Does Minimum Tillage with Planting Basins or Ripping Raise Maize Yields? Meso-panel Data Evidence from Zambia

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EXECUTIVE SUMMARY

Raising agricultural productivity to meet growing food demands while increasing the resilience of rain-fed farm systems to climate variability is one of the most pressing contemporary development challenges in Sub-Saharan Africa (SSA). Anchored on the three core principles of minimum tillage (MT), crop residue retention, and crop rotation; conservation agriculture (CA) technologies have been actively promoted over nearly the last two decades as potential solutions to raise farm productivity in the context of increased climate variability. Despite the long CA promotion histories in the region, there is a dearth of evidence of its yield impacts on smallholder farmers' plots and under typical smallholder management practices and conditions. In this paper, we examine the yield effects of CA under smallholder systems in Zambia. In particular, we assess the effects of MT on maize yields under smallholder conditions in Zambia. Maize is the most widely grown smallholder crop in Zambia, while MT is the most prevalent component of CA practiced by smallholders.

Whether CA does indeed raise farm productivity under real smallholder farm conditions in SSA has been the subject of intense debates over the recent past. The intensity of these debates is, in large measure, the result of limited and at times contradictory empirical evidence. Indeed, the bulk of the evidence on CA is derived from experimental plots, based on small samples and relies on bivariate mean comparisons. This paper uses nationally-representative survey data from nearly 48,000 smallholder maize plots from 2008-2011 to estimate the *ceteris paribus* effects of planting basins and ripping on maize yields in Zambia. These data are drawn from the Ministry of Agriculture and Livestock and the Central Statistical Office's crops forecast surveys and are panel at the standard enumeration area (SEA) level for the period under consideration. The large sample and meso-panel structure of the data[1], respectively, allow the current analysis to benefit from asymptotic properties and thereby obviate the small sample biases, and to exploit panel data methods to control for higher order unobservables that may confound the results.

After applying a pooled ordinary least squares-correlated random effects approach to control for time invariant unobserved heterogeneity at the enumeration area level, we find positive maize yield gains from minimum tillage over conventional tillage methods when tillage is done before the onset of the rains (holding other factors constant). When tillage is done *before the rains*, rip tillage confers average maize yield gains over conventional plow tillage of 577 kg/ha nation-wide, and 821 kg/ha in agro-ecological zones 1 and 2a (the two zones most suitable for CA). Planting basins also increase maize yields relative to conventional hand-hoe tillage when tillage is done before the onset of the rains, but the yield gains are smaller at an average of 191 kg/ha nation-wide, and 194 kg/ha in agro-ecological zones 1 and 2a. A caveat in interpreting these results is in order because they represent the average sample *ceteris paribus* effects under smallholder farm conditions regardless of farmers' past experience with the technologies.

The results of this paper suggest that MT combined with early land preparation can substantially raise smallholder maize yields in Zambia relative to conventional hand-hoe tillage and plowing. Results also suggest that the realizable *ceteris paribus* yield gains of minimum tillage under smallholder farm conditions are only attainable if farmers follow the recommended agronomic practices. While the results in this paper suggest that minimum tillage could help to raise maize yields in Zambia, further analysis is needed to establish whether these yield gains are large enough to offset the potentially higher costs, such as increased labor demands in the first years of adoption, associated with minimum tillage.

[1] Because it is panel at the standard enumeration area level.

Given the main findings of the paper, that minimum tillage can boost yields over conventional tillage methods *if tillage is done before the onset of the rains*, there is need to emphasize this critical factor in extension messaging about ripping and planting basins and to demonstrate its potential benefits where the technologies are appropriate. Finally, given the larger yield benefits of ripping over conventional plowing (compared to the yield benefits of planting basins over conventional hand-hoeing), policies and programs to improve the availability and accessibility of rippers and ripping services could play a key role in boosting smallholders' maize yields in Zambia.

CONTENTS

LIST OF TABLES

TABLE **PAGE**

LIST OF FIGURES

FIGURE **PAGE**

LIST OF ACRONYMS

AEZ	Agro-ecological zone
CA	Conservation agriculture
CDF	cumulative distribution function
CF	Conservation Farming
CFS	Crop forecast survey
CRE	Correlated random effects
FE	fixed effects
FGD	Focus Group Discussions
kg/ha	kilograms/hectare
MAL	Ministry of agriculture and livestock
MT	Minimum tillage
RALS	Rural Agriculture Livelihoods Survey
SEA	Standard Enumeration area
SS	Supplemental Survey
SSA	Sub-Saharan Africa

1. INTRODUCTION

Food and agricultural systems in Sub-Saharan Africa (SSA) are under mounting pressure. Throughout the region, smallholders must increasingly contend with the interrelated challenges of climate change and increasing climate variability, declining soil fertility, and declining land availability. At the same time, rising and more volatile food prices, coupled with higher food demand resulting from population and per capita income growth, place increased pressure on domestic production systems (Deininger 2013; Laurance, Sayer, and Cassman 2013). Under these conditions, it is essential to develop strategies to substantially increase crop yields, while at the same time increasing the resilience of rain-fed farm systems to climate variability. Farm productivity levels in SSA suggest that significant opportunities exist to meet this challenge. For example, Deininger (2013) demonstrates that current smallholder productivity is less than 25% of its potential in Africa's sparsely populated countries such as the Democratic Republic of Congo, Zambia, Tanzania, and Sudan.

Conservation agriculture (CA) technologies are increasingly seen as a potentially effective strategy to address low agricultural productivity in SSA, while enhancing smallholders' capacity to mitigate and adapt to the effects of climate change (Corbeels et al. 2014; Friedrich, Derpsch, and Kassam 2012; Giller et al. 2011; Thierfelder and Wall 2010; Verhulst et al. 2012). CA technologies are based on three core principles of: (i) no or minimal mechanical soil disturbance; (ii) permanent soil cover or crop residue retention; and (iii) crop diversification or rotation (Haggblade and Tembo 2003).

Despite the potential benefits of CA and almost three decades of its active promotion in SSA (Grabowski and Kerr 2013; Umar et al. 2011), CA adoption remains low (Kassam et al. 2009). Even in Zambia and Zimbabwe - the two countries often highlighted for the diffusion of CA technologies (Andersson and D'Souza 2014; Arslan 2014; Giller et al. 2009; Knowler and Bradshaw 2007). For example, national estimates in Arslan et al. (2014) suggest a 5% CA tillage use rate in 2008 in Zambia, while Ngoma, Mulenga, and Jayne (2014) found less than 10% minimum tillage use rates between 2008 and 2012 in the Zambian districts with the highest use rates. These rates are far below the government target of 40% CA adoption by 2016 (GRZ 2013). However, adoption estimates from within CA project areas are much higher, as expected. For example, Kasanga and Daka (2013) suggest 41% MT adoption in the 16 districts. Kuntashula, Chabala, and Mulenga (2014) and Grabowski et al. (2014), respectively, found 12% and 13% adoption in their study areas in agro ecological zones 1 and 2a.

Generally, less than 1% of cropland is under CA in Zambia and Zimbabwe compared to over 50% in South America (Corbeels et al. 2014). Furthermore, CA adoption in SSA is partial (Andersson and D'Souza 2014; Grabowski and Kerr 2013; Umar et al. 2011). For example, Arslan et al. (2014) found that only 3% of the farmers used the two principles of minimum tillage and crop rotation in 2008 in Zambia.

Despite low current adoption rates, the promotion of CA practices remains a cornerstone strategy in SSA for raising smallholder crop productivity under heightened climatic variability. Yet, the empirical evidence on the productivity impact of CA among smallholder farmers in SSA remains mixed (Andersson and D'Souza 2014; Brouder and Gomez-Macpherson 2014; Giller et al. 2009). Indeed, if CA is having little or no impact on smallholder productivity, this may be a key reason for its low uptake. Some studies suggest that CA offers clear pathways towards higher productivity among resource poor smallholder farmers because it optimizes input use, reduces peak season labor demands and improves water harvesting (Friedrich, Derpsch, and Kassam 2012; Haggblade, Kabwe, and Plerhoples

2011; Umar et al. (2012). Others question the suitability of CA for real smallholder farm conditions. This latter body of literature contends that there is little empirical evidence that CA raises crop yields under real farm conditions; rather, most of the evidence comes from experimental on-station or on-farm trials. These often involve higher levels of input use, weeding, and other crop management skills than is typical of smallholder farms in SSA (Andersson and Giller 2012; Giller et al. 2009). Moreover, higher yields combined with higher input use do not necessarily raise total farm productivity and income. Additionally, some studies suggest that, to the extent that CA does offer yield benefits, those benefits may only be realized in the medium to long term (Giller et al. 2009; Thierfelder, Mwila, and Rusinamhodzi 2013).

This could further discourage CA use among African smallholders, many of whom are thought to have high discount rates and very short planning horizons due to poverty and imperfect credit markets (Holden and Lunduka 2014).[2] The emerging consensus is that CA may improve productivity under some conditions, but that these conditions may not be ubiquitous on African smallholders' farms (Andersson and Giller 2012). Overall, the empirical evidence base for the productivity effects of CA under real smallholder farm conditions in SSA remains thin.

This paper seeks to bolster that evidence base and contribute to the debate over the suitability of CA for African smallholders by analyzing the maize yield effects of some CA technologies using survey data from smallholders in Zambia. In particular, the paper examines the yield effects of planting basins and ripping, the two most important minimum tillage CA practices in Zambia.[3] Planting basins and ripping are tillage systems with minimal soil disturbance save for permanent planting stations /basins and rip lines, respectively. Basins are dug using manual labor[4] while rip lines made by animal draft or mechanical-drawn rippers. Henceforth, we refer to planting basins and ripping collectively as minimum tillage (MT).

We focus on MT because it is a necessary condition for any CA-based farming system. The paper aims to estimate econometrically the *ceteris paribus* effects on maize yields of ripping and planting basins versus conventional tillage methods (especially plowing and hand-hoeing) under typical smallholder farm conditions. We focus on maize because it is the country's main staple food and arguably the most economically and politically important crop in Zambia.

Our paper is not the first empirical study of the effects of CA tillage methods on maize yields in SSA or Zambia. We group the previous studies into three main categories, those based on: (i) experimental plots; (ii) case studies or seasonal snapshots; and (iii) those based on nationally representative observational data but that are not specifically focused on

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[2] For further information regarding debates surrounding CA, see http://conservationag.wordpress.com/2009/12/01/ken-gillers-paper-on-conservation-agriculture/ (last accessed August 2014).

[3] Although zero tillage is another variant of minimum tillage CA practiced in Zambia, we focus only on ripping and planting basins in this study because our data do not distinguish between CA zero tillage and a similar traditional shifting cultivation system known as Chitemene. Chitemene is a slash-and-burn system where trees are cut in a large area and then piled on a smaller area and burnt. Crops are then grown in the ash for a few years, before moving on to the next site while leaving old sites in fallow (Holden 1993). So as not to confound CA minimum tillage and Chitemene, we exclude from the analysis plots reportedly using 'zero tillage'.

[4] These basins are often dug using Chaka hoes into precise grids of 15,850 basins per hectare (Haggblade and Tembo 2003). Chaka hoes are specifically designed to somewhat ease the digging of deep basins because they have wider blades and are heavier than regular hand hoes (Umar et al. 2012). Some farmers use regular hand hoes to dig planting basins.

explaining the influence of tillage methods on yields. The first category includes cross country studies (Rockström et al. 2009; Thierfelder and Wall 2010) that compare maize yields between CA and conventional tillage plots in Zambia, Tanzania, Kenya, and Zimbabwe. In addition, there are also in-country studies that do the same in Malawi (Ngwira, Aune, and Mkwinda 2012; Ngwira, Thierfelder, and Lambert 2013), and Zambia (Thierfelder, Mwila, Rusinamhodzi 2013), and cross-country studies in Malawi, Mozambique, Zambia, and Zimbabwe (Thierfelder, Matemba-Mutasa, and Rusinamhodzi 2015). Based on experimental plots and bivariate mean comparisons, they find that CA offers maize yield advantages over conventional tillage. This begs the question of whether these results still hold under the real every day-life conditions of smallholders (as opposed to on-station or on-farm experimental plots) and when multivariate regression analysis is used.

The second category focus on a sub-segment of MT adopters and how CA tillage systems offer maize yield advantages among a sub-segment of MT adopters (Haggblade et al. 2011; Haggblade and Tembo 2003; Haggblade et al. 2010; Kuntashula, Chabala, and Mulenga 2014; Shitumbanuma 2013; Umar et al. 2011, 2012). These studies typically use data drawn from case studies of selected areas where CA has been most promoted (Kuntashula 2014), and for one agricultural season. Some of these also focus on MT yield effects, grouping together ripping and planting basins rather than allowing these two fundamentally different tillage methods to have different effects on yields. In third category is econometric analysis of nationally-representative panel data. Burke (2012) investigates the effect of inorganic fertilizer on maize yields but includes tillage variables as controls. He finds no evidence of statistically significant MT effects on maize yields, but MT is not the focus of his study.

The analysis presented in the current paper differs from and compliments previous studies in three main ways. First, unlike studies in category one whose results may not be a true reflection of on-farm conditions, we use farm household survey data that is representative of actual farmer situations. Second, unlike previous studies based on observational data, we attempt to test and control for the potential endogeneity of MT adoption to maize yields and go a step further to estimate the maize yield effects of the individual MT elements as opposed to lumping them together. We also go a step further to provide perspectives at national level and for agro-ecological zones 1 and 2a, (the two zones most suitable for CA). Third, the current study complements available case study or seasonal snapshot analyses in category two by using the newer and more extensive data of nearly 48,000 maize plots from 2008-2011.

These data are statistically representative at both national and district levels, and are from the Central Statistical Office/Ministry of Agriculture and Livestock - Crop Forecast Surveys (CFS). The data are a panel at the standard enumeration area (SEA) [5] level, and are the best data available to give the big picture of *MT usage as main tillage at plot level* by smallholder farmers in all districts and agro-ecological zones in Zambia. Use of these data rather than the data used in previous analyses is important because: (i) it allows us to analyze the effects of MT on maize yields over a longer time horizon and across the country and beyond CA promotional project sites; (ii) the large sample size allows our analysis to benefit from asymptotic properties, thereby, reducing many statistical and econometric problems common in small samples; and (iii) it also allows us to exploit the meso-panel data structure of the data to control for some time-constant unobserved factors that may confound the results.

[5] SEAs typically contain 150-200 households or about 2-4 villages.

Exploiting the higher order panel structure of a national crop survey is also a methodological contribution, and an approach that could be replicated in other countries in SSA.

The remainder of the paper is organized as follows:

- Section 2 presents a brief background on CA in SSA with a focus on Zambia;
- data and methods are described in sections 3 and 4, respectively;
- results are presented in section 5; and
- conclusions and policy implications are drawn in section 6.

2. DEVELOPMENT AND PRODUCTIVITY IMPACT OF CONSERVATION AGRICULTURE IN SUB-SAHARAN AFRICA

2.1. Development and Promotion of CA in Sub-Saharan Africa

Many SSA countries have fairly long histories of active CA promotion among small scale farmers (see Andersson and D'Souza (2014) for a readable account on the development of CA in SSA). Despite different initial motives for CA promotion across countries, for example food security-enhancing humanitarian motives in Zimbabwe; agricultural production intensification in Malawi; and addressing land degradation, water scarcity, and productivity losses in Zambia (Andersson and D'Souza 2014; Haggblade and Tembo 2003), the objectives of increasing agricultural productivity and sustainably intensifying agricultural production are central components of all CA promotion efforts in the region.

In the Zambian context, CA research and development started around mid-1980s but it wasn't until the 1990s that full scale promotion among smallholder farmers started in the drier agro-ecological zones (AEZs) 1 and 2a (Haggblade and Tembo 2003). CA is based on the three core principles of no or minimum tillage, permanent soil cover or crop residue retention, and crop rotation or diversification. Planting basins and ripping are the two most commonly practiced forms of minimum tillage in Zambia (Ngoma, Mulenga, and Jayne 2014). The planting stations are supposed to be placed in permanent positions so that farmers can use the same stations year after year, thereby reducing labor requirements past the first year (Haggblade and Tembo 2003). These permanent planting stations optimize input use, improve water retention, and help to build up soil organic matter. Basin and rip tillage operations are supposed to be done soon after harvest when soils are still moist. Dry season land preparation facilitates early planting which improves yields (Nafziger 1994), and allows crops to benefit from the initial nitrogen flush in the soil that comes with the first few rains, a phenomenon also known as the "Birch Effect" (Birch 1964; Jarvis et al. 2007). It also allows farmers to use freely available family labor during the lean season (Haggblade et al. 2011). CA crop residue retention involves leaving at least 30% of residues in the fields.

Recommended crop rotations involve cereal-legume crop rotations. Legumes are important to replenish soil nutrients, especially nitrogen. Agroforestry is another important aspect of CA and involves intercropping of cereals with nitrogen-fixing tree species such as *Sesbania sesban*. [6] Despite this long history of CA promotion in Zambia and much of SSA, evidence of its adoption and productivity impacts remains mixed. The next subsection reviews the evidence on the latter.

2.2. Productivity Impacts of CA in Sub-Saharan Africa

The emerging consensus in the existing literature is that CA-based farming systems have the *potential* to increase crop yields relative to conventional farming systems *under certain conditions* (Kassam et al. 2009). However, there is less agreement in the literature about the magnitude of the yield impacts and how many years it takes from initial adoption of CA to the realization of yield benefits. For example, recent studies find significant CA yield benefits

[6] The term conservation farming (CF) is also frequently used in the literature and especially in Zambia. Some groups use CF and CA interchangeably while others make a distinction between the two. In the latter case, CF involves minimum tillage practices in conjunction with crop residue retention and crop rotations with legumes, and CA is CF plus agroforestry. The differences are not important in the context of the current paper, and we use the terms CA and CF interchangeably.

after two or more years (Brouder and Gomez-Macpherson 2014; Corbeels et al. 2014; Thierfelder, Mwila, and Rusinamhodzi 2013), with negative to neutral yield advantages in the short term. In Thierfelder, Mwila, and Rusinamhodzi (2013), long term CA trials in the southern and eastern parts of Zambia were found to confer significant yield advantages only after two seasons. In contrast, anecdotal evidence from CA proponents suggests that CA confers immediate yield benefits. The CA yield advantages are attributed to improved water infiltration, soil moisture, soil porosity, soil organic matter, and crop management (Corbeels et al. 2014; Thierfelder, Mwila, and Rusinamhodzi 2013).

In Zambia, studies on productivity impact of CA technologies have been plagued by challenges in defining CA adoption. For example, some studies do not mention how CA adoption is defined and measured or for how long adopters have used the practices, and what proportion of cultivated land is under CA among adopters. Yet others equate adoption of MT to adoption of CA, even if farmers do not practice other CA principles, see Umar et al. (2011). Such definitions may lead to overestimates of CA adoption by including farmers who are only experimenting with the technologies. While some studies isolate the individual elements of CA, others do not, making it difficult to determine which CA component(s) is (are) responsible for the yield effects.

Evidence on the yield effects of MT in Zambia is mixed. For example, use of basins was found to confer maize yield advantages in (Haggblade et al. 2011; Haggblade and Tembo 2003; Umar et al. 2011), but not in Burke (2012), while use of MT (in general) was found to increase maize yields in Kuntashula, Chabala, and Mulenga (2014). Additionally, experienced CF adopters were found to have as much as 2,000 kilograms/hectare (kg/ha) yield advantage over less experienced CF farmers and conventional farmers based on bivariate mean comparisons on data collected by taking physical measurements of plot sizes and harvest in Shitumbanuma (2013). Most of the aforementioned studies are based on small samples and seasonal snapshots, and draw their samples from within concentrated CA promotion areas. Others rely on experimental data, which has low external validity and can therefore offer only limited insights on the impacts of CA on real farmer conditions. This paper therefore approaches the productivity impact of CA from an empiricist’s perspective while paying particular attention to definitional and estimation issues that may confound extant empirical results.

3. DATA

3.1. Sources

This study uses data from the annual Crop Forecast Surveys (CFS) conducted by the Ministry of Agriculture and Livestock (MAL) and the Central Statistical Office for the period 2008 to 2011 (i.e., the 2007/08 through 2010/11 agricultural years). During this period, the CFS was conducted in the same standard enumeration areas (SEAs) each year. The CFS data are the most current and largest farm household survey data sets available in Zambia, allowing analysis of actual smallholder farm conditions across time and space.[7] The CFS is conducted between February and April each year and collects basic demographic information (household size, and gender, age, and marital status of household members) and detailed information on households' crop production activities (area planted, input use, tillage method, whether land preparation was done before or during the rainy season, etc.). Sampling for the CFSs is discussed below.

A limitation of the CFS data is that it is mainly a production-oriented survey, as opposed to an incomes- or livelihoods-oriented survey; as such, the CFS does not capture detailed socio-economic and demographic information. However, the CFS does capture data on the most important maize yield determinants in the Zambian context. We therefore do not anticipate major issues with omitted variable bias. A second limitation of the CFS data is that the survey is conducted before harvest but after maize plants have reached physiological maturity. Production quantities are therefore based on farmers' estimates of how much they expect to harvest (as opposed to actual quantities harvested). Fortunately, comparisons of farmers' production estimates in the CFS to actual production quantities captured in post-harvest surveys suggest only small and non-systematic differences between expected and actual production (Zulu and Sitko 2014) [8].

Another potential limitation of large scale surveys like the CFS is that the sampling protocols used do not take into account the clustering of agricultural technologies like CA (Grabowski et al. 2014). While this might be a serious concern if one were trying to estimate aggregate adoption rates, it is not a major concern here because we are focused on the yield impacts of minimum tillage among sampled farmers. Despite these limitations, we think that the CFS data are the best data available to address the core research question of this study (what are the *ceteris paribus* effects of ripping and planting basins on maize yields in Zambia) because the CFS data provide the most up-to-date, widest, and statistically representative coverage of smallholder farmers at national, provincial, and district levels in Zambia.

In the econometric analysis, we supplement the CFS data with dekadal (10 day period) rainfall data provided by the Zambia Meteorological Department from 36 rainfall stations throughout the country. Descriptive results are from the CFS as well as from the 2008 Supplemental Survey (SS) and the 2012 Rural Agricultural Livelihoods Survey (RALS), both of which are nationally representative surveys of smallholder farm households. See Mason and Tembo (2014) for details on the SS and RALS. In the discussion of the results, we also draw on information collected during focus group discussions (FGDs) held with 57 farmers

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[7] Smallholder farm households are defined as those cultivating less than 20 ha of land.

[8] We use data from the CFS instead of from the Supplemental Survey (SS), a three-wave household-level longitudinal survey of smallholders, because those data are more dated (they cover the 1999/2000, 2002/03, and 2006/07 agricultural seasons) and are not representative at the district level. The CFS data are more recent and are representative at the district level. The CFS better captures changes over time and space in the use of CA in Zambia. The tradeoff is that while the SS data would allow us to control for time-constant unobserved effects at the household level, the CFS data only allow us to control for such effects at the SEA level.

in Chipata, Choma, and Chongwe districts in August 2014. Of these 57 farmers, 27 were consistent users of CA each year since 2009; the remaining 30 either never used CA or used it in only a subset of years. We held separate FGDs with each of the three farmer groups in all the districts visited. The three districts in which the FGDs were conducted had some of the highest variability in MT use rates in Zambia between 2008 and 2012 (Ngoma, Mulenga, and Jayne 2014). Participants in the focus group discussions were selected with the help of camp extension officers in the districts.

3.2. Sampling

Sampling for the 2008-2011 CFSs was based on the 2000 Census of Housing and Population. The sampling frame mainly included rural SEAs, but urban SEAs with 70% or more of their households engaged in agricultural activities were also included. A two-stage cluster sampling scheme was used. In the first stage, 680 SEAs were selected out of a total of 12,789 SEAs nationwide using probability proportional to size, with the number of agricultural households serving as the measure of size. At the second stage, all households in selected SEAs were listed and agricultural households identified. Listed agricultural households were then stratified into three categories, A, B, and C, on the basis of total area under crops; presence of some specified special crops; numbers of cattle, goats and chickens raised; and sources of income. Systematic sampling was then used to select 20 households distributed across the three strata in each SEA. This resulted in a total national sample size of 13,600 households per year and a total of 51,156 maize plots between 2008 and 2011.

3.3. Data Processing and Caveats

We put the data through a series of filters to prepare it for use in the analysis. Starting with 51,156 maize plots owned by 37,169 households in panel SEAs between 2008 and 2011, we dropped 5% of the fields with seed rates exceeding 100 kg/ha; 0.08% which did not report any seed used; 0.7% with yields greater than 8,000 kg/ha; 0.4% and 0.1% with basal and top dressing application rates, respectively, exceeding 400 kg/ha; and two fields that were larger than 20 ha. These cutoff points were determined based on reasonable input use and yield rates in Zambia and on the basis of recommendations by MAL.[9] Altogether, these changes resulted in the exclusion of 3,197 maize plots (or 6.2% of the original sample), bringing the analytical sample to 47,959 total maize plots. This data filtering is within acceptable levels; for example, Sheahan, Black, and Jayne (2013) excluded 9.7% of observations from their original sample after implementing similar cutoffs for a study of factors affecting maize yields in Kenya.

[9] The recommended maize seeding rate in Zambia is 20 kg/ha, and the recommended fertilizer application rates are 200 kg/ha each of basal and top dressing. Fields larger than 20 ha were excluded because these exceed the definition of a smallholder farmer (i.e., those cultivating less than 20 ha of land).

4. METHODS

4.1. Conceptual Framework

The main objective of this paper is to estimate the *ceteris paribus* effects of planting basins and ripping on smallholder maize yields in Zambia. This is accomplished through econometric estimation of a maize production function following Xu et al. (2009) and Burke (2012) for Zambia, and Sheahan (2013) for Kenya. The general production function is specified as

$$y = f(\boldsymbol{tillage}, \boldsymbol{X}, \boldsymbol{Z}) \quad (1)$$

where y is field-level maize yield in kg per ha; ***tillage*** is a vector of dummy variables capturing the tillage method used on the field (i.e., planting basins, ripping, and various conventional tillage methods), and capturing the timing of when tillage was done (i.e., before or during the rainy season); ***X*** is a vector of inputs controlled by the farmer (e.g., use of hybrid seed, fertilizer application and seeding rates, labor quantity and quality, etc.); and ***Z*** is a vector of strictly exogenous yield determinants such as rainfall and other agro-ecological conditions (Burke 2012). The specific variables included in ***tillage***, ***X***, and ***Z*** are discussed in detail in the next sub-section. A quadratic functional form is used for the production function in equation (1). As discussed in Sheahan, Black, and Jayne (2013), the quadratic functional form is generally thought to be a good approximation of the underlying data generating process of crop yields and is frequently used in analyses of crop yield response in developing countries. See Burke (2012) and Xu et al. (2009) for other applications of the quadratic production functions in yield estimation in Zambia.

4.2. Empirical Model

Bringing equation (1) to the data, we represent the empirical model as:

$$y_{sij} = \boldsymbol{tillage}_{sij}\boldsymbol{\beta}_1 + \boldsymbol{X}_{sij}\boldsymbol{\beta}_2 + \boldsymbol{Z}_{sij}\boldsymbol{\beta}_3 + \boldsymbol{year}\boldsymbol{\beta}_4 + c_s + u_{sij}, \quad (2)$$

where y_{sij} is the maize yield in kg/ha in SEA s for household i on plot j, and we have excluded time-subscripts to indicate the fact that the data are a panel at the SEA-level and not at the household- or plot-level. ***tillage***, ***X***, and ***Z*** are defined as in equation (1) above; ***year*** is a vector of year dummies; c_s is unobserved time invariant SEA-level heterogeneity; u_{sij} is the idiosyncratic error term; and the $\boldsymbol{\beta}$'s are parameters to be estimated.[10]

The specific explanatory variables included in the production functions estimated here were selected based on previous studies on the determinants of smallholder maize yields in eastern and southern Africa (Burke 2012; Sheahan, Black, and Jayne 2013; Xu et al. 2009), agronomic principles of maize production in Zambia, and data availability. Table 1 presents summary statistics for the variables used in the regressions. The dependent variable, plot-level maize yield, averaged 1,796 kg/ha over the four-year study period.

[10] To keep the notation simple, we have also excluded the squared and interaction terms from equation (2) but they are included in the estimated models.

Table 1. Variables Used in the Econometric Analysis

Variable	Description	Mean	Std. dev.	p10	p25	p50	p75	p90
yield	Maize yield (kg/ha)	1796.52	1460.26	283.95	690.00	1419.75	2555.56	3904.32
age_hh	Age of hh head (years)	43.84	14.45	27.00	32.00	41.00	53.00	65.00
sex_hh	Male hh head (=1)	0.79	0.41	0.00	1.00	1.00	1.00	1.00
p_married	Polygamously married (=1)	0.07	0.26	0.00	0.00	0.00	0.00	0.00
m_married	Monogamously married (=1)	0.70	0.46	0.00	0.00	1.00	1.00	1.00
adults	# adults 14 - 65 years	3.94	2.50	2.00	2.00	3.00	5.00	7.00
b_fert	Used basal fertilizer (=1)	0.43	0.50	0.00	0.00	0.00	1.00	1.00
tp_fert	Used top fertilizer (=1)	0.45	0.50	0.00	0.00	0.00	1.00	1.00
brate	Basal fertilizer rate (kg/ha)	60.50	87.38	0.00	0.00	0.00	100.00	200.00
tprate	Top fertilizer rate (kg/ha)	62.74	87.46	0.00	0.00	0.00	123.46	200.00
seedingrate	Seed rate (kg/ha)	21.06	17.16	4.68	10.00	17.40	25.00	46.40
hyb_seed	Used hybrid seed (=1)	0.45	0.50	0.00	0.00	0.00	1.00	1.00
aez3	AEZ 3 (=1)	0.34	0.21	0.00	0.00	0.00	1.00	1.00
aez2a	AEZ 2a (=1)	0.48	0.07	0.00	0.00	0.00	1.00	1.00
aez2b	AEZ 2b (=1)	0.07	0.50	0.00	0.00	0.00	0.00	0.00
aez1	AEZ 1 (=1)	0.11	0.47	0.00	0.00	0.00	0.00	1.00
rain	Season rainfall (mm)	1020.46	0.50	666.00	792.00	982.00	1172.00	1329.00
rain_stress	Rainfall season stress periods (#)	1.03	0.25	0.00	0.00	1.00	2.00	3.00
plot_size	Plot size (ha)	0.93	0.31	0.25	0.38	0.60	1.00	2.00
t_till	Tillage before rains (=1)	0.30	0.46	0.00	0.00	0.00	1.00	1.00
bund	Used bunding (=1)	0.02	0.14	0.00	0.00	0.00	0.00	0.00
ridge	Used ridging (=1)	0.28	0.45	0.00	0.00	0.00	1.00	1.00
pl_basins	Used planting basins (=1)	0.01	0.12	0.00	0.00	0.00	0.00	0.00
ripping	Used ripping (=1)	0.01	0.08	0.00	0.00	0.00	0.00	0.00
plow	Used plowing (=1)	0.33	0.47	0.00	0.00	0.00	1.00	1.00
hhoe	Used hand hoe (=1)	0.34	0.46	0.00	0.00	0.00	1.00	1.00

Source: Authors' computations from CFS 2008-2011.

Included in ***tillage***, the vector of tillage-related variables, are separate dummy variables equal to one if the plot was tilled using planting basins, ripping, plowing, bunding, or ridging. Conventional hand hoe tillage is the base tillage method and therefore excluded from the regressions[11]. As indicated in Table 1, the vast majority of maize plots were tilled using conventional tillage methods: 31%, 33%, and 28% were tilled by hand hoe, plowing, and ridging, respectively. About 2% of plots were tilled via bunding, and only 1% of plots each were tilled with ripping and planting basins. Also included in ***tillage*** is a dummy equal to one if the field was tilled before the onset of the rainy season, and equal to zero if the field was tilled during the rainy season. Overall, 30% of the plots in the sample were tilled before the rains (Table 1). Of these, 52%, 23%, 12%, and 43% under basins, ripping, plowing, and hand hoeing, respectively, were tilled done before the rains. To capture potential differential effects of tillage method on yields depending on when tillage is done, we interact the tillage method dummies with the tillage-before-the-rains dummy.

[11] Does not include chitemene.

Included in ***X***, the vector of other yield determinants under the control of the farmer, are basal and top dressing inorganic fertilizer application rates (kg/ha), whether hybrid maize seed was used (=1), and the seeding rate for all types of seed (kg/ha). On average, households used 61 kg/ha of basal dressing, 63 kg/ha of top dressing, 21 kg/ha of maize seed, and 20 kg/ha of seed. Overall, less than half of the smallholder population used fertilizer and hybrid seed over the study period. *A priori*, increases in the fertilizer and seed application rates are expected to increase maize yields up to a point, beyond which decreasing marginal returns are likely to set in. The quadratic functional form allows for such effects. Our models also include interactions between basal and top dressing fertilizer to capture the effects of combined fertilizer application. We include interactions of hybrid seed use and fertilizer application rates to capture the combined effects of improved input use.

Also included in ***X*** are the area of the plot (ha), and proxies for household labor quantity and quality, namely: the number of adults (15-65 years) in the household (3.94 on average); the age of the household head (44 years on average) – older household heads may have more farming experience but may be less amenable to new management practices such as MT; a dummy equal to one if the household is male-headed (79% of the sample); and dummies for whether the household head is monogamously married (70%) or polygamously married (7%); the remaining household heads are not married. We hypothesize that households with heads that are polygamously married might have more family labor available for maize production than households with monogamously married heads. Households with married households heads might have more family labor available than households with unmarried heads. The CFS data do not consistently capture information on labor input to maize production, so we use the marital status variables and number of adults as proxies.

Included in ***Z***, the vector of strictly exogenous yield determinants are growing season rainfall in millimeters (November to March) and rainfall stress measured as the number of 20-day periods during the growing season with less than 40 mm of rainfall. The former is expected to increase yields up to a point, while the latter is expected to reduce yields. We also control for different soil and rainfall conditions by including dummies for AEZs 2a, 2b, and 3 (with AEZ 1 serving as the base). Year dummies (***year*** in equation 2) are included in the empirical model to control for year-specific yield effects.

Due to data limitations, we are not able to explicitly control for the number of times a plot is weeded, whether or not the plot is irrigated, or the use of herbicide, other crop protectants, or lime on the plot. To a certain extent, the labor quantity-related variables serve as proxies for the number of weedings. Very few smallholder plots in Zambia are irrigated, and use of herbicide (2% according to RALS12), crop protectants, and/or lime is very rare among Zambian smallholders. There is also evidence suggesting that the majority of farmers using herbicides are under- and mis-applying it (Umar et al. 2011).

We also do not observe in the CFS data the number of years in which a given plot has been under planting basins or ripping. Thus, our estimates of the effects of these tillage methods on maize yields should be interpreted as averages for plots currently under the tillage method.

4.3. Estimation Strategy

The empirical model is linear in parameters and is estimated via pooled ordinary least squares with standard errors clustered at the SEA level. We estimate models using all observations (national-level model) as well as models using only observations from the two AEZs where CA has been most heavily promoted and is arguably most suitable (AEZs 1 and 2a).

The major econometric challenge in estimating the causal effects of planting basins and ripping on maize yields is the potential endogeneity of farmers' tillage method choices. Tillage methods are not randomly assigned to households or fields, and there may be systematic correlation between farmers' use of planting basins and ripping (and other tillage methods and inputs) and unobserved factors affecting maize yields. For example, farmers that are more motivated or progressive, or have greater farming skill or management ability, may be more likely to adopt planting basins or ripping, but would likely have higher yields than other farmers even if they used conventional tillage methods. (We use the age and gender of the household head to proxy for these factors.) As a second example, use of MT on a given plot could be correlated with unobserved plot-level factors such as soil quality that also affect yields.

To address these concerns, we control for as many observed plot- and household-level maize yield determinants as possible given the available data. While we are somewhat constrained in what we can do to address the potential endogeneity of the observed explanatory variables in equation (2) given that we do not have plot- or household-level panel data, we do have SEA-level panel data. We take advantage of this data structure to control for time invariant SEA-level heterogeneity (c_s) using a correlated random effects (CRE) approach (Chamberlain 1984; Mundlak 1978). The CRE approach or Mundlak-Chamberlain device enables us to control for SEA-level time-invariant unobserved factors c_s affecting maize yields that could be correlated with the observed yield determinants (e.g., average farming management ability, motivation, soil quality, and agro-ecological conditions in a household's SEA).[12] Under the CRE approach, c_s is assumed to be a function of the SEA-level averages (across all time periods) of the time-varying covariates, which are included as additional regressors in equation 2. [13] Further details on the CRE approach can be found in Wooldridge (2010).

While the CRE approach described above allows us to control for correlation between the unobserved time-invariant SEA-level heterogeneity (c_s) and observed factors affecting maize yields, there still may be correlation between the farmer's choice of tillage method and timing (***tillage***) and input use decisions (***X***), and the idiosyncratic error term (u_{sij}). This is a common challenge in production analysis because most right-hand-side variables are choice variables. While some authors acknowledge this potential endogeneity, possibly use CRE, and move on (e.g., Xu et al. 2009; Sheahan, Black, and Jayne 2013), others try to go further and combine the CRE approach with instrumental variables or control function techniques to test and control for the endogeneity of the key covariate(s) of interest (e.g., Burke (2012) for inorganic fertilizer).

In our study, the key covariates of interest are the planting basins and ripping dummy variables. We attempted to follow the latter approach by using a control function approach (Wooldridge 2010) and instrumenting for a farmer's use of planting basins with a dummy variable equal to one if the household is in a district where the CFU has promoted CA and equal to zero otherwise; and by instrumenting for ripping using a dummy variable equal to one if the household is in a district where Dunavant Cotton/NWK Agri-Services Zambia has

[12] While a fixed effects (FE) approach would also have been possible, a CRE approach is generally preferred when using meso-panel data with time-varying sampling weights, as in the current application (personal communication, J. Wooldridge June 2014). Nonetheless, as a robustness check, we estimated the models without sampling weights using both FE and CRE approaches and the results are very similar. Note that both the FE and CRE approaches allow the unobserved time invariant heterogeneity and the observed covariates to be correlated. This is a key difference between the CRE and 'regular' random effects approaches.

[13] As an example, the SEA-level time average of the planting basins dummy would be the proportion of maize plots in the SEA under planting basins over the 2008-2011 study period.

promoted CA and equal to zero otherwise.[14] A priori, where CFU and Dunavant choose to promote CA should be exogenous to plot-level yields after controlling for observed input use levels ($\boldsymbol{X}$), other observed factors ($\boldsymbol{Z}$), and SEA-level time invariant unobserved heterogeneity. CA promotion by CFU and Dunavant is likely to affect a farmer's decision to use planting basins or ripping but is unlikely to be correlated with the idiosyncratic plot-level error term in the yield function. Unfortunately, these IVs were only weakly correlated with farmer's use of planting basins and ripping ($0.05 < p < 0.10$) and the control function results suggested that ripping and planting basin decisions are exogenous to maize yields.[15] As such, and to avoid the bias and inconsistency created by weak IVs (Cameron and Trivedi 2010), we did not pursue this approach further.

[14] Household- or plot-level IVs would have been better but no such IVs are available.

[15] These results are available from the authors upon request.

5. RESULTS

5.1. Descriptive Results

As a prelude to the econometric results of the paper, the bivariate mean comparisons in Table 2 address the question of whether there are systematic differences between MT and non-MT plots in terms of maize yields and/or the main covariates used in the econometric analysis. Based on these bivariate comparisons, there is no statistically significant difference between yields on MT and non-MT plots.[16] Among the explanatory variables, the only statistically significant difference among MT and non-MT plots was in the gender of the household head (MT plots had a slightly higher percentage of male-headed households (83%) compared to non-MT plots (79%)).

Although there are no statistically significant differences between mean yields on MT and non-MT plots in general, there may be differences between specific MT practices and their conventional tillage counterparts – i.e., between planting basins and hand-hoed plots, and/or between ripped and plowed plots.

Table 2. Bivariate Mean Comparisons of Key Variables between Minimum Tillage Plots and Non-minimum Tillage Plots between 2008 and 2011

		Used minimum tillage on plot		
Variable	Description	**No**	**Yes**	p-value
yield	Maize yield (Kg/ha)	1796.99	1772.97	0.701
plot_size	Plot size in ha	0.93	0.95	0.568
age_hh	Age of hh head	43.85	43.58	0.685
sex_hh	Male hh *(yes=1)*	0.79	0.83	0.015
adults	Number of adults per hh	3.95	3.81	0.204
p_married	Polygamously married	0.07	0.08	0.416
m_married	Monogamously married	0.70	0.73	0.140
b_fert	Used basal mineral fertilizer	0.43	0.42	0.810
tp_fert	Used top mineral fertilizer	0.45	0.46	0.762
brate	Basal fertilizer rate (kg/ha)	60.50	60.38	0.976
tprate	Top fertilizer rate (kg/ha)	62.70	64.28	0.710
hyb_seed	Used hybrid maize seed	0.45	0.46	0.651
seedingrate	Seeding rate (kg/ha)	21.07	20.75	0.648
rain	Growing season rainfall	1019.83	1052.00	0.110
rain_stress	# of 20 day periods with < 40mm	1.02	1.07	0.431

Source: Authors' computations from CFS 2008-2011.

[16] Throughout the paper and unless otherwise specified, we use p<0.10 as the cutoff of statistical significance.

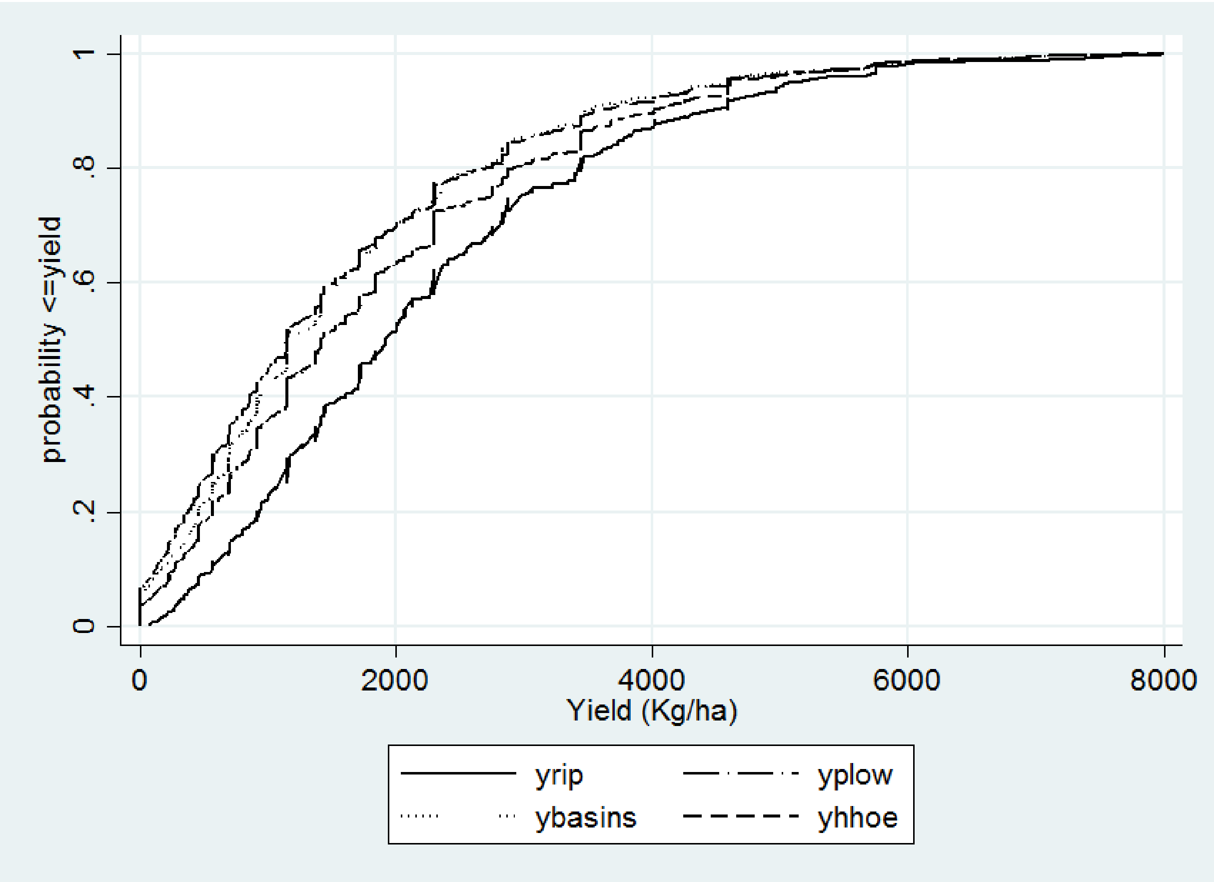
Following Tatwangire and Holden (2009) and Tatwangire (2011), we explore any such differences using the cumulative distribution function (CDF) plots of maize yields under the different tillage options in Figure 1. The ripping CDF lies to the right of the plowing CDF at all yield levels, suggesting that ripping first-order stochastically dominates plowing; that is, farmers would prefer ripping to plowing based on expected maize yield. The ripping CDF also lies to the right of the other tillage CDFs at all yield levels.

While Figure 1 suggests that ripping might offer a yield advantage over plowing, the figure suggests that yields on planting basin plots (without controlling for other factors) are consistently below the yields on conventional hand-hoed plots. This is evident from the planting basins CDF consistently lying to the left of the hand-hoe CDF. Unlike the descriptives presented in this section, the next section presents the multivariate econometric results of the effects of planting basins and ripping on maize yield.

5.2. Econometric Results

We estimated three different specifications of the model in equation (2). The first specification (spec.1) excludes interaction and squared terms. The second specification (spec.2) includes interactions and squared terms for many of the variables but excludes interactions between the tillage method dummies and fertilizer application rate variables.

Figure 1. Cumulative Distribution Functions of Smallholder Farmer Yields by All Tillage Options between 2008 and 2011 in Zambia



Source: Authors' computations from CFS 2008-2011.

The third specification (spec.3) is similar to spec.2 but includes tillage-fertilizer interactions. The results are robust to alternative model specifications, so we focus our discussion of the results mainly on spec.3, which is the most fully elaborated model. The average partial effects (APEs) estimates from the econometric models are reported in Table 3 while coefficients estimates are reported in Table A1 in the appendix. Each table reports the results from the national and AEZs 1/2a models. Because of the large number of interactions and squared terms included in spec.2 and spec.3, caution must be exercised when interpreting individual coefficient estimates in Table A1. For example, the overall effect (APE) of basal dressing fertilizer application rate is reported in Table 3 and not simply to the parameter estimate *brate* in Table A1.

Table 3. Maize Production Function Average Partial Effect (APE) Estimates (Dependent Variable: Maize Yield in kg/ha)

	National			**Agro-ecological zones 1 and 2a**		
Variables	**Spec.1**	**Spec.2**	**Spec.3**	**Spec.1**	**Spec.2**	**Spec.3**
pl_basins (yes=1)	-41.417	-109.654	-112.264	-5.561	-83.107	-73.763
	(69.421)	(70.607)	(75.249)	(74.999)	(68.546)	(71.244)
ripping (yes=1)	186.190*	187.298*	233.789**	276.028**	266.637**	329.941**
	(110.531)	(107.872)	(108.591)	(139.718)	(134.146)	(135.323)
plow (yes=1)	-0.212	-6.720	-4.457	5.162	-6.893	-1.808
	(29.216)	(29.653)	(30.078)	(36.964)	(38.343)	(39.095)
bunding (yes=1)	178.598**	144.869	77.369	496.252***	463.384***	459.146***
	(85.104)	(91.881)	(92.889)	(148.980)	(149.626)	(140.091)
ridging (yes=1)	114.475***	103.386***	98.295***	115.305***	98.279**	100.875**
	(27.539)	(27.959)	(27.862)	(37.262)	(38.744)	(39.837)
Tillage before rains (yes=1)	-22.486	-24.298	-24.450	36.195	19.623	20.203
	(21.171)	(22.812)	(22.732)	(29.686)	(33.435)	(33.374)
hybrid seed (yes=1)	180.629***	147.735***	146.055***	158.678***	137.000***	134.754***
	(22.693)	(23.034)	(22.985)	(29.072)	(29.854)	(29.824)
Seeding rate (kg/ha)	1.879***	0.691	0.749	1.946***	0.583	0.706
	(0.557)	(0.939)	(0.935)	(0.675)	(1.172)	(1.161)
basal fert use rate (kg/ha)	3.128***	4.072***	4.113***	3.180***	3.868***	3.922***
	(0.328)	(0.386)	(0.382)	(0.383)	(0.459)	(0.447)
top fert use rate (kg/ha)	4.832***	4.927***	4.822***	4.962***	5.162***	5.047***
	(0.320)	(0.389)	(0.387)	(0.369)	(0.478)	(0.470)
plot size in ha	-12.730	-39.094***	-39.636***	-13.270	-42.975***	-43.947***
	(9.187)	(13.037)	(12.998)	(11.390)	(16.551)	(16.526)
Growing season rainfall (mm)	0.001	-0.008	-0.009	0.014	0.017	0.011
	(0.106)	(0.108)	(0.108)	(0.145)	(0.147)	(0.148)
# of 20 day periods with < 40mm rainfall	-30.277*	-40.335**	-40.213**	9.666	0.146	-1.978
	(15.913)	(19.994)	(19.917)	(19.554)	(23.420)	(23.455)
Male head (yes=1)	37.179	45.866	44.331	17.066	22.335	19.409
	(29.562)	(29.683)	(29.664)	(40.368)	(40.383)	(40.330)
Age of hh head (years)	-0.290	0.993	0.970	-0.789	-0.080	-0.151
	(0.550)	(0.717)	(0.717)	(0.753)	(1.010)	(1.007)
Polygamously married (yes=1)	44.937	42.823	41.631	54.684	51.440	50.420
	(39.070)	(39.117)	(39.106)	(48.425)	(48.439)	(48.369)
Monogamously married (yes=1)	20.046	20.514	20.893	31.095	33.561	34.286
	(28.883)	(29.119)	(29.056)	(38.584)	(38.818)	(38.711)
Number of adults (15-65 years)	-0.733	-3.044	-2.933	-2.487	-3.984	-3.819
	(3.995)	(5.178)	(5.128)	(4.914)	(6.721)	(6.617)

	National			Agro-ecological zones 1 and 2a		
Variables	**Spec.1**	**Spec.2**	**Spec.3**	**Spec.1**	**Spec.2**	**Spec.3**
2009.year	252.316***	237.026***	239.449***	377.950***	367.354***	370.649***
	(40.945)	(40.979)	(40.921)	(51.572)	(52.882)	(52.394)
2010.year	565.090***	541.306***	543.539***	792.754***	779.171***	776.082***
	(46.990)	(48.263)	(48.302)	(67.339)	(70.312)	(70.444)
2011.year	533.487***	519.053***	519.221***	576.920***	577.220***	581.136***
	(42.154)	(41.840)	(41.439)	(58.691)	(58.404)	(57.552)
AEZ 2a (yes=1)	17.997	45.055	59.577			
	(50.775)	(54.239)	(54.045)			
AEZ 2b (yes=1)	15.609	15.716	-21.610			
	(67.342)	(77.257)	(76.277)			
AEZ 3 (yes=1)	355.503***	345.079***	334.802***			
	(63.136)	(65.732)	(63.375)			
Observations	**47,838**	**47,838**	**47,838**	**25,808**	**25,808**	**25,808**

Source: Authors' computations from CFS 2008-2011.
Notes: Standard errors clustered at the SEA level in parentheses; ***, **, * statistically significant at 1%, 5% and 10%, respectively; base tillage method, based year, and base agro ecological zone are conventional hand hoe, 2008, and AEZ 1, respectively.

5.2.1. Effects of Planting Basins on Maize Yields

The APEs in Table 3 suggest that maize yields on plots using planting basins are not statistically different from the yields on plots using conventional hand hoe tillage, *ceteris paribus*[17]. We, therefore, conclude that compared to hand hoe tillage, use of basins *in and of itself* does not significantly increase maize yields in Zambia.[18] However, we find positive and significant interaction effect between planting basins and tillage before the rains (Table A1). This suggests that planting basins have a more positive effect on yields when tillage is done *before* the rains. For example, the yield boost from planting basins over conventional hand-hoe tillage is 371 kg/ha larger when tillage is done before rather than after the rains. A similar result holds for the AEZs 1/2a model. The simulated marginal effects of planting basins on maize yields (compared to conventional hand-hoeing) when tillage is done before versus after the rains in panel A of Table 4 suggest yield gains of 191-194 kg/ha. This result is significant at the 10% level in the national results but only weakly significant in AEZs 1/2a (p=0.17).

When tillage is done *after* the rains, yields are 179 kg/ha and 168 kg/ha *lower* on planting basin plots than hand-hoed plots in the national-level and AEZs 1/2a models, respectively (Table 4, panel A). Overall, the results suggest that when tillage is done early, planting basins can raise smallholders' yields relative to conventional hand-hoeing. However, improper use of planting basins — which results in late planting and additional weed pressure — does not confer yield advantages over hand hoe tillage, on average. Further, we surmise three reasons for the lower yield effects of basins if tillage is done in the rainy season. First, it may difficult for farmers to dig basins to the required dimensions during the rainy season especially under water-logged conditions and in clay loamy soils. This directly affects plant populations and input use. Second, digging basins after the onset of the rainy season may lead to late planting which negatively affects yields (Nafziger 1994). And third, hand hoe farmers are more likely to use conventional hand hoe tillage compared to basins (if tillage is done after the onset of

[17] All econometric results are drawn from specification 3 unless otherwise stated.

[18] Timing of basin tillage, how well basins are done, timely planting, and input use are key. How long the planting basins have been in place could also affect the yield impacts thereof. However, as mentioned above, the data do not include information on the latter.

the rains) because the former also helps clear all emerging weeds since it involves complete soil inversion.

5.2.2. Effects of Ripping on Maize Yields

The APEs in Table 3 suggest significant and positive ripping effects on maize yields after controlling for other factors. For example, at national level and in AEZs 1/2a, respectively, the maize yields on ripped plots are 234 kg/ha and 330 kg/ha higher than on conventional hand hoed plots. Moreover, compared to yields on plowed plots, yields on ripped plots are 238 kg/ha and 332 kg/ha higher at national level and in AEZs 1/2a, respectively (Table 3). We also find that ripping yield gains over plowing are 481 kg/ha and 653 kg/ha larger when practiced before the rains compared to after the rains at the national and AEZ 1/2a levels, respectively (Table A1). Simulated results in panel B of Table 4 show that yields on ripped fields are 577-821 kg/ha higher than on plowed fields when tillage is done before the rains, *ceteris paribus*. This result is highly significant ($p<0.01$) in both the national and AEZs 1/2a models. However, like planting basins, ripping only confers yield benefits over its conventional analogue when tillage is done before the rains.

5.2.3. Other Maize Yield Determinants

Moving beyond the tillage method effects on maize yields, the results for the other covariates in equation (2) are generally consistent with a priori expectations. Using hybrid maize seed significantly increased average maize yield by 146 kg/ha and 135 kg/ha at national level and in AEZs 1/2a, respectively (Table 3). Similar positive effects of hybrid seed use on yield are reported in (Xu et al. 2009; Burke 2012) for Zambia, and in Sheahan (2013) for Kenya.

Table 4. Marginal Effects on Yields of Planting Basins vs. Hand Hoe Tillage, and Ripping vs. Plowing, by Timing of Tillage (Based on Specification 3 in Table A1)

Panel A: Simulated yield differences (kg/ha) for planting basins (compared to hand hoe tillage) for tillage done before vs. after the rains[a]

	Tillage *before* the rains		Tillage *during* the rains	
	Marginal effect	t-stat.	Marginal effect	t-stat.
National results	191.45*	1.71	-179.25**	-2.21
AEZs 1 and 2a results	194.01	1.42	-168.41*	-1.88

Panel B: Simulated yield differences (kg/ha) for ripping (compared to plowing) for tillage done before vs. after the rains, and with average inorganic fertilizer[b]

	Tillage *before* the rains		Tillage *during* the rains	
	Marginal effect	t-stat.	Marginal effect	t-stat.
National results	576.54***	2.96	95.79	0.77
AEZs 1 and 2a results	820.94***	3.30	167.77	1.11

Source: Authors’ computations from CFS 2008-2011.
Note: [a]The planting basins-fertilizer application rate interaction effects are *not* statistically significant in specification 3, and so are set to zero in these simulations. [b]The ripping-fertilizer application rate interaction effects *are* statistically significant in specification 3; the marginal effects of ripping vs. plowing in the table above are evaluated at the average basal and top dressing fertilizer rates in the sample (61 kg/ha basal and 63 kg/ha top dressing in the national model, and 56 and 59 kg/ha, respectively, in the AEZs 1 and 2a model). ***, **, * statistically significant at 1%, 5% and 10% respectively.

Additionally, results suggest that average maize yield increases by 3-4 kg and 5 kg per additional kg of basal and top dressing fertilizer, respectively (Table 3). We also find existence of a negative plot size-productivity relationship among smallholder farmers in Zambia. Increasing plot area by one hectare significantly reduces average maize yields by 40 kg/ha and 44 kg/ha at national level and in AEZs 1/2a, respectively. Additionally, all else constant, an increase in the number of rainfall stress periods significantly reduced maize yields by 40 kg/ha on average at national level. These results bring to light the need to adapt agricultural systems to increasing rainfall variability in Zambia as highlighted in Chabala, Kuntashula, and Kaluba (2013). And are also in line with findings in Lobell et al. (2008) where maize yields in SSA are projected to decline by 30% owing to climate variability.

5.2.4. Discussion

Our findings that combining MT with early land preparation (early planting) boosts yields are consistent with the CA literature (Haggblade et al. 2011) and are consistent with farmer experiences from the FGDs. Our econometric results for ripping corroborate bivariate findings in (Thierfelder, Mwila, Rusinamhodzi 2013; Umar et al. 2011, 2012) that indicate ripping provides yield benefits over conventional plowing. Our results are contrary to econometric results in Burke (2012), who finds that use of basins and ripping had no statistically significant on yields. Our results are somewhat different from those of Haggblade and Tembo (2003), who find positive planting basin effects but no ripping effects on yields. Our econometric results for basin tillage are also in contrast to bivariate results for planting basin tillage in Umar et al. (2011) that indicate higher maize yields on basin tilled plots compared to hand hoe tilled plots. A plausible explanation for these differences in the results may be the omission of key interaction terms involving all tillage options, timing of tillage, and fertilizer application rates in Burke (2012) and Haggblade and Tembo (2003), and the failure to control for other yield determinants in the studies that rely on bivariate mean comparisons.

Other potential reasons for the differential yield effects of ripping and basins depending on the timing of the tillage may be associated with differing knowledge requirements of the two MT tillage options. Planting basins have to be dug to specific dimensions using hand hoes, but few farmers manage to follow the specifications to the letter as was found in Umar et al. (2012), and Haggblade and Tembo (2003). Farmers also confirmed this during the FGDs where they mentioned that yield benefits are realized only if basins are dug to specifications with timely field operations. Given the main results of the paper that both ripping and planting basins do confer maize yield advantages if the agronomics are right, it remains unclear why so few farmers are adopting MT in Zambia and SSA in general. Albeit an important question, it is beyond the scope of the current paper and we leave it to other researchers to address it.

In summary, our overall results (Table 3) suggest that use of rip tillage confers significant maize yield benefits over common conventional tillage options (especially plowing and hand hoe). Moreover, we found that both ripping and planting basins confer yield benefits over their conventional counterparts (plowing and hand-hoeing, respectively) when tillage is done before the rains, but not when tillage is done after the rains (Table 4). These results reflect the short term effects since we are not able to tell how long farmers have used the different tillage options from the data we have used.

6. CONCLUSIONS AND POLICY IMPLICATIONS

Raising agricultural productivity to meet growing food demands while increasing the resilience of rain-fed farm systems to climate variability is perhaps one of the most pressing contemporary development challenges in Sub-Saharan Africa. Conservation agriculture technologies have been actively promoted for nearly two decades as potential solutions to these problems in the region. Our results suggest that minimum tillage dimensions of CA practices offer viable options for improving smallholder cereal yields, but they are not likely the panacea.

After controlling for time invariant unobserved heterogeneity at the enumeration area level by applying the correlated random effects-pooled ordinary least squares estimator to nationally-representative survey data, we find positive maize yield gains from minimum tillage over conventional tillage methods when tillage is done before the onset of the rains, holding other factors constant. When tillage is done *before* the onset of the rains, rip tillage conferred average maize yield gains of 577-821 kg/ha over conventional plow tillage, while basins tillage conferred average maize yield advantages of 191-194 kg/ha over conventional hand-hoe tillage. When tillage is done *after* the onset of the rains, rip tillage confers *no yield gains* over conventional plow tillage, while basins tillage actually resulted in yields that were 168-179 kg/ha *lower* than conventional hand-hoe tillage. These results reinforce the importance of early land preparation and planting to maize productivity and highlight the potential of minimum tillage to improve smallholder productivity in Zambia and the region. Results also suggest that the realizable *ceteris paribus* yield gains of minimum tillage under smallholder farm conditions are only attainable if farmers follow the recommended agronomic practices. While the results in this paper suggest that minimum tillage could help to raise maize yields in Zambia, further analysis is needed to establish whether these yield gains are large enough to offset the potentially higher costs associated with minimum tillage.

Given the main findings of the paper, that minimum tillage can boost yields over conventional tillage methods *if tillage is done before the onset of the rains*, there is need to emphasize this critical factor in extension messaging about ripping and planting basins. Moreover, although CA extension messaging to smallholders has increased over the last five years in Zambia’s drier agro-ecological zones 1 and 2a, additional extension efforts are needed to further spread information about CA and to demonstrate its potential benefits where the technologies are appropriate. Finally, given the larger yield benefits of ripping over conventional plowing (compared to the yield benefits of planting basins over conventional hand-hoeing), policies and programs to improve the availability and accessibility of rippers and ripping services could play a key role in boosting smallholders’ maize yields in Zambia.

APPENDIX

Table A1. Maize Production Function Coefficient Estimates (Dependent Variable: Maize Yield in kg/ha)

	National			Agro-ecological zones 1 and 2a		
Variables	Spec.1	Spec.2	Spec.3	Spec.1	Spec.2	Spec.3
pl_basins (yes=1)	-41.417	-219.272**	-179.267**	-5.561	-173.561**	-168.406*
	(69.421)	(88.663)	(81.090)	(74.999)	(78.004)	(92.194)
ripping (yes=1)	186.190*	19.951	300.786*	276.028**	64.596	398.131**
	(110.531)	(123.169)	(159.691)	(139.718)	(150.042)	(195.024)
plow (yes=1)	-0.212	-13.468	-13.894	5.162	-3.952	-6.192
	(29.216)	(34.250)	(37.299)	(36.964)	(44.715)	(46.130)
bunding (yes=1)	178.598**	174.062**	206.237**	496.252***	479.996***	476.441***
	(85.104)	(85.666)	(96.982)	(148.980)	(163.688)	(181.034)
ridging (yes=1)	114.475***	92.440***	48.806	115.305***	73.874	17.483
	(27.539)	(32.260)	(36.803)	(37.262)	(45.202)	(48.702)
Tillage before rains (yes=1)	-22.486	-48.624	-50.218*	36.195	-5.798	-7.076
	(21.171)	(29.799)	(29.858)	(29.686)	(44.098)	(44.090)
Basins-tillage before rains[#]		369.755***	370.717***		360.296***	362.414***
		(125.448)	(124.623)		(135.027)	(136.802)
Ripping-tillage before rains[#]		564.484**	503.349**		804.773***	642.958**
		(238.307)	(219.160)		(302.363)	(280.045)
Plowing-tillage before rains[#]		22.761	22.593		-11.713	-10.217
		(59.664)	(59.638)		(75.867)	(75.727)
Bunding-tillage before rains[#]		-98.473	-68.607		-66.169	-65.300
		(201.193)	(200.207)		(240.151)	(245.552)
Ridging-tillage before rains[#]		36.924	41.291		97.210	108.449
		(44.243)	(44.267)		(66.885)	(66.177)
hybrid seed (yes=1)	180.629***	103.917***	102.729***	158.678***	87.756**	86.129*
	(22.693)	(34.050)	(34.051)	(29.072)	(43.980)	(43.980)
Seeding rate (kg/ha)	1.879***	-3.338**	-3.273**	1.946***	-3.799*	-3.560
	(0.557)	(1.614)	(1.632)	(0.675)	(2.170)	(2.176)
seedingrate squared		0.014	0.012		0.022	0.019
		(0.019)	(0.019)		(0.025)	(0.025)
Hybridseed-c.seedingrate[#]		2.081*	2.057*		2.086	2.060
		(1.164)	(1.167)		(1.352)	(1.352)
basal fert use rate (kg/ha)	3.128***	4.505***	4.518***	3.180***	3.998***	3.490***
	(0.328)	(0.634)	(0.735)	(0.383)	(0.773)	(1.023)
brate squared		-0.009***	-0.009***		-0.008**	-0.007**
		(0.003)	(0.003)		(0.004)	(0.004)
top fert use rate (kg/ha)	4.832***	4.455***	4.204***	4.962***	4.687***	4.821***
	(0.320)	(0.641)	(0.745)	(0.369)	(0.790)	(1.033)
Tprate squared		-0.001	0.000		-0.001	0.000
		(0.003)	(0.003)		(0.003)	(0.003)
Brate-tprate[#]		0.003	0.002		0.003	0.002
		(0.003)	(0.003)		(0.004)	(0.004)
Brate-seedingrate[#]		0.023	0.028*		0.022	0.023
		(0.016)	(0.016)		(0.018)	(0.019)
Tprate-seedingrate[#]		0.018	0.014		0.019	0.019
		(0.016)	(0.016)		(0.019)	(0.020)
Basins-brate[#]			0.611			2.509
			(1.516)			(1.611)
Basins-tprate[#]			-1.273			-2.327
			(1.250)			(1.460)
Ripping-brate[#]			6.002**			5.491**

	National			Agro-ecological zones 1 and 2a		
Variables	Spec.1	Spec.2	Spec.3	Spec.1	Spec.2	Spec.3
			(2.798)			(2.713)
Ripping-tprate#			-9.233***			-9.149***
			(2.899)			(2.907)
Plowing-brate#			-0.774			0.178
			(0.693)			(0.942)
Plowing-tprate#			0.790			-0.051
			(0.678)			(0.903)
Bunding-brate#			-1.378			-0.153
			(3.694)			(3.856)
Bunding-tprate#			-0.401			0.130
			(3.143)			(3.616)
Ridge-brate#			0.731			2.075*
			(0.743)			(1.162)
Ridge-tprate#			-0.111			-1.017
			(0.731)			(1.101)
plot size in ha	-12.730	-49.434***	-50.115***	-13.270	-56.414***	-57.530***
	(9.187)	(15.250)	(15.206)	(11.390)	(19.961)	(19.913)
plot size squared		5.576***	5.651***		6.294***	6.361***
		(1.548)	(1.550)		(2.013)	(2.006)
Growing season rainfall (mm)	0.001	0.010	0.000	0.014	-0.122	-0.125
	(0.106)	(0.257)	(0.258)	(0.145)	(0.284)	(0.287)
rain squared		-0.000	-0.000		0.000	0.000
		(0.000)	(0.000)		(0.000)	(0.000)
# of 20 day periods with < 40mm rainfall	-30.277*	-49.810	-49.719	9.666	-16.341	-19.754
	(15.913)	(31.428)	(31.270)	(19.554)	(40.564)	(40.365)
rain stress squared		4.623	4.637		5.931	6.394
		(7.388)	(7.354)		(8.368)	(8.304)
Male head (yes=1)	37.179	45.866	44.331	17.066	22.335	19.409
	(29.562)	(29.683)	(29.664)	(40.368)	(40.383)	(40.330)
Age of hh head (years)	-0.290	9.714***	9.548***	-0.789	4.255	3.803
	(0.550)	(3.422)	(3.419)	(0.753)	(4.610)	(4.597)
Age squared		-0.099***	-0.098***		-0.050	-0.045
		(0.033)	(0.033)		(0.044)	(0.044)
Polygamously married (yes=1)	44.937	42.823	41.631	54.684	51.440	50.420
	(39.070)	(39.117)	(39.106)	(48.425)	(48.439)	(48.369)
Monogamously married (yes=1)	20.046	20.514	20.893	31.095	33.561	34.286
	(28.883)	(29.119)	(29.056)	(38.584)	(38.818)	(38.711)
Number of adults (15-65 years)	-0.733	0.828	0.537	-2.487	-3.830	-3.983
	(3.995)	(8.775)	(8.635)	(4.914)	(10.872)	(10.699)
hhsize squared		-0.491	-0.440		-0.019	0.021
		(0.592)	(0.580)		(0.653)	(0.646)
2009.year	252.316***	237.026***	239.449***	377.950***	367.354***	370.649***
	(40.945)	(40.979)	(40.921)	(51.572)	(52.882)	(52.394)
2010.year	565.090***	541.306***	543.539***	792.754***	779.171***	776.082***
	(46.990)	(48.263)	(48.302)	(67.339)	(70.312)	(70.444)
2011.year	533.487***	519.053***	519.221***	576.920***	577.220***	581.136***
	(42.154)	(41.840)	(41.439)	(58.691)	(58.404)	(57.552)
AEZ 2a (yes=1)	17.997	45.055	59.577			
	(50.775)	(54.239)	(54.045)			
AEZ 2b (yes=1)	15.609	15.716	-21.610			
	(67.342)	(77.257)	(76.277)			

	National			Agro-ecological zones 1 and 2a		
Variables	Spec.1	Spec.2	Spec.3	Spec.1	Spec.2	Spec.3
AEZ 3 (yes=1)	355.503***	345.079***	334.802***			
	(63.136)	(65.732)	(63.375)			
SEA average	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Constant	1,574.66***	2,142.41***	1,854.86***	1,403.15***	2,121.525*	1,292.151
	(282.170)	(712.453)	(703.859)	(413.908)	(1,095.769)	(1,073.067)
Observations	47,838	47,838	47,838	25,808	25,808	25,808
R-squared	0.376	0.383	0.385	0.352	0.362	0.366
F statistic	148.37	101.14	81.1	78.2	63.86	59.75
p value	0.000	0.000	0.000	0.000	0.000	0.000

Source: Authors’ computations from CFS 2008-2011.
Notes: Standard errors clustered at the SEA level in parentheses; ***, **, * statistically significant at 1%, 5% and 10%, respectively; base tillage method, year, and agro-ecological zone are conventional hand hoe, 2008, and AEZ 1, respectively. #- interaction terms.

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