential to shed light on how the structural transformation of agriculture might play out in developing countries. Historically, structural transformation of economies entails the gradual decrease of agriculture in term of employment and output (Timmer, 1988; Duarte and Restuccia, 2010). That implies that some households will be pushed or pulled out from the farming sector (Alvarez-Cuadrado and Poschke, 2011). If land reforms in countries like Burkina Faso are successful in sustaining a fully functioning land markets, their impact on productivity will depend on the productivity and efficiency differentials between renters and leasers (Jin and Jayne, 2013; Vranken and Swinnen, 2006). If land rental markets efficiently transfer land to the most productive and efficient households, and if those farmers invest more in modern inputs, then crop productivity and production will increase. The findings of this study will be useful to understand the potential gain from land reforms that seek to secure land rights and promote the development of land markets and land transactions.

Our study contributes to a sparse literature on the impact of land markets on agricultural development in Africa. The recent dynamization of land markets has sparked a new wave of empirical studies on the effects of land rental and land sales of agricultural development (Deininger and Jin, 2008). Earlier studies focus mainly on Asian and transition countries where land sales and land rental markets are well developed (Kung, 2002; Deininger and Jin, 2005; Vranken and Swinnen, 2006). In recent years, several studies on Africa have emerged. However, most of these studies focus on southern and eastern African countries (Holden et al., 2010). Examples of such studies were done in Kenya (Jin and Jayne, 2013), Ethiopia (Benin et al., 2005; Deininger et al., 2008), Malawi and Zambia (Chamberlin and Ricker-Gilbert, 2016). Very few studies exist on land rental markets in West Africa. Exceptions are Colin and Ayouz (2006) and Chauveau and Colin (2010) for Côte d'Ivoire, and more recently Koussoubé (2015) that uses cross-sectional data for only one region - the Hauts-Bassins region of Burkina Faso. Our study extends the analysis by Koussoubé (2015) using national representative panel data covering the years 2009 to 2012.

Our study also extends the current literature in two other aspects. Most of the previous studies, with few exceptions, focus on the analysis of the determinants of household participation in land rental markets (Deininger et al., 2003). First, while we also examine this question, we extend our analysis to investigate the impact of land rental markets on agricultural input intensification, productivity, and production efficiency. Our data enable us to present evidence of the difference in input intensification between rented and non-rented plots, and between households participating in land rental and those who are not. This analysis also allows us to test the hypothesis that participation in land rental markets has any spillover effects on input intensification beyond rented plots.

Our paper also differentiates itself from previous studies with its approach to assessing the efficiency-enhancing effect of land rental markets. Most theoretical models of land rental markets identify household ability in agriculture as a key driver of the decision to rent in or rent out land. Empirical analyses typically use a proxy for ability in a regression of land rental demand to indirectly test the efficiency-enhancing effect of land rental markets (Deininger, Jin, and Nagarajan, 2008; Deininger and Jin, 2005). We explore a more direct alternative using a stochastic production frontier analysis that differentiates a model for production and a model for inefficiency in the production system to test the hypothesis that households participating in land rental markets are efficient farm managers.

Our empirical analysis uses a panel data covering the years 2010, 2011, and 2012 in Burkina Faso. We focus on cereals, maize, rice, millet, and sorghum, producers. This choice is motivated by the need to have a homogeneous group of farmers and to keep the analysis concise. Since nearly all households in our sample cultivate at least one of these cereals, the findings are readily generalizable to the broader group of agricultural producers. We begin the analysis by analyzing the determinants of farmers' participation in land rental markets. Next, we investigate the implication of such land rental decisions for farm investment in terms of the use of modern inputs by comparing input utilization and input intensity for households participating in land rental markets with those not involved in these markets. We use descriptive analysis and mean comparison tests and further control for potential endogeneity of participation in land rental markets using regression and instrumental variable methods. Finally, we assess the efficiency-enhancing effect of land rental markets using stochastic production frontier analysis.

Overall, we find evidence that land rental is increasingly prevalent in Burkina Faso and driven by various socio-demographic, economic, and institutional factors. Households with higher farming abilities are more likely to expand farm operations through land rental. We find weak evidence that households renting in land invest more in modern inputs, particularly those cash-intensive such as mineral fertilizer and crop protection chemicals. However, there is no evidence that they are more likely to use hybrid seeds, manure, or hired labor. The result from the stochastic production function analysis suggests that land renters have fewer inefficiencies in their production process and obtain relatively higher output per hectare. Taken together, our results are suggestive that land rental markets transfer land to able and more efficient farmers raising hopes that removing the impediments to the development of these markets would lead to increased aggregate productivity and ultimately higher income.

The remainder of the paper is organized as follows. In section 4.2, we review the literature on land markets in Africa and discuss our contribution. Next, we present in section 4.3 a conceptual framework that guides our empirical analysis. Section 4.4 presents the empirical models. Section 4.5 discusses the data and basic descriptive statistics. Section 4.6 presents and discusses the results. Finally, we present some concluding remarks and discuss the implications in 4.7.

4.2 Related literature

Our paper fits in the broad literature on land reforms and agricultural development (Deininger and Jin, 2005; Jin and Jayne, 2013) and is more closely related to the growing strand examining the determinants and impact of land markets development. Earlier studies on land markets have focused on Asian, Latin American, and Central Europeans countries. Yao (2000) develops a model of land lease and shows that productive heterogeneity among farmers and the possibility to find off-farm employment drive household participation in land lease markets. The author tests this prediction using a panel data in China and finds supportive evidence. Similar studies in China include Kung (2002), Deininger and Jin (2005). Examples of other similar studies include Deininger, Jin, and Nagarajan (2008) in India, Deininger and Jin (2008) in Vietnam, Deininger, Zegarra, and Lavadenz (2003) in Nicaragua, and Vranken and Swinnen (2006) in Hungary.

In the recent years, several studies focusing on Africa, where land rights are primarily customary and land markets less developed, have emerged. Examples of such studies include Jin and Jayne (2013) in Kenya, Deininger et al. (2008) and Benin et al. (2005) for Ethiopia, Ainembabazi and Angelsen (2016) for Uganda, and Chamberlin and Ricker-Gilbert (2016) for Malawi and Zambia. Most of the existing studies in Africa focus on Eastern and Southern Africa. In West Africa, Colin and Ayouz (2006) and Chauveau and Colin (2010) examine the case of Côte d'Ivoire, Benjaminsen et al. (2009) analyze land markets in Mali and Niger, and more recently Koussoubé (2015) analyze land markets for Burkina Faso. Our study contributes to this emerging literature on land rental markets in West Africa and complements the existing literature by providing an empirical analysis of the impact of land rental markets agricultural development in Burkina Faso.

Most studies on land rental markets focus on the determinants of households' participation in land rental markets (Deininger et al., 2003; Koussoubé, 2015; Chamberlin and Ricker-Gilbert; 2016). Among others, the determinants often identified are the household farming ability, initial land endowment, labor endowment, participation in off-farm employment, household headship, migration, and climatic shocks. Our study, in line with this trend in the literature, also examines the determinants of household participation in land rental markets in Burkina Faso focusing on the demand side. We test whether some of the determinants in the literature are relevant to the particular context of Burkina Faso.

More recently, however, several studies have assessed the consequences of land rental looking at various outcomes including productivity (Deininger et al., 2013), and income and poverty (Jin and Jayne, 2013; Chamberlin and Ricker-Gilbert, 2016). Our study follows this emerging strand of the literature by also analyzing the impact of participation in land rental markets on farm productivity. We complement the literature with our analysis of the impact of land rental markets on farm investment in modern variable inputs contributing to the understanding of drivers for household input intensification. To our best knowledge, no previous studies have looked at the effect of land rental on farm investment.

We also complement the literature by assessing the impact of land markets on efficiency. Previous studies on this question uses the indirect approach of testing whether households with higher farm ability are more likely to rent in land or households with lower farming capability are more likely to rent out land (Deininger and Jin, 2005). We follow this approach but also propose an alternative direct approach with the estimation of household stochastic production frontier allowing for a direct modeling of technical inefficiencies as a function of participation in land rental markets. Stochastic frontier analysis has been widely used to study the efficiency of agricultural systems (Bravo-Ureta et al., 2007; Theriault and Serra, 2014). Our application of this framework to analyze the efficiency-enhancing effect of land rental markets in Burkina Faso also represents a distinctive contribution to the literature.

Overall, our study provides a broad assessment of the drivers and consequence of household participation in land rental markets. To our knowledge, no other study has provided such a comprehensive assessment of land rental markets on-farm investment and efficiency. In particular, our study is the first of its kind in West Africa and Burkina Faso. Our assessment of the direct effect of land rental on modern input use and inefficiencies constitutes a substantial contribution to the literature. As policy agendas, in developing countries in general and Burkina Faso in particular, continue to push forward land reforms to strengthen land rights, we expect that land rental markets will continue to develop at a faster rate. The evidence we present is relevant to the understanding of the potential gains from policies that actively support such development.

4.3 Conceptual framework

To guide our empirical analysis, we develop a simple conceptual framework that embeds farmers' land rental decision with input decisions and productivity. The model builds on the work by Deininger and Jin (2005) and Deininger et al. (2008) to analyze the role of transaction costs and heterogeneity in land rental decision. It differs from their model in the sense that it incorporates input use decision and extends the analysis to the impact of land rental on productivity. In the model, households differ in their farming ability (and commitment to agriculture) denoted by s_h, their labor endowment $\bar{L}_h$, and land endowments $\bar{A}_h$. Farmers can decide to rent in or rent out land but face a certain transaction cost γ which is assumed, without loss of generality, to be symmetric; that is the transaction costs for renting in or renting out land are the same. Farmers allocate labor between agricultural production l_h^a and off-farm activities l_h^o. Production technology is described by a standard quasi-concave function $q = F(s_h, l_h^a, A_h)$ with A_h representing the observed demand for land. Following Deininger et al. (2008), let us define the amount of land rented in (if any) as $a_h^{in} = A_h - \bar{A}_h$ and the amount land rented out (if any) as $a_h^{out} = \bar{A}_h - A_h$. For now, we focus the analysis on labor, land, and total production but will later incorporate variable inputs and productivity.

Assuming that households maximize profit from farm operation, the problem can be formulated as follows:

$$\underbrace{Max}_{l_h^a, A_h} pF(s_h, l_h^a, A_h) + w(\bar{L}_h - l_h^a) + 1_{(A_h \geq \bar{A}_h)}[A_h - \bar{A}_h](r + \gamma) + 1_{(A_h \leq \bar{A}_h)}[\bar{A}_h - A_h](r - \gamma) \tag{4.1}$$

Where p represents output price, w wage, r rental rate, and 1 an indication function that takes the value 1 if the condition is satisfied and 0 otherwise. Taking the first order conditions yields the following equations :

$$pF_l(s_h, l_h^a, A_h) = w \tag{4.2}$$

$$pF_A(s_h, l_h^a, A_h) = r + \gamma \quad \text{if rent in} \quad (A_h \geq \bar{A}_h) \tag{4.3}$$

$$pF_A(s_h, l_h^a, A_h) = r - \gamma \quad \text{if rent out} \quad (A_h \leq \bar{A}_h) \tag{4.4}$$

$$r - \gamma < pF_A(s_h, l_h^a, A_h) < r + \gamma \quad \text{if autarky} \quad (A_h = \bar{A}_h) \tag{4.5}$$

From these conditions, and following Deininger et al. (2008), we can show that for households renting in land, $\partial a_h^{in})/(\partial s_h \geq 0$. The proof is a straightforward application of the implicit theorem function applied to the first two equations 4.3 and 4.3 and using the assumption that the production function is quasi-concave . This shows that the likelihood to rent in land and the amount of land rented in are increasing functions of farming skill and commitment to agriculture. We can write $a_h^{in} = f(s_h)$ with $f' \geq 0$.

To incorporate input use in this framework, we make the assumption that farmers with a high farming ability are more likely to seek out more actively modern inputs and adopt them. If this is the case - something that we will formally test in the empirical analysis - we can express modern input use as an increasing function of $s_h : I_h = g(s_h)$ where $g' \geq 0$. As long as f is locally monotonic and differentiable, it is also locally invertible (Simon and Blume, 1994). Letting f^{-1} be the inverse of f and assuming f^{-1} is also differentiable, we can show that I_h an increasing function of a_h^{in}. To see that, recognize that we can write $s_h = f^{-1}(a_h^{in})$ and $I_h = g(f^{-1}(a_h^{in}))$ with $\partial I_h/(\partial a_h^{in} = \frac{1}{f'(f^{-1}(a_h^{in}))} * g'(f^{-1}(a_h^{in})) \geq 0$.

If land rental is associated with higher investment in modern inputs, and given that utilization of modern inputs is associated with higher productivity (Feder, Just, and Zilberman, 1985), we should also expect to find a positive association between participation in land rental and crop yield. Whether land renters are more efficient is an empirical question. Higher utilization of modern inputs and higher yield are not necessarily associated with a higher efficiency which is a concept that related to a cost effective use of input to obtain the maximum attainable yield (Chavas et al., 2005).

4.4 Empirical strategies and models

We are interested in three fundamental questions: i) What drives household participation in land rental markets? ii) Does renting in land imply greater agricultural input intensification? iii) Are land renters more productive and more efficient than farmers in autarky? In this section, we discuss the specific empirical strategy and models to answer each of these questions.

4.4.1 Methods to analyze the determinants of household's participation in land rental

We measure households' participation in land rental markets with two different variables: a binary variable indicating whether a farmer has rented in at least one plot of any size during the farming season and a continuous variable measuring the total amount of land rented. The first variable captures the decision to participate in land rental markets and the second measures the intensity of participation. Depending on the nature of the dependent variable, we choose an appropriate estimation method.

To model households' participation in land rental markets measured as a binary decision variable, we estimate the following probit model:

$$p_{ht} = P_r[1(A_{ht} > \bar{A}_{ht}) = 1|X_{ht}] = \Phi(X_{ht}^{'}\beta) \tag{4.6}$$

Where p is the probability of a household h operating at least one rented plot in the year$t$; $1(A_{ht} > \bar{A}_{ht})$ is a binary variable indicating whether farmed land A_{ht} is greater than land endowment $\bar{A}_{ht}; X_{ht}$ is a set of control variables carefully selected among the potential determinants of land rental we find in the literature, and Φ is the cumulative distribution function of the normal distribution. For robustness, we also consider a linear probability model treating the function Φ as the identity function.

For a continuous dependent variable R_{ht} indicating the intensity of household participation in land rental markets, we consider the following censored model:

$$R_{ht} = \begin{cases} 1 & \text{if } R_{ht}^{*} > 0, \\ 0 & \text{Otherwise} \end{cases} \tag{4.7}$$

with $R_{ht}^{*} > 0 = X_{ht}' \beta + \epsilon_{ht}$

As before, X_{ht} is a set of control variables. Given that land rental decisions potentially have a corner solution, when some households might not find it optimal to rent in any amount of land, the variable R_{ht} is left-censored at 0 and we estimate the model using a Tobit regression and double hurdle model proposed by Cragg (1971). The double hurdle model is a flexible alternative to the Tobit model that allows the decision to rent in land and the amount of land leased to be made sequentially and be determined by entirely different processes. It estimates two tier-equations: one for the participation in land rental markets and a second for the intensity of participation in land rental markets. After the estimation, we perform a likelihood ratio test to choose the one that better fits the data between the Tobit and the Cragg models.

Following Deininger et al. (2003) and Chamberlin and Ricker-Gilbert (2016), our control variables include household socio-demographics characteristics, assets and endowments proxied by the total amount of land owned, the total number of tropical livestock units owned, and non-farm income. Given the poor degree of mechanization of African agriculture, availability of labor is often a key determinant of farm expansion. As such, we include the total number of household members by age group and gender as a proxy for family labor endowment. We include region dummies to capture regional differences in agricultural conditions, institutional arrangements, migration, and policies that affect spatial mobility and access to land. Given the longitudinal nature of our data, we control for year fixed-effects and use the correlated random effect device to account for unobserved household heterogeneity (Mundlak, 1978; Chamberlain, 1984). We also include dummies for whether the households have grown maize, sorghum, rice or millet to control for crop fixed effects.

One important implication of the conceptual framework is that households with a high farming ability and a strong commitment to agriculture expand farm operations by renting in land. Following Chamberlin and Ricker-Gilbert (2016), Jin and Jayne (2013), and Jin and Deininger (2009), we estimate a modified Cobb-Douglas production function to elicit the household's time-variant farming ability. The model is specified as follows:

$$q_{ht} = \alpha_h + Z'\beta + V'\gamma + \epsilon_{ht} \tag{4.8}$$

Where q_{ht} is the logarithm of the total value of cereal production estimated as the total production valued at the average market price in the village, aggregated across all cereals (maize, rice, sorghum, and millet). The vector of inputs Z includes the cost of seeds, the cost of mineral fertilizer, the cost of crop protection chemicals (such as herbicide, insecticide, rodenticide, fungicide, etc.), the amount of manure applied, total labor used differentiated by type (family and hired) and by gender and age group (male, female, children, adults, and seniors). The term V captures regional and crop fixed effects to account for difference in institutional and production environments across region. We also control for time fixed effects to account for technological changes in production systems resulting from the simple evolution of time. The model is estimated using household fixed effects, and the unobserved farming ability is recovered as the predicted household fixed effects $\hat{\alpha}_h$ and added as explanatory variable in the model of the determinant of households' participation in land rental markets.

4.4.2 Methods to analyze the impact of land rental on input intensification

A key prediction from our conceptual framework is that farmers renting land are more likely to use modern inputs. For the analysis, we aggregate input use and land plot ownership and evaluate the effect of household participation in land rental markets on input intensification at the household level. We consider two treatment variables: a binary variable indicating whether the household has at least one rented plot and a continuous variable measuring the total amount of rented land. We consider various empirical approaches. First, we use simple mean comparison tests of input use between households in land rental markets and those who are not. We further extend the analysis in a regression setting to control for other factors that affect input demands and address identification concerns using various econometrics approaches.

We consider multivariate probit to account for the simultaneous nature of the demand for inputs and use latent class models that link observed household's decisions to use modern inputs to latent variables which capture the perceived net benefit of the utilization of those inputs (Maddala 1986). The demand for a particular input is characterized by the following:

$$I_{ht} = \begin{cases} 1 & \text{if } I^*_{ht} > 0, \\ 0 & \text{Otherwise} \end{cases} \tag{4.9}$$

with $I^*_{ht} = \alpha_h R_{ht} + X'_{ht}\beta + V'\gamma + \epsilon_{ht}$

Where is I_{ht} is input use decision by a household h during the year t, R_{ht} is a binary variable indicating whether the household has rented a plot or not; X is a vector household characteristics which affect input use such as access to credit, contact with extension service, demographic characteristics, and economic variables. Here, again, V captures region fixed effects and T captures time fixed effects.

Our parameter of interest is the coefficient α measuring the effect of land rental on input use. Endogeneity is a serious threat to identification of causal effects given that households obviously self-select themselves into renting in land based on observable and unobservable characteristics. It is possible that there is reverse causality since households that are more likely to use modern inputs could actively seek land to rent in.

Our identification relies on variation in the data and various assumptions to address this endogeneity. We exploit household fixed effects and use the correlated random effects approach developed by Chamberlain (1984) and Mundlak (1978) to account for household heterogeneity and attrition bias due to non-random loss of households between waves of the survey. While this approach addresses part of the bias due to potential endogeneity, it is possible that bias due to time-varying unobservable would persist. Addressing this source of endogeneity is particularly challenging and depends on finding an instrument that satisfies the standard exclusion-restriction conditions (Wooldridge, 2010). Such an instrument should be strongly correlated with the household decision to rent in land (and the amount of land leased) and uncorrelated with the unobserved factors affecting input use. While finding and using such an instrument is ideal, the bias resulting from a weak or inappropriate instrument is worse than the bias with no instrument. Failing to find an adequate instrument, we restrict our analysis in addressing household heterogeneity, recognizing that some bias might persist. However, given that the decision to rent in land and the amount of land rented are typically made several years before we observe input data, and are therefore predetermined, we can argue that the endogeneity issue related to time-varying unobservable might be less severe.

4.4.3 Methods to analyze the impact of land rental of productivity and efficiency

A key result from the conceptual framework is that farmers with a higher ability (and a stronger commitment to agriculture) will expand agricultural production by renting in land. This implication is in line with the argument often advanced that land markets have the potential to transfer land to more efficient producers, improving aggregate productivity and efficiency. To provide an empirical test of this argument, we estimate a parametric stochastic frontier production function as developed by Aigner et al. (1977). This approach allows us to perform a direct test of the argument that farmers in land rental markets are better managers and are more efficient.

The stochastic production frontier analysis is described as follows: Assume that a household h uses the vector of inputs Z in the year t to produce its crop according to the technology $Q^*_{ht} = F(Z_{ht}, \beta)$. In this function, β is vector of unknown technical parameters. If there are inefficiencies in the production system, households produce less than predicted by the production function and the observed level of output is $Q_{ht} = \epsilon_{ht} F(Z_{ht}, \beta)$ where ϵ_{ht} is a measure of the level of inefficiency and satisfies the condition $0 < \xi_{ht} < 1$. The closer ξ_{ht} is to 1, the more efficient is the farmer in combining inputs to produce the highest possible level of output.

We assume that production takes the form of a Cobb-Douglas function with K inputs subject to additional random, multiplicative, and symmetric shocks $exp(v_{pht})$. Taking the log of the stochastic production function above, and letting $u_{pht} = -ln(\epsilon_{ht})$, we have:

$$q_{ht} = \beta_0 + \sum_{i=1}^{K} \beta_i ln Z_{iht} + v_{ht} - u_{ht} \tag{4.10}$$

Next, we specify a model for the inefficiency parameter allowing household participation in land rental markets to affect the inefficiency level, conditional on observable characteristics.

$$u_{pht} = \theta_0 R_{ht} + X'_{ht}\theta_1 + V'\theta_2 + \varsigma_{ht} \tag{4.11}$$

Here, R_{ht} measures household participation in land rental markets, X is a set of socio-demographic and economic control variables, and V and T capture region and time fixed effects, respectively. We use the correlated random effects framework described in the section on land rental and farm investment to address potential endogeneity of land rental. Assuming a half-normal distribution for the inefficiencies and a normal distribution for the error terms, both the production function and the inefficiency models are estimated jointly using maximum log likelihood.

4.5 Data and descriptive statistics

The data are from the continuous agricultural survey (Enquête Permanente Agricole - EPA) conducted by the Ministry of Agriculture and Food Security of Burkina Faso every year to estimate crop areas and yields for rainfed crops and to track food security for emergency response. We use the latest available three waves of the panel for the years 2009-2010, 2010-2011, and 2011-2012. The sampling framework consists of a multi-stage stratified sampling to assure it is nationally representative . The sample size of the initial survey consists of 4130 households per year. However, our analysis focuses on the subsample of cereal producers, mainly maize, rice, millet, and sorghum producers which are nearly 99% of the households in the sample. These cereals are the main staple food in Burkina Faso. The survey includes various information on socio-demographic and economic characteristics of households, input use, production, sales, and consumption.

We use two primary treatment variables: a binary variable indicating whether a household has rented at least one plot to farm and a continuous variable indicating the amount of land leased. We use various dependent variables corresponding to the question addressed. In the first analysis of the drivers for household participation in land rental markets, the dependent variables are the household decisions to rent in land and the amount of land rented. For the analysis of the implications of land rental markets for farm investments, the dependent variables are binary variables indicating the household's input use decisions. Finally, for the analysis of the efficiency effect of land rental markets, the dependent variable is inefficiency estimated from the stochastic production frontier.

The control variables are households socio-demographic characteristics such as the age of household head, the age and gender composition of the household, proxy variables for household wealth, the number of livestock units, and non-farm income. There are also institutional variables such as contact with the extension service or NGO and access to credit during the year before the growing season. We also include variables such input prices and output prices at the village level. Finally, all models control for region fixed effects, time fixed effects, and mean of time-varying variables to account for household heterogeneity.

Table 4.1 presents descriptive statistics on input use, the cost of inputs, and the value of production differentiated by household status in land rental markets. Table 4.2 presents descriptive statistics on the rest of variables used in the empirical analysis. There is substantial variation in the data.

The rate of mineral fertilizer use is 40% and is higher among farmers who rent land than those who do not (43% for 39%). Adoption rates of hybrid seeds are low and statistically similar in the two groups of farmers. Land renters are more likely to use manure and crop protection chemicals, and to spend more on these modern inputs. Finally, there are no differences in farm size and use of hired labor between land renters and non-renters. All the difference in input use translates into a higher production for land tenants.

4.6 Econometric results

4.6.1 Determinants of farmer participation decision to rent in land

The first step in the analysis it to elicit the household's farming ability which is a key determinant of their decision to rent land and the amounted of land rented. For this , we estimate a modified Cobb-Douglas production function via household fixed effects. The results are presented in Table 4.3. The coefficients of input costs are all positive and statistically significant indicating that modern input uses are associated with high outputs. The result also shows that large farms, both in term of total cultivated land and household size, obtain relatively larger crop production. However, there is no evidence that the use of hired labor substantially increases crop production. We also find that the value of crop production for rice, sorghum, and millet are significantly higher than for the value of maize output. The results are consistent with most previous findings on production functions (Chamberlin and Ricker-Gilbert, 2016).

We use the estimated model to elicit household farming ability as the time-constant error component of the model. This variable is then used in the analysis of the determinant of the farmers' decision to rent in land. Preliminary comparative analyses of the kernel density of farming ability (Figure 4.1) suggest that a significant proportion of farmers renting in land have a high farming ability. To further examines the relationship between farming ability and land rental, we estimate a bivariate non-parametric regression of total land rented on the farming ability using an Epanechnikov local kernel-weighted polynomial smoothing. The result presented in Figure 4.2 clearly indicates that the intensity of participation in land rental markets is increasing with farmers' ability.

The previous analysis is bivariate and does not control for other confounding factors that could potentially explain household participation in land rental markets. To analyze further the determinants of household participation in land rental markets in Burkina Faso, we estimate and compare various econometric models. First, we estimate a probit regression of the decision to rent in land then a Tobit regression of the amount of land rented. Finally, we estimate a double hurdle model to account for the possibility that the decision to rent in land and the amount of land rented might be interlinked and sequential.

The results are presented in Table 4.4 below. Qualitatively, the results of the Tobit model and the double hurdle model are similar. However, the log likelihood test comparing the two models suggests that the later better fits the data generating process. Thus, we can infer that households first decide whether they want to rent in land for farming and subsequently decide how much to rent based on their unobserved farming ability, demographic and economic characteristics, and various institutional and region-level factors. We base the interpretations on the results from double hurdle model.

The results of the double hurdle model are presented in columns (5) for the participation equation, column (6) for factors explaining the amount of land rented, and column (7) for unconditional marginal effects of the explanatory variables that account for the likelihood to rent in land. In both tiers, the coefficient for the variable measuring the household's ability is positive and statistically significant. Other determinants of farmer participation in land rental markets include demographic, socioeconomic, and institutional variables. We find that female-headed households are less likely to rent in land, and large households are more likely to rent in more land. Consistent with our expectations, the more land a household owned either through inheritance or through purchase, the less likely its members rent in land. However, richer households, in terms of livestock assets and households with access to credit expand their farm through land rental. The effects for most of these variables also appear to be consistent with studies.

Overall, our results suggest that many factors influence the farmer's decision to rent in land, but high farming ability is one of them and such farmers rent in a large amount of land. This finding is consistent with previous studies in various contexts (Chamberlin and Ricker-Gilbert, 2016; Jin and Jayne, 2013; Jin and Deininger, 2009; Deininger and Jin, 2005). It provides empirical support to the argument that rental markets contribute to efficiency by transferring land to more committed and technically able producers. We will further test this argument using an alternative empirical approach in the subsequent sections.

4.6.2 Land rental and farm investment

One testable implication of our conceptual framework relates to the potential effect of land rental on farm investment. We show in the model that if farmers with high farming ability actively seek to adopt modern inputs, then indirectly, participation in land rental markets will be associated with greater investment in these modern inputs. To empirical test this prediction, we run a multivariable probit model of input demand with a binary variable indicating household participation in land rental markets as a key explanatory variable. The results of the model are presented in Table 4.5.

The model considers the household's decision to use mineral fertilizer, hybrid cereal seeds, manure, crop protection chemicals, and hired labor as dependent variables. The use of multivariate probit regression and the extension of the model to hired labor allow us to account for interlinkages among input use decisions as well as labor demand. Panel B of the Table 4.5 clearly indicates that the correlations among the residuals of the individual demand equations are statistically significant. This result confirms that input decisions are made jointly and are interlinked. The log likelihood test of the comparison of the multivariable probit regression to separate individual probit regressions shows strongly strong support for the former.

The main result from the estimation is that participation in land rental markets does not significantly increase farm investment in modern inputs such as mineral fertilizer and hybrid seeds. Although the estimated coefficients are positive, they are not statistically significant at conventional levels. In addition, participation in land rental markets has no significant effects on the use of manure and the use of hired labor. These results contrast the initial finding from the descriptive analysis that, on average the proportion of farmer using mineral fertilizer and manure are higher among land renters than non-renters. After controlling for various confounding factors and accounting for the simultaneity in input use and unobserved household heterogeneity, this apparent effect disappears. However, we find in various alternative models using different treatment variable (the amount of land rented) and different econometric models, that land rental is positively correlated with mineral fertilizer use and negatively associated with the use of hybrid seeds and manure. Across all models and specifications, we consistently find that the likelihood to use crop protection chemicals increases when households engage in land rental.

To our best knowledge, these results are the first evidence of the implications of land rental markets for modern inputs use in Burkina Faso. The absence of significant effects of household participation in land rental markets on mineral fertilizer, hybrid seed, manure, and hired labor use could raise concerns about the potential of land rental markets to improve modern input adoption in African agriculture. One explanation of these results may be the fact that land renters are generally less endowed and poorer to begin with, so that their land rental status does not necessarily translate into higher farm investment.

4.6.3 Land rental and efficiency

To further analyze the implications of land rental markets for agricultural development, we examine the correlation between household participation in land rental markets and allocative efficiency. The analysis complements the findings that household's farming ability is positively correlated with the likelihood to rent in land and the amount of land rented. We estimate a stochastic production frontier with a fully specified model to explain technical inefficiencies. We find substantial inefficiencies in the cereal production in Burkina Faso. On average, farmers reach about 66% of the potential output they could obtain using the same amount of input. There are many sources of inefficiencies related to the late access to and low quality of inputs, low household managerial and technical abilities, the non-conducive institutional situation and production environment.

The stochastic production frontier model allows us to estimate the determinants of inefficiencies with a particular focus on the role of land rental markets. The results are presented in Table 4.8 below. In the first column, we use a dummy variable indicating household participation in land rental markets. The second column uses the amount of land rented as a proxy for the intensity of household participation in land rental markets. In both models, the coefficient for the variable measuring land rental markets is negative and statistically significant. This implies that household participation in land rental markets is associated with lower inefficiencies in the production process. Furthermore, the higher is the amount of land rented, the larger is the reduction in inefficiencies. In other terms, the results suggest that households renting in land are more efficient in using agricultural inputs to achieve the largest possible cereal output.

The result has important implication for agricultural productivity. Although households in land rental markets do not substantially invest more in modern inputs, they appear to have higher farming abilities and stronger commitments in agriculture, and these translate into less inefficiency in the production process. This result is consistent with our finding that land rental markets transfer land to more farmers that are more talented . It is also consistent with previous findings both in the African context and outside (Chamberlin and Ricker-Gilbert, 2016; Jin and Jayne, 2013; Jin and Deininger, 2009; Deininger and Jin, 2005).

In addition to household participation in land rental markets, many other factors are associated with less inefficiency in cereal production. For instance, we find that household head age and female-headship are both positively correlated with inefficiencies. Large households are less efficient that smaller one. This finding could be translating the fact that larger households may be disproportionally using more labor, particularly family-labor, than other modern inputs. We also find that off-farm employment does not appear to reduce production inefficiencies. Combined with our finding that off-farm income does significantly affect input use, our results corroborate the strand of literature suggesting that off-farm work may be a distraction from an efficient agricultural production (Smale et al., 2016). However, affluent households both in term of livestock asset and land endowment are more efficient.

4.7 Conclusion

Land is increasingly recognized as an important policy issue for rural development in Africa. In Burkina Faso, where land rights have been essentially customary, important actions are being taken to address land right security and promote land markets. Rural land rental markets continue to develop progressively in the country as a medium for land transfer among households. In this study, we analyze the development of land rental markets in Burkina Faso with a particular focus on the determinants of farmer's participation in these markets and its impact on farm investment and production efficiency.

Our empirical analyses use panel data covering the years 2010, 2011, and 2012 in Burkina Faso and focus on cereals, millet, maize, rice, and sorghum producers. We consider various econometric models to address our specific questions. To analyze the determinants of household participation in land rental markets, we estimate a double hurdle model that accounts for the sequentiality of the decision to rent in land and the amount of land rented. We find that land rental is increasingly prevalent in Burkina Faso and driven by various socio-demographic, economic, and institutional factors. Household farming ability is a key determinant as farmers with high ability are more likely to expand farm operations through land rental.

Next, we test the hypothesis that participation in land rental markets has spillover effects on input intensification beyond rented plots. To this end, we use multivariable probit regressions to assess the impact of land rental on the household's decision to use various modern inputs such as hybrid seeds, mineral fertilizer, manure, crop protection chemicals, and hired labor. We address potential endogeneity controlling for various confounding effects and the correlated random effects approach to account for unobserved household heterogeneity and attrition bias. We find that input decisions are made jointly and farmer's participation in land rental markets has a positive effect on the likelihood to use crop protection chemicals. The effect on the use of mineral fertilizer and manure are positive but weak, and there is no significant effect on the use hybrid seeds or hired labor. The results are robust to alternative treatment variable and estimation methods.

Finally, we use stochastic production frontier analysis to assess the efficiency-enhancing effect of land rental markets. This analysis enables us to test the hypothesis that, although they do not use more inputs, households participating in land rental markets might be efficient farm managers. The results support this argument, and consistent with previous studies, we argue that land renters have fewer inefficiencies in their production process and obtain relatively higher output per hectare.

Our findings highlight the mixed effects of land rental markets on input intensification in Burkina Faso. Taken together, our results are suggestive that land rental markets transfer land to able and more efficient farmers raising hopes that removing the impediments to the development of these markets will lead to increased aggregate productivity and ultimately higher income.

4.8 Tables and figures for chapter 4

Table 4.1: Summary statistics for input use and production variables

	All farmers (1)	Farmers with rented land (2)	Farmers without rented land (3)	Difference (4)=(2)-(3)
Use of mineral fertilizer	0.400	0.427	0.385	0.042***
	(0.49)	(0.495)	(0.487)	[4.734]
Use of hybrid seeds	0.080	0.081	0.079	0.002
	(0.271)	(0.273)	(0.27)	[0.333]
Use of manure	0.522	0.543	0.512	0.031***
	(0.5)	(0.498)	(0.5)	[3.37]
Use of protection chemicals	0.394	0.431	0.374	0.057***
	(0.489)	(0.495)	(0.484)	[6.351]
Use of hired labor	0.419	0.410	0.423	-0.013
	(0.493)	(0.492)	(0.494)	[-1.474]
Log value of production	10.554	10.747	10.448	0.298***
	(3.2)	(3.106)	(3.245)	[5.09]
Log cost of seeds	8.941	8.864	8.983	-0.119***
	(1.849)	(1.867)	(1.838)	[-3.523]
Log cost of mineral fertilizer	1.354	1.706	1.164	0.542***
	(7.374)	(7.387)	(7.36)	[4.008]
Log cost of protection chemicals	-0.373	-0.034	-0.554	0.519***
	(5.379)	(5.388)	(5.365)	[5.272]
Log amount of manure	-2.739	-2.525	-2.855	0.330***
	(2.452)	(2.485)	(2.427)	[7.344]
Log total cereal area	2.687	2.725	2.668	0.057
	(2.691)	(2.55)	(2.764)	[1.16]

Notes: For variables with zero values, the log is obtained by translating the variable by 0.01. For binary variables, the means represent the proportion of households with 1. Numbers in parenthesis () are standard deviations; the numbers in bracket [] are t-statistics of the means comparison test. *** p<0.01, ** p<0.05, * p<0.1. Year-specific summary statistics tables are available in the appendix.

Table 4.2: Summary statistics for other variables

	Min	Max	Mean	Std Dev
Outcome variables				
Use of mineral fertilizer (0/1)	0	1	0.400	0.490
Use of hybrid seeds (0/1)	0	1	0.080	0.271
Use of manure (0/1)	0	1	0.522	0.500
Use of protection chemicals (0/1)	0	1	0.394	0.489
Use of hired labor (0/1)	0	1	0.419	0.493
Log value of production (Log FCFA)	-2.129	17.237	10.554	3.199
Treatment variables				
Participation in land rental markets	0	1	0.351	0.477
Amount of land rented	0	52.804	0.587	1.678
Control variables				
Log cost of seeds (Log FCFA)	-4.605	16.328	8.941	1.849
Log cost of mineral fertilizer (Log FCFA)	-4.605	16.547	1.354	7.374
Log cost of protection chemicals (Log FCFA)	-4.605	12.284	-0.373	5.378
Log amount of manure (Log FCFA)	-4.605	8.741	-2.739	2.452
Log total cereal area (Log Ha)	0.051	79.356	2.687	2.690
Family labor (boys under 12) (man-days)	0	1,456	25.142	61.237
Family labor (girls under 12) (man-days)	0	1,563	16.103	45.286
Family labor (male adult 12-65) (man-days)	0	5,107	136.395	180.836
Family labor (female adult 12-65) (man-days)	0	6,058	132.013	200.636
Family labor (male senior above 65) (man-days)	0	570	6.399	26.024
Family labor (female senior above 65) (man-days)	0	497	2.502	15.448
Hired labor (man-days)	0	870	16.115	40.579
Maize Producer (0/1)	0	1	0.750	0.433
Rice Producer (0/1)	0	1	0.187	0.390
Sorghum Producer (0/1)	0	1	0.814	0.389
Millet Producer (0/1)	0	1	0.594	0.491
Member of an association a management level (0/1)	0	1	0.103	0.304
Age of the head of household (years)	15	99	50.084	14.771
Female-headed household (0/1)	0	1	0.050	0.218
Household head is alphabetized (0/1)	0	1	0.730	0.444
Household size (count)	1	88	9.948	6.098
Log of total own land (Log Ha)	-23.361	4.374	-0.116	4.111
Number of tropical livestock units	0	0.987	0.049	0.056
Log of off-farm income (Log FCFA)	-4.605	16.861	4.611	7.579
Access to credit (0/1)	0	1	0.112	0.315
Contact with Extension or NGO (0/1)	0	1	0.176	0.380

Notes: For variables with zero values, the log is obtained by translating the variable by 0.01. For binary variables, the means represent the proportion of household with 1.

Table 4.3: Cobb-Douglas Production

	Coefficient (1)	Standard Error (2)
Log cost of seeds	0.0241***	(0.0052)
Log cost of fertilizer	0.0045**	(0.0018)
Log cost protection chemicals	0.0075***	(0.0022)
Log amount of manure	0.0091**	(0.0045)
Log total farm land	0.2188***	(0.0135)
Family labor (boys under 12)	-0.0001	(0.0002)
Family labor (girls under 12)	0.0003	(0.0002)
Family labor (male adult 12-65)	0.0004***	(0.0001)
Family labor (female adult 12-65)	0.0001	(0.0001)
Family labor (male senior above 65)	0.0004	(0.0004)
Family labor (female senior above 65)	0.0005	(0.0006)
Hired labor	0.0002	(0.0003)
Maize Producer	0.0477	(0.0337)
Rice Producer	0.1150***	(0.0339)
Sorghum Producer	0.1142***	(0.0355)
Millet Producer	0.1349***	(0.0266)
Constant	11.0528***	(0.0729)
Observations	13,063	
R-squared	0.8581	

Notes: The dependent variable is the log value of total cereal production. The regression includes time, region and household fixed effects. Robust standard errors in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 4.4: Double hurdle model of the determinants of household participation in land rental markets

	Tier1 Coeff (1)	Tier2 Coeff (2)	Marg Effect (3)
Estimated household farming ability	0.4609***	6.0015***	0.3789***
	(0.0367)	(1.6622)	(0.0195)
Member of an association a management level	0.1019	0.3872	0.0460
	(0.0650)	(0.4295)	(0.0454)
Age of the head of household	-0.0007	0.0297***	0.0010
	(0.0010)	(0.0078)	(0.0007)
Female-headed household	-0.4209***	0.8114**	-0.0933***
	(0.0769)	(0.3527)	(0.0185)
Household head is alphabetized	-0.0111***	0.3803	0.0120
	(0.0028)	(0.5322)	(0.0099)
Household size	0.0196***	0.0484***	0.0078**
	(0.0031)	(0.0054)	(0.0036)
Log total cereal land	0.1615***	1.3963***	0.1044***
	(0.0074)	(0.2508)	(0.0006)
Log of total own land	-0.8284***	-0.6084***	-0.2722***
	(0.0475)	(0.1196)	(0.0028)
Number of tropical livestock units	1.2665***	16.2164***	1.0301***
	(0.0540)	(1.9801)	(0.2595)
Log of off-farm income	-0.0002	-0.0206	-0.0009
	(0.0066)	(0.0133)	(0.0045)
Access to credit	-0.1005	1.6680**	0.0369***
	(0.1120)	(0.8371)	(0.0134)
Contact with Extension or NGO	0.0636	1.8022***	0.0914
	(0.0667)	(0.3620)	(0.0628)
Maize producer	0.1868***	0.9595***	0.0944***
	(0.0484)	(0.0920)	(0.0185)
Rice producer	0.1865***	-0.0459	0.0539*
	(0.0304)	(1.2364)	(0.0302)
Sorghum producer	0.3120***	1.5680**	0.1563***
	(0.0010)	(0.6166)	(0.0288)
Millet producer	0.2907***	2.3374***	0.1808***
	(0.0445)	(0.3172)	(0.0052)
Constant	-0.6026**	-15.3536***	
	(0.2875)	(0.2522)	
Sigma		3.8348***	
		(0.5281)	
Observations	11,950	11,950	11,950

Notes: Standard errors in parentheses are obtained by 100 bootstrap replications*** p<0.01, ** p<0.05, * p<0.1.

Table 4.5: Multivariate probit regression of input demand and land rental in Burkina Faso

	Mineral Fertilizer	Hybrid seeds	Manure	Protection Chemicals	Hired labor
Panel A: Coefficient estimates					
Participate in land rental market	0.0245	0.0176	-0.0369	0.1510***	0.0189
	(0.0274)	(0.0382)	(0.0264)	(0.0269)	(0.0263)
Age of the head of household	-0.0038***	-0.0000	0.0023***	-0.0036***	0.0013
	(0.0009)	(0.0013)	(0.0009)	(0.0009)	(0.0009)
Female-headed household	-0.0804	-0.1332	-0.3725***	-0.1274**	0.0711
	(0.0637)	(0.1043)	(0.0578)	(0.0642)	(0.0568)
Household size	0.0231***	0.0082**	0.0105***	0.0031	-0.0285***
	(0.0028)	(0.0033)	(0.0026)	(0.0027)	(0.0025)
Household head is alphabetized	-0.1405***	-0.1274***	0.0443	-0.0714**	-0.0621**
	(0.0304)	(0.0409)	(0.0293)	(0.0297)	(0.0292)
Access to credit	0.1985**	0.0415	0.1455*	-0.0370	0.0131
	(0.0840)	(0.0955)	(0.0781)	(0.0803)	(0.0771)
Contact with Extension or NGO	0.0379	-0.0168	0.0496	0.0764	0.0020
	(0.0596)	(0.0741)	(0.0564)	(0.0579)	(0.0561)
Log total farm land	0.0287**	0.0122	0.0313***	0.0350***	0.0741***
	(0.0132)	(0.0153)	(0.0120)	(0.0130)	(0.0120)
Number of tropical livestock units	0.4183	0.8455	0.8938	-0.4677	0.5845
	(0.5804)	(0.7129)	(0.5644)	(0.5552)	(0.5315)
Log of off-farm income	0.0040	-0.0070	0.0038	0.0046	0.0023
	(0.0032)	(0.0044)	(0.0030)	(0.0032)	(0.0031)
Log of price of fertilizer	-0.0150	0.0121	0.0753**	-0.0005	-0.0008
	(0.0317)	(0.0426)	(0.0306)	(0.0319)	(0.0307)
Log of price of seeds	0.0058	-0.0019	0.0303**	0.0237	-0.0052
	(0.0150)	(0.0220)	(0.0148)	(0.0147)	(0.0150)
Log of price of protection chemicals	0.0012	0.0182	-0.0230	-0.0023	0.0326
	(0.0227)	(0.0349)	(0.0229)	(0.0227)	(0.0227)
Log price of maize	-0.0558**	0.0483	-0.0287	0.0388*	-0.0065
	(0.0250)	(0.0423)	(0.0210)	(0.0216)	(0.0236)
Log price of rice	0.0706	-0.1513**	-0.0349	-0.1056**	-0.0144
	(0.0493)	(0.0705)	(0.0467)	(0.0478)	(0.0465)
Log price of sorghum	0.0654	0.0626	0.0405	0.1161**	0.0371
	(0.0571)	(0.0785)	(0.0518)	(0.0532)	(0.0553)
Log price of millet	0.0271	0.0468	0.0555	0.0293	0.0682
	(0.0437)	(0.0633)	(0.0444)	(0.0436)	(0.0439)
Maize producer	0.6537***	0.8060***	0.3689***	0.3338***	0.0753**
	(0.0349)	(0.0724)	(0.0326)	(0.0330)	(0.0324)
Rice producer	0.5063***	0.3643***	-0.0798**	0.2361***	0.2677***
	(0.0352)	(0.0425)	(0.0338)	(0.0355)	(0.0335)
Sorghum producer	-0.1997***	-0.1199**	0.1937***	0.0525	-0.1152***
	(0.0359)	(0.0466)	(0.0336)	(0.0349)	(0.0332)
Millet producer	-0.2147***	-0.0982**	0.2852***	-0.2562***	-0.0410
	(0.0281)	(0.0386)	(0.0267)	(0.0273)	(0.0268)
Observations	12,496	12,496	12,496	12,496	12,496

Table 4.5: Multivariate probit regression of input demand and land rental in Burkina Faso (continued)

Panel B: Correlation matrix					
Mineral Fertilizer	-				
	-				
Hybrid seeds	0.2492***	-			
	(0.0229)	-			
Manure	0.0633***	0.0799***	-		
	(0.0156)	(0.0189)	-		
Protection Chemicals	0.3068***	0.0921***	0.0666***	-	
	(0.0163)	(0.0199)	(0.0157)	-	
Hired labor	0.0389**	0.0469**	0.0490***	0.0815***	-
	(0.0155)	(0.0186)	(0.0151)	(0.0153)	-

Standard errors in parentheses are obtained by 100 bootstrap replications*** p<0.01, ** p<0.05, * p<0.1.

Table 4.6: Alternative models for input demand and land rental in Burkina Faso

	Mineral Fertilizer	Hybrid seeds	Manure	Protection Chemicals	Hired labor
Treatment: Has rented land					
Multivariate Probit	0.0245	0.0176	-0.0369	0.1510***	0.0189
	(0.0274)	(0.0382)	(0.0264)	(0.0269)	(0.0263)
Separate probit	0.0247	0.0162	-0.0377	0.1495***	0.0167
	(0.0335)	(0.0475)	(0.0394)	(0.0301)	(0.0203)
Separate linear probit model	0.0074	0.0014	-0.0125	0.0471***	0.0058
	(0.0094)	(0.0037)	(0.0082)	(0.0112)	(0.0091)
Treatment: Amount of land rented					
Multivariate Probit	0.0245	0.0176	-0.0369	0.1510***	0.0189
	(0.0274)	(0.0382)	(0.0264)	(0.0269)	(0.0263)
Separate probit	0.0336***	-0.0156*	-0.0148*	0.0356***	-0.0083***
	(0.0063)	(0.0090)	(0.0085)	(0.0087)	(0.0031)
Separate linear probit model	0.0067**	-0.0030**	-0.0048**	0.0086***	-0.0031
	(0.0027)	(0.0014)	(0.0021)	(0.0032)	(0.0026)

Notes: Standard errors in parentheses are obtained by 100 bootstrap replications*** p<0.01, ** p<0.05, * p<0.1. Only the coefficients of land rental variables are presented. All the regression include the same list of control variables are in previous tables.

Table 4.7: Determinants of allocative inefficiencies

	(1)	(2)
Participate in land rental market	-0.0784***	
	(0.0227)	
Amount of land rented		-0.0560*
		(0.0308)
Age of the head of household	0.0021*	0.0022**
	(0.0011)	(0.0011)
Female-headed household	0.0763**	0.0771*
	(0.0377)	(0.0393)
Household size	0.0144***	0.0153***
	(0.0056)	(0.0047)
Household head is alphabetized	-0.1367***	-0.1364***
	(0.0364)	(0.0339)
Access to credit	-0.1159	-0.1104
	(0.0796)	(0.1038)
Contact with Extension or NGO	0.0868	0.0869
	(0.0590)	(0.0563)
Log total farm land	-1.7920***	-1.7848***
	(0.0473)	(0.0403)
Number of tropical livestock units	-1.2259**	-1.2024***
	(0.5051)	(0.3660)
Log of off-farm income	0.0033	0.0031*
	(0.0021)	(0.0017)
Maize producer	0.3585***	0.3569***
	(0.0493)	(0.0706)
Rice producer	0.1078*	0.1049**
	(0.0569)	(0.0419)
Sorghum producer	0.2276***	0.2251***
	(0.0519)	(0.0757)
Millet producer	0.1693*	0.1641***
	(0.0896)	(0.0551)
Constant	2.0905***	2.0686***
	(0.1797)	(0.0971)
Observations	12,502	12,510

Notes: The regressions include the production function, not shown since they are similar to the regression presented in table 3. All regressions also include regional and time fixed effects. Standard errors in parentheses are obtained by 100 bootstrap replications*** p<0.01, ** p<0.05, * p<0.1.

Table 4.8: Determinants of allocative inefficiencies

	Participation - Probit		Intensity - Tobit	
	Coeff (1)	Marg Effect (2)	Coeff (3)	Marg Effect (4)
Estimated household farming ability	0.4609***	0.1834***	0.3559***	0.1005***
	(0.0252)	(0.0129)	(0.0793)	(0.0216)
Member of an association	0.1019***	0.0404**	0.0655	0.0185
a management level	(0.0389)	(0.0184)	(0.1172)	(0.0286)
Age of the head of household	-0.0007	-0.0003	-0.0003	-0.0001
	(0.0007)	(0.0004)	(0.0017)	(0.0006)
Female-headed household	-0.4209***	-0.1656***	-0.4913***	-0.1388***
	(0.0837)	(0.0304)	(0.1165)	(0.0429)
Household head is alphabetized	-0.0111	-0.0044	0.0807	0.0228
	(0.0425)	(0.0132)	(0.0508)	(0.0192)
Household size	0.0196***	0.0078***	0.0281**	0.0079***
	(0.0044)	(0.0013)	(0.0111)	(0.0028)
Log total cereal land	0.1615***	0.0643***	0.2005***	0.0566***
	(0.0183)	(0.0069)	(0.0585)	(0.0147)
Log of total own land	-0.8284***	-0.3296***	-0.2837***	-0.0801***
	(0.0349)	(0.0124)	(0.0156)	(0.0045)
Number of tropical livestock units	1.2665***	0.5039**	6.1513*	1.7374
	(0.4628)	(0.2521)	(3.2109)	(1.0863)
Log of off-farm income	-0.0002	-0.0001	-0.0043	-0.0012
	(0.0045)	(0.0014)	(0.0089)	(0.0020)
Access to credit	-0.1005*	-0.0401	-0.0439	-0.0124
	(0.0534)	(0.0364)	(0.1400)	(0.0599)
Contact with Extension or NGO	0.0636	0.0253	0.1626	0.0459
	(0.0620)	(0.0255)	(0.1050)	(0.0427)
Maize producer	0.1868***	0.0744***	0.2589***	0.0731***
	(0.0237)	(0.0145)	(0.0669)	(0.0201)
Rice producer	0.1865***	0.0737***	0.3238***	0.0914***
	(0.0291)	(0.0154)	(0.0532)	(0.0251)
Sorghum producer	0.3120***	0.1239***	0.4177***	0.1180***
	(0.0450)	(0.0169)	(0.0651)	(0.0251)
Millet producer	0.2907***	0.1155***	0.2645***	0.0747***
	(0.0330)	(0.0126)	(0.0676)	(0.0185)
Constant	-0.6026		-3.7009***	
	(0.4146)		(1.2743)	
Sigma			2.4206***	
			(0.2052)	
Observations	11,950	11,950	11,958	11,958

Notes: All regressions also include regional and time fixed effects. Standard errors in parentheses are obtained by 100 bootstrap replications*** p<0.01, ** p<0.05, * p<0.1.

Figure 4.1: Density of farming ability by rental status

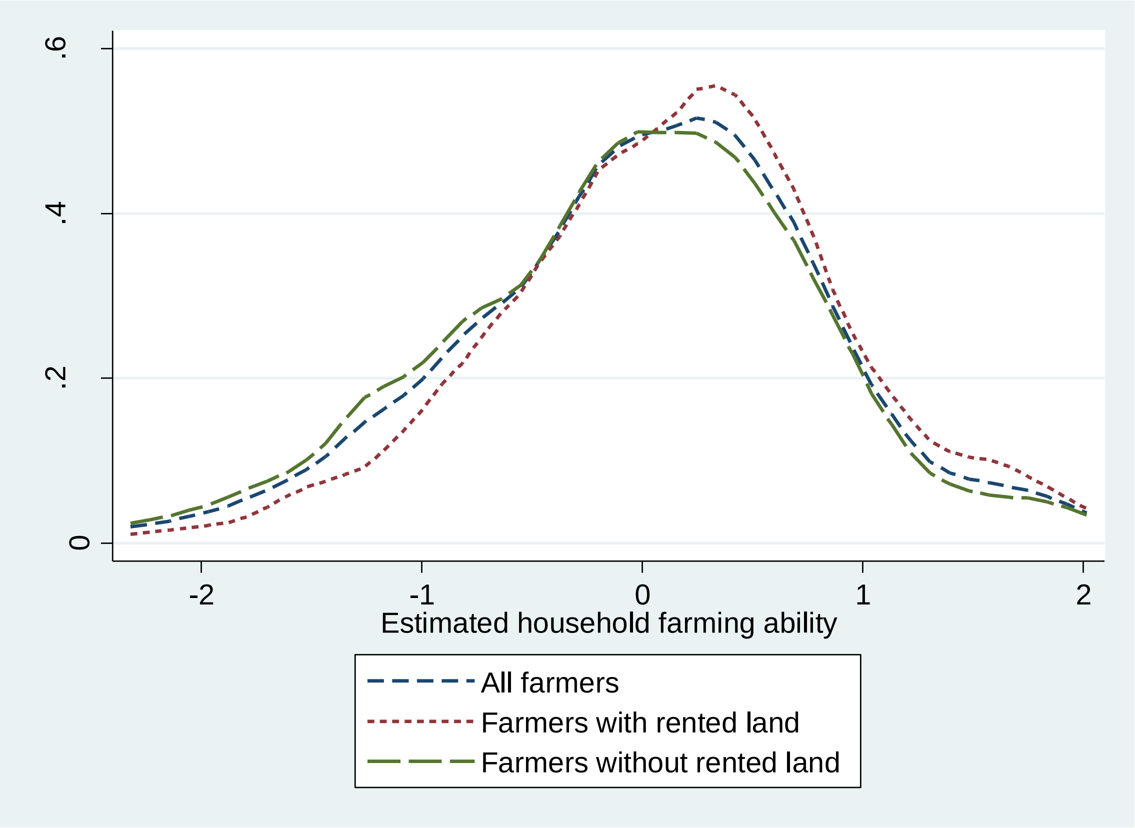
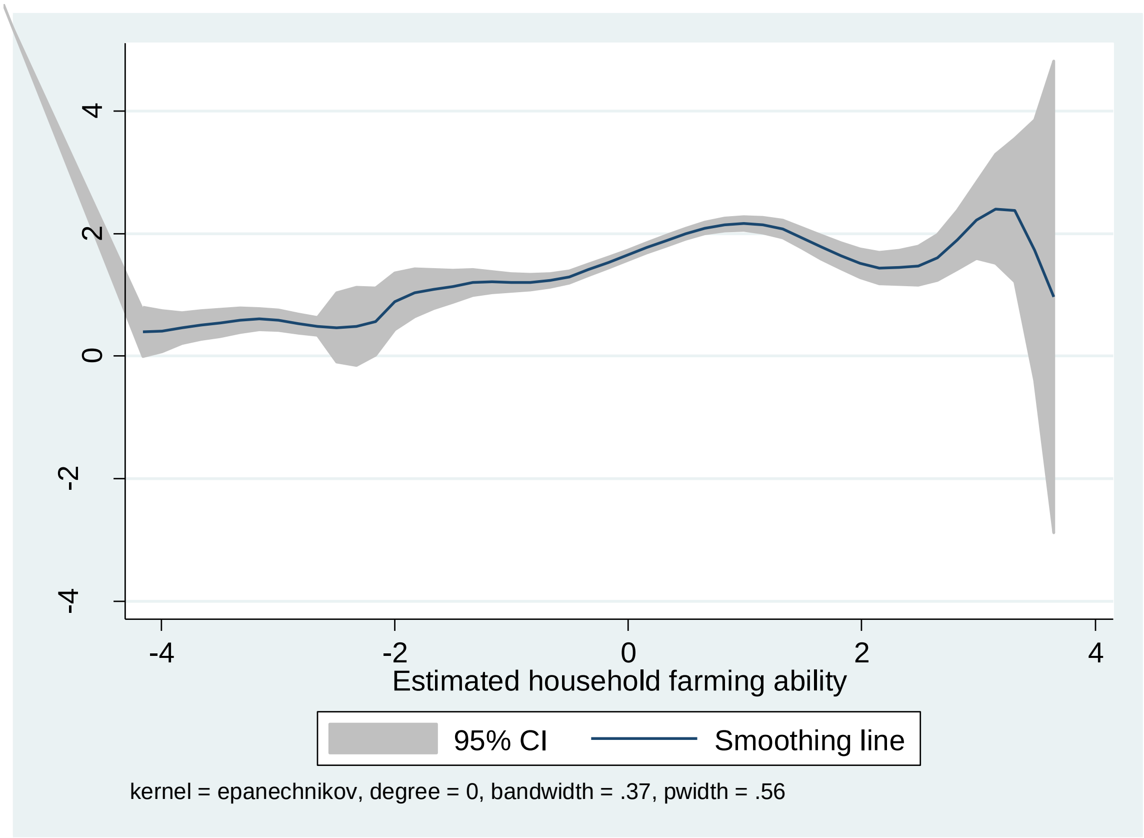


Figure 4.2: Relation between the amount of rented land and farming ability



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Vita

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EDUCATION

DOCTORAL STUDIES

Ph.D. in Agricultural Economics	University of Kentucky, Expected, August 2017

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Sept. 2006	:	M.S in Mathematics University of Abomey-Calavi, Benin
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PROFESSIONAL EXPERIENCE

Sep. 2012 - Dec. 2017	:	Research Assistant University of Kentucky
June 2014 - June 2015	:	Research Assistant European Centre for Development Policy Management
Jan. 2010 - July 2012	:	Statistician-Economist AfricaRice, Cotonou, Benin
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PUBLICATIONS

JOURNAL ARTICLES

Alia, D., A. Diagne, P. Adegbola, and F. Kinkingninhoue (2017). Distributional impact of Nerica adoption on farmer expenditure in Benin: Quantile Treatment Effect Estimation. *Forthcoming Journal of African Development*

Alia, D., Ponty, N., and Kamga, I. (2017). *Altruism or exchange? A quest into the motives of inter-household private transfers in Burkina Faso. Forthcoming International Journal of Socio-Economics* .

Alia, D., A. Floquet, and E. Adjovi (2017). Heterogeneous welfare effects of cotton pricing on households in Benin. *African Development Review*, 29 (2)107-121.

Alia, D. (2017). Progress toward the Sustainable Development Goal on poverty: Assessing the effect of income growth on the exit time out of poverty in Benin, *Sustainable Development* (forthcoming).

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Alia, D., K. Jossa-Jouable, and R. Fiamohe (2016). On poverty and persistence of poverty in Benin. *Journal of Economic Studies*, 2016, 43 (4): 661 676.

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Alia, D. (2014). Geographical orientation of export in the manufacturing sector in sub-Sahara Africa. *Global Economy Journal*, 15 (3) 337-351.

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BOOK CHAPTERS

Diagne, A, D. Alia, M. Wopereiss, K. Saito and T. Nakelse (2013). Impact of Rice Research on Income and Poverty in Africa: An Ex-ante Analysis. Chapter in *Realizing Africa's Rice Promise.* Wopereis, M.C.S., Johnson, D.E., Ahmadi N., Tollens, E. and Jalloh, A., CABI Publishing, October 2013.

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WORKING PAPERS AND WORKS IN PROGRESS

"Institutional change, industrialization and structural change out of agriculture" with Michael Reed and Yoko Kusunose

"Spatial urban development and transformation of African agriculture: A view from space" with C. Boone

"Trade effects of food regulations and standards: Assessing the impact of SPS measures on market structure" With Y. Zheng , and M. Reed

"Cross - markets transmission of price and price volatility in international grain markets" with M. Reed

“Foreign aid effectiveness in African economies: evidence from a threshold panel” with R. Anago

“Dust in the brain? Early childhood exposure to micro particles and educational performance in West Africa”

“Is young always better? Farmers’age - productivity profile in African agriculture”

PRESENTATIONS

2017	Agricultural and Applied Economics Association, Chicago, IL
2016	African Economic Conference, Abuja, Nigeria
2016	Agricultural Association Applied Economics Association, Boston, MA
2016	Southern Agricultural Economics Association, San Antonio, TX
2015	Centre for the Study of African Economies, Oxford - United Kingdom
2014	African Economic Conference, Addis Ababa, Ethiopia
2014	UNCTAD Workshop, Geneva, Switzerland
2014	Young African Statistician Conference, Pretoria, South Africa
2014	Agricultural and Applied Economics Association, Minneapolis, MN
2013	African Association of Agricultural Economists, Hammamet, Tunisia
2013	Africa Rice Congress, Yaoundé, Cameroon
2013	Kentucky Economics Association Annual Conference, Frankfort, KY
2013	World Statistics Congress, Hong Kong, China
2012	Kentucky Economics Association, Georgetown, KY

TEACHING EXPERIENCE

University of Kentucky	
Teaching assistant	Spring 2017, Fall 2016, Spring 2016
Trainer PAM - Haiti	March and August 2016
Workshop Leader	Fall 2013
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African Rice	
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FELLOWSHIPS AND AWARDS

2012-2017	Graduate Research Assistantship, University of Kentucky
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2011-2012	AERC/UNU-WIDER Research Grant
2006-2009	Best Student Award, MSc Studies at ISSEA
2006-2009	Excellence Scholarship, Government of France
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2002	Silver Medal, 12th Pan-African Mathematics Olympiad

ADDITIONAL INFORMATION

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Memberships	Agricultural and Applied Economics Association (AAEA) Southern Agricultural Economics Association (SAEA) African Association of Agricultural Economists (AAAE) African Finance and Economic Association (AFEA) Fellow, Cornell University STAARS Program Research Affiliate, IFPRI-AGRODEP