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Yield effects of conservation farming practices under fall armyworm stress: The case of Zambia

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A R T I C L E I N F O

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A B S T R A C T

Conservation farming (CF) aims to achieve increased agricultural productivity while ensuring environmental sustainability through a system of agronomic practices, including minimum soil disturbance (MSD), crop residue retention (RR), and crop rotation (CR). Although inconclusive, there is some evidence that CF can improve crop yields in smallholder farming systems of sub-Saharan Africa (SSA). In this article, we examined whether the implementation of CF practices (either separately or in tandem) can offset the negative yield effects of fall armyworm (FAW), a new invasive pest that is causing devastating effects on maize in SSA. We used data from 1048 smallholder maize plots across the major maize-producing agro-ecological zones of Zambia. Results showed that 86% of the plots had at least one of the CF practices, but only 26% of the plots were under the full CF package. Factors that consistently influenced the use of the various CF packages included agro-climatic conditions, land tenure security, livestock raising and credit constraints. We found suggestive evidence that CR, when adopted in isolation or in combination with RR, can increase maize yield by up to 360 kg/ha (28%) under FAW stress. On the other hand, none of the MSD-related practices (including the full CF package) had a significant effect on maize yield. Overall, our analyses suggest that certain components of CF can mitigate short-term yield loss, but high-rainfall environments and the use of modern inputs (improved seeds and agrochemicals) are the most robust determinants of smallholder maize yields in the face of FAW invasion.

1. Introduction

Smallholder farmers in sub-Saharan Africa (SSA) face multiple agricultural production constraints, including land degradation, declining soil fertility, labour shortages, climate change and variability, and pests and diseases. Recent efforts to address these challenges and ensure sustainable food production to meet the demands of a growing population have included the promotion of a suite of agricultural technologies and practices under the paradigm of 'sustainable intensification' (The Montpellier Panel, 2013) and 'climate-smart agriculture' (Lipper et al., 2014). One of such technologies is conservation agriculture (CA). In Zambia, CA promoted as conservation farming (CF), which consists of the following main components: 1) MSD (minimum soil disturbance, zero tillage, or planting in either hand-hoe basins or rip lines; 2) RR (retaining crop residues on the field as mulch (no burning); and 3) CR (rotation of cereals with legumes (Haggblade and Tembo, 2003; Arslan et al., 2014; Ng'ombe et al., 2017).

Conservation agriculture (CA) has been argued to provide a number of agronomic, economic and environmental advantages, such as reduced erosion, soil moisture conservation, increased and sustained crop yields, labour savings, lower production costs, carbon sequestration, increased resilience to climate variability and enhanced biodiversity (Thierfelder et al., 2017; FAO, 2020a). Given these potential benefits, there has been a sustained promotion of CA in SSA, particularly in southern Africa (Corbeels et al., 2014). However, the uptake of the technology remains very low. For instance, only 1.1% of the cropland area in Africa was reportedly under CA in 2015/2016 (Kassam et al., 2019). Widespread adoption is hampered by several challenges, including increased labour requirements, high opportunity costs of retaining crop residues in the field, and high costs of complementary inputs (Giller et al., 2009; Rusinamhodzi, 2015). The low adoption rates of CA, coupled with the varying degrees of success and several adoption constraints, have led to questions and debates about its suitability for smallholder farming systems in SSA (Giller et al., 2009, 2011; Andersson and D'Souza, 2014).

There is some evidence that CA can increase smallholder crop yields, especially under low rainfall conditions (Corbeels et al., 2014; Pittelkow

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et al., 2015; Thierfelder et al., 2017). Here, we investigate whether CA practices can also increase yields during periods of outbreak of fall armyworm (FAW), *Spodoptera frugiperda*, a highly destructive pest of maize (De Groote et al., 2020). Native to the Americas, the invasive FAW was first detected in West Africa in 2016 and has since spread rapidly to nearly all of SSA, at least 18 Asian countries, and Australia (CABI, 2020). A study by Rwomushana et al. (2018) has shown that for 12 maize-producing countries in SSA alone, the pest has the potential to cause losses of up to 17.7 million tonnes of maize annually, thereby posing a significant threat to food security and livelihoods in the region. Moreover, the rapid spread of FAW in SSA has spurred increased use of synthetic pesticides (Tambo et al., 2020b), which can have adverse effects on human, animal and environmental health. Hence, understanding the extent to which CA can mitigate yield losses from FAW in smallholder farming systems can be useful in efforts towards the promotion of agro-ecological or integrated pest management (IPM) options for FAW management in SSA.

There are a number of possible mechanisms through which CA practices could mitigate yield loss due to FAW infestation. For instance, CA can improve soil health and water retention, thereby ensuring healthy growth of plants, which can better withstand FAW infestation, and increase yields to compensate for foliar damages caused by the pest (Prasanna et al., 2018; Harrison et al., 2019). The CA practices can also provide favourable microclimate for insect predators (such as ants, spiders, and beetles), pathogens and parasitoids, which can suppress FAW populations, and thus lower crop damage (Rivers et al., 2016; Prasanna et al., 2018; Baudron et al., 2019; Harrison et al., 2019). Furthermore, the crop rotation component of CA may help to disrupt FAW life cycle and prevent population build-up of the pest (Harrison et al., 2019).

While data from experimental plots in the Americas suggest that certain CA practices can significantly reduce FAW incidence and damage to crops (All, 1988; Rivers et al., 2016), little is known about the extent to which the adoption of the various CA practices can reduce yield loss under FAW infestation in smallholder farming systems of SSA (Prasanna et al., 2018). Using data from 1048 smallholder maize plots in Zambia, this paper contributes to filling this knowledge gap by estimating the yield effects of different CF packages in the presence of FAW infestation. The research questions addressed in this study include: (1) what factors determine the use of CF practices when adopted either separately or in tandem?; (2) does the adoption of CF practices provide significant yield benefits even under FAW stress?; and (3) in the context of FAW invasion, does the adoption of CF practices in combination result in larger yield gains than when adopted in isolation? By addressing these research questions, we also expand on the limited literature regarding the unique and combined effects of the three CF principles (Ng'ombe et al., 2017; Tambo and Mockshell, 2018). The effects of the different combinations of the three CF principles have rarely been assessed, as most studies tend to examine individual CF components separately.

Zambia is a particularly interesting case to study the yield effects of CA in the wake of FAW invasion in Africa. It is among the countries that have suffered the worst infestation of FAW (Stokstad, 2017). Moreover, there have been many initiatives to promote CA in Zambia, and the country is estimated to have the second largest crop area under CA in Africa after South Africa (Kassam et al., 2019).

The remainder of the paper is structured as follows. Section 2 provides a brief overview of CF and FAW in Zambia, as well as a description of the data used in this study and the estimation techniques. Results are provided and discussed in Section 3, and Section 4 concludes with a summary and implications of the main findings.

2. Context and methods

2.1. Conservation farming in Zambia

Conservation farming (CF) activities were initiated in Zambia more than three decades ago as a response to declining land quality and productivity (Haggblade and Tembo, 2003). The widespread promotion of the technology in the country received extensive support from several national and international development agencies, such as the Zambia Ministry of Agriculture (MoA), the Zambian National Farmers Union (ZNFU), and the Food and Agriculture Organisation of the United Nations (FAO). In particular, the establishment of the Conservation Farming Unit (CFU) in 1995 by the ZNFU has supported the promotion of CF through the adaptation of the practices to suit small-scale farmers' environments and the provision of extension support and practical training to farmers, using the lead farmer extension model (Hodson, 2016). Several donor-funded projects have also been implemented in the country over the years to enhance CF technology adoption and sustainably increase productivity. A recent example is the European Union-funded Conservation Agriculture Scaling-up Project (2013–2017), which was implemented by the FAO and estimated to have reached nearly 270,000 smallholder farmers in 48 districts across nine provinces of Zambia (FAO, 2018).

Despite the promotional efforts, several empirical works suggest that there is low adoption of CF practices (especially MSD) in Zambia (Arslan et al., 2014; Kuntashula et al., 2014; Ngoma et al., 2015; Grabowski et al., 2016; Ng'ombe et al., 2017; Ngoma, 2018). For instance, in a survey of 1231 farm households across six Zambia districts, Kuntashula et al. (2014) showed that only about 12% and 19% of the households were adopters of MSD and CR, respectively. Using nationally representative panel data, Arslan et al. (2014) observed that only 13% and 5% of households practiced CF in 2004 and 2008, respectively, signifying low adoption and high dis-adoption rates. Grabowski et al. (2016) also reported low use of MSD (12% of cotton area and 20% of maize area) even in areas with relatively high adoption rates (Eastern province) in Zambia. On the other hand, Ng'ombe et al. (2017) observed that some form of CF (but not the complete package) was practiced on about 66% of crop plots, suggesting that partial adoption is common. Among the major challenges to the practice of CF in Zambia include labour constraints, inadequate amounts of crop residues and high opportunity costs of retaining them in the field, unavailability and unaffordability of complementary inputs, as well as the knowledge-intensiveness of the technology package (Haggblade and Tembo, 2003; Arslan et al., 2014; Thierfelder et al., 2015).

Given the extensive promotion of CF practices in Zambia, evaluation of their effects on crop productivity and related outcomes has also attracted growing interest in recent years. Studies involving field experiments have generally reported positive yield effects of CF compared to conventional practices (Rockström et al., 2009; Thierfelder et al., 2015, 2017). However, studies that drew on household surveys reached a more nuanced conclusion on the effects of CF practices under smallholder farm conditions in Zambia. For example, an impact study by Kuntashula et al. (2014) showed maize productivity gains of about 26–38% and 21–24% from the adoption of MSD and CR, respectively. Similarly, using data from nearly 48,000 smallholder maize plots in Zambia, Ngoma et al. (2015) found that MSD practices generate significant yield advantages (ranging from 194 kg/ha to 821 kg/ha) over conventional tillage methods, only if minimum tillage is done before the onset of the rains. On the contrary, Arslan et al. (2015) found no significant impact of MSD and CR on maize yield, while Ngoma (2018) showed that the adoption of MSD is significantly associated with higher crop yield, but not crop income. Going beyond farm-level outcomes, Abdulai (2016) demonstrated that the adoption of a CF technology significantly reduces household poverty, as measured by poverty headcount, poverty gap, and severity of poverty indices. Lastly, Ng'ombe et al. (2017) evaluated the unique and combined effects of the three CF practices and found that they significantly increase net crop revenue per hectare when adopted either singly or jointly, but the adoption of the practices in combination (especially MSD and RR) produce higher outcomes than adoption in isolation. We extend the scope of these studies by examining the yield effects of the CF practices when

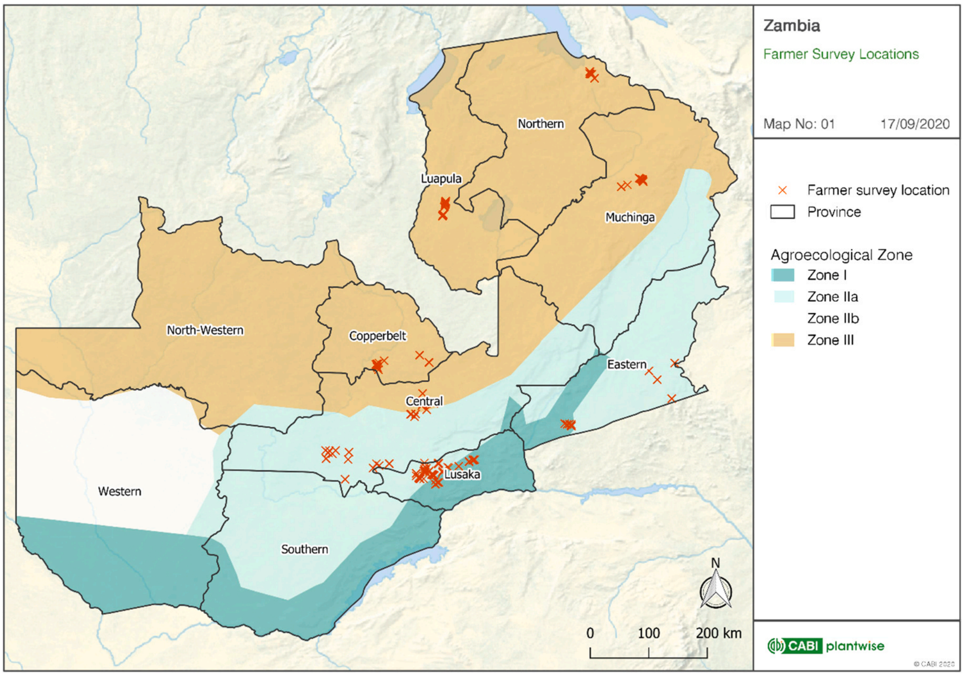

Fig. 1. Map of Zambia showing the survey locations.

adopted in periods of FAW invasion.

2.2. *Fall armyworm in Zambia*

In Zambia, FAW was first detected around the end of 2016, during which it infested maize fields in over 100 districts across the country's 10 provinces (Kabwe et al., 2018). The Zambian government swiftly declared the FAW outbreak a national disaster (Kabwe et al., 2018), and reportedly allocated US$ 3 million towards its control, including the procurement and distribution of more than 100,000 litres of free pesticides (mostly lambda-cyhalothrin and cypermethrin), sprayers and personal protective equipment to farmers (Abrahams et al., 2017; Stokstad, 2017). During the 2016/2017 cropping season, the FAW pest was reported to have attacked about 223,000 ha of maize, with about 90,000 ha of these plots experiencing total crop loss (Stokstad, 2017). Findings from surveys of affected households suggested FAW-induced maize yield losses of up to 50% during the 2016/2017 cropping season (Abrahams et al., 2017; Kansiime et al., 2019). The pest continues to spread and cause devastating damage in the country, with reports of infestations on about 15% of the total maize acreage during the recent 2019/2020 production season (FAO, 2020b). Rwomushana et al. (2018) estimated that in Zambia, the pest has the potential to cause an annual maize yield loss of about 966,000 tonnes, translating into revenue loss of nearly US$ 160 million. Given that maize is the main staple crop in Zambia, the pest poses a serious threat to food security in the country, if no control actions are taken.

Several studies have also examined the choice and implications of FAW management strategies among Zambian farmers. The most widely used FAW control option in the country is chemical pesticide, which is largely influenced by access to free or subsidised inputs (Rwomushana et al., 2018; Kansiime et al., 2019; Tambo et al., 2020a, 2020b). These studies further showed that some of the farmers also applied cultural and physical management strategies such as handpicking and crushing of egg masses and larvae, application of detergents or ash on larvae, and destroying of infested plants, with considerable levels of success in preventing or controlling the pest. Tambo et al. (2020a) observed that the FAW management strategies implemented by smallholders in Ghana and Zambia significantly increased maize yield, with as high as 125% yield gain when pesticides were combined with handpicking of larvae. However, there is evidence that some of the pesticides used against FAW in Zambia are highly hazardous, and the farmers hardly wear protective clothing while spraying pesticides, potentially leading to health and environmental problems (Kansiime et al., 2019; Tambo et al., 2020b). The present study will provide insight into the extent to which sustainable CF practices can offset the detrimental yield effects of FAW in Zambia.

2.3. *Data*

This study draws on survey data from 837 smallholder households and 1048 maize plots for the 2018/2019 cropping season in Zambia. A three-stage sampling procedure was used to select the sample households. In the first stage, three agro-ecological zones (AEZs I, IIa and III) that constitute the major maize-growing areas of the country were selected.[1] Secondly, 12, 24 and 14 representative agricultural camps were chosen from AEZs I, IIa and III respectively, based on the importance of maize production and incidence of FAW,[2,3] Within each selected camp, about 10–20 maize-producing households were randomly selected from household lists provided by camp extension officers. Overall, our sample included 187 (145), 475 (364) and 386 (328) maize plots (households) in AEZs I, IIa and III, respectively. The data also cover seven (Central, Copperbelt, Eastern, Luapula, Lusaka, Muchinga and Northern) of the country's 10 provinces. A map of the study locations is illustrated in Fig. 1.

Data were collected between August and September 2019 through face-to-face interviews conducted by 17 enumerators who were trained and supervised by the first author. The enumerators used tablet-based

[1] Zambia has four AEZs. AEZ I: low-rainfall area (annual rainfall <800 mm), hot and drought-prone region; AEZ IIa: soils and rainfall (800–1000 mm of rain/year) are more favourable for farming; AEZ IIb: sandy soils with 800–1000 mm annual rainfall; AEZ III: high rainfall area (>1000 mm of rain/year).

[2] Data on the incidence of FAW across the country were obtained from the Plantwise Online Management System.

[3] A camp is the lowest tier of agricultural administration in Zambia.

Table 1
Summary statistics of study variables.

Variable	Description	Mean	SD
Outcome variable			
Yield	Quantity of maize harvested per plot (kg/ha)	1521.85	1611.38
Fall armyworm infestation			
Minor infestation	Less than half of the maize plants were attacked by FAW (1/0)	0.55	0.50
Moderate infestation	About half of the maize plants were attacked by FAW (1/0)	0.33	0.47
Major infestation	More than half of the maize plants were attacked by FAW (1/0)	0.12	0.33
Fall armyworm control measures			
Chemical control	Used synthetic pesticides to control FAW (1/0)	0.34	0.47
Botanical control	Used plant derivatives or extracts to control FAW (1/0)	0.31	0.46
Mechanical control	Handpicked FAW larvae or destroyed infested plants (1/0)	0.51	0.50
Cultural control	Used cultural practices to prevent FAW infestation (1/0)	0.46	0.50
Plot characteristics			
Plot size	Size of plot (hectares)	1.46	1.39
Tenure	Household has secure rights over the plot (1/0)	0.91	0.28
Plot distance	Distance of plot from homestead (km)	1.77	3.87
Slope	Plot is sloped (1/0)	0.47	0.50
Male managed	The plot manager is a male (1/0)	0.33	0.47
Female managed	The plot manager is a female (1/0)	0.30	0.46
Jointly managed	The plot is jointly managed by male and female (1/0)	0.36	0.48
Other pest shock	Plot was attacked by other pests besides FAW (1/0)[a]	0.42	0.49
Plot-level investment			
Improved seed	Plot was cultivated with improved maize seed (1/0)	0.90	0.30
Fertilizer	Expenses on inorganic fertilizer (ZMW/ha)[b]	782.53	1315.93
Manure	Plot received manure (1/0)	0.19	0.39
Herbicide	Expenses on herbicide (ZMW/ha)	93.68	186.23
Hired labour	Expenses on hired labour (ZMW/ha)	187.90	445.96
Household characteristics			
Age	Age of household head (years)	50.34	13.23
Education	Years of schooling of household head	7.69	3.44
Household size	Number of household members	7.08	3.21
Off-farm activity	Household member has off-farm job (1/0)	0.48	0.50
Credit constrained	Household needed credit and did not get (1/0)	0.23	0.42
Asset index	Household asset index[c]	-0.10	1.62
Livestock holding	Household livestock holding in Tropical Livestock Unit (TLU)	2.47	4.75
Distance to extension	Distance from household to the nearest extension office (km)	9.80	10.15
Farmer group	Household member belongs to a farmer group (1/0)	0.87	0.34
Agro-climatic characteristics			
Rainfall	Total rainfall during the last cropping season (mm)	891.23	306.11
AEZ I	Household is located in agro-ecological zone I	0.17	0.38
AEZ IIa	Household is located in agro-ecological zone IIa	0.44	0.50
AEZ III	Household is located in agro-ecological zone III	0.39	0.49
No. of observations	Number of plot (household) observations	1408 (837)	

Notes:
[a] Other pests include maize stalk borer and maize streak virus.
[b] ZMW=Zambian Kwacha. At the time of the survey, 1 USD= 13 ZMW.
[c] The asset index was constructed using principal component analysis based on household ownership of 11 durable assets.

questionnaires that included information on plot-level characteristics and investments; household composition and characteristics; maize production; FAW infestation and management practices; and access to institutional support services. Camp-level rainfall data were extracted from the Climatology Resource for Agroclimatology of NASA.

2.4. Empirical approach

To examine the relationship between the adoption of CF practices and maize yield, we first estimate an ordinary least squares (OLS) model as follows:

$$Y_{ip} = \beta_0 + \beta_1 CF_p + \beta_2 P_p + \beta_3 H_i + \beta_4 A_i + \beta_5 FS_p + \beta_6 FM_p + \mu_{ip} \quad (1)$$

where Y_{ip} is the outcome variable, measured by the quantity of maize harvested (expressed in kg/hectare) by household *i* on plot *p*. The main covariate of interest, *CF*, measures the adoption of CF practices. Given that the three CF practices can be applied independently or jointly, the *CF* variable consists of eight alternatives: 1) non-adoption; 2) MSD only; 3) RR only; 4) CR only; 5) MSD+RR; 6) MSD+CR; 7) RR+CR; and 8) MSD+RR+CR, which is the full package. It is expected that households will adopt the CF option that maximizes yield benefits. *P* is a vector of plot characteristics, such as size, location, slope, tenure security, and gender of the plot manager. It also includes plot-level input use variables, such as improved seed, fertilizer, herbicide and labour. *H* captures household characteristics, including, age and education of household head, household size, wealth, and access to institutional services such as credit and extension. *A* is a vector of agro-climatic variables, including rainfall and agro-ecological location of households.

FS measures plot-level FAW incidence. All the maize plots in our sample were reportedly affected by FAW; hence, the *FS* variable captures the severity of infestation (i.e., minor, moderate or major infestation) based on self-reported information from the plot managers. A plot was considered to have suffered minor infestation if FAW caused damage on less than half of the maize plants on the plot; moderate infestation means that about half of the maize plants were attacked by FAW; while major infestation implies that more than half of the maize plants were affected by the pest. We recognise that field scouting during the growing season would have been a more appropriate method of assessing the severity of infestation, but this was not possible in the current study that uses data from household surveys conducted at the end of the cropping season. *FM* represents plot-level management strategies against FAW. β is a vector of coefficients associated with the explanatory variables, and μ is the error term. The main coefficient of interest is β_1, which gives estimates of the average effects of the CF technology options on maize yield. The description of the covariates in the OLS model is given in Table 1.

The OLS model above assumes that adoption of CF practices in exogenously given. However, the farmers' choices of CF practices were not based on random assignment; hence, the *CA* variable in Eq. 1 is potentially endogenous. In other words, it is possible that adopters and non-adopters of a CF option may be systematically different in observable and unobservable characteristics that could influence maize yield, and thus bias the OLS estimates. To reduce this potential bias, we apply the doubly robust estimator in which the OLS model is weighted by an

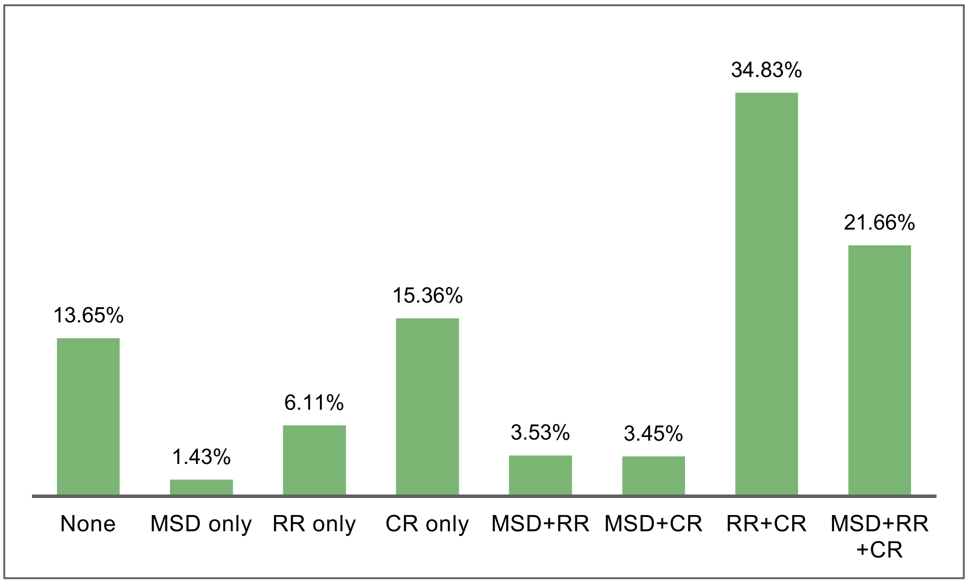

Fig. 2. Percentage of maize plots under CF practices (n = 1048). Note: MSD=minimum soil disturbance; RR=residue retention; and CR=crop rotation.

inverse propensity score to balance the observable characteristics between adopters and non-adopters of the CF practices.

In the doubly robust procedure, inverse-probability weights are computed from a multinomial logit regression of CF adoption decisions, which is specified as:

$$CF_{ip} = \alpha_0 + \alpha_1 P_p + \alpha_2 H_i + \alpha_3 A_i + \varepsilon_{ip} \quad (2)$$

where α is the parameters to be estimated, ε is the error term, and the rest of the variables are as defined in Eq. (1). All the plot-level covariates in Eq. (1) are included here except those that could be affected by the adoption of CF practices, such as the input use variables. Using the estimated inverse-probability weights, weighted OLS models are fitted to obtain the expected yield outcomes of the probabilities of adoption and non-adoption of CF practices. The differences in mean outcomes between adopters and non-adopters of the CF practices provide estimates of the average yield effects of the CF practices. An important benefit associated with the doubly robust method is that it is robust to misspecification in either the treatment model (Eq. (2)) or the outcome model (Eq. (1)). Thus, even if only one of the two models is correctly specified, the average yield effect estimates are still consistent (Imbens and Wooldridge, 2009).

Given that the doubly robust approach relies on the weak overlap or common support assumption (Imbens, 2004), we examine whether or not this assumption is violated by checking for covariate balancing using the overidentification test proposed by Imai and Ratkovic (2014), and by visually checking the extent of propensity score overlap. It should be mentioned that the doubly robust method assumes unconfoundedness and thus corrects for selection bias due to observable characteristics but may not address potential bias stemming from unobservable factors. While the inclusion of a rich set of plot and household level characteristics in our models may help to reduce unobserved heterogeneity, instrumental variables (IV) techniques are usually used to address this potential source of bias in cross-sectional study designs. However, finding instruments that satisfy exclusion restriction conditions is challenging, particularly when there are multi-valued endogenous regressors, as in our study. This should be taken into consideration when interpreting the regression results.

3. Results and discussion

3.1. Descriptive statistics

Fig. 2 shows the plot-level adoption of the CF practices. We find that 14% of the sample plots did not have any of the CF practices, while the full package consisting of MSD, RR and CR was adopted on 22% of the plots. This differs from the findings of Ng'ombe et al. (2017) who reported non-adoption and full CF package adoption rates of 33% and 0.75%, respectively, based on a 2007/2008 nationally representative data from Zambia. This may be suggestive of higher levels of adoption of the complete CF package in Zambia in recent years. Almost two-thirds of the plots were under only one or two of the CF practices, confirming previous reports of the prevalence of partial adoption of CF among African farmers (Brown et al., 2018; Tambo and Mockshell, 2018; Ward et al., 2018). While some studies have shown that the most widely adopted CF option in Zambia is CR singly (Ng'ombe et al., 2017; Tambo and Mockshell, 2018), we find that RR+CR is the most common practice. The adoption of MSD only or in combination with either RR or CR is much less common in our data, which is consistent with reports of low adoption and high rates of dis-adoption of minimum tillage in Zambia, mostly due to labour constraints and equipment costs (Arslan et al., 2014; Grabowski et al., 2016; Ngoma, 2018).[4]

Table 1 presents the list and descriptive statistics of plot and household-level variables used in the analysis. The study sample consists of smallholder farmers who cultivate an average 1.5 ha of maize and have full user rights on majority (91%) of the cultivated plots. Approximately one-third each of the plots are managed solely by male and female farmers, while the remaining plots are jointly managed. Improved maize seeds and inorganic fertilizers were reportedly used on over 90% of the plots, while only about one-fifth of the plots received manure. A typical household head in our sample is middle-aged with low level of education. A majority of the households are not credit constrained and are members of farmer associations, and almost half of them are engaged in other economic activities besides farming.

FAW infestation was moderate to severe on 45% of the plots. The most common FAW control option used was mechanical methods, such as handpicking and crushing of egg masses and caterpillars or rogueing

[4] Given the low adoption rate of MSD only, this CF option is excluded from the regression analysis.

Table 2
Maize yield and FAW infestation by CF practices.

	Maize yield (kg/ha)		Severity of FAW infestation		
	Mean	SD	Minor	Moderate	Major
Non-adopters	1770.58	1520.10	0.66	0.28	0.06
MSD only	1276.67	1134.35	0.40 * *	0.47	0.13
RR only	1109.06 * **	1274.82	0.50 * *	0.38	0.12 *
CR only	1842.24	1976.68	0.65	0.31	0.04
MSD+RR	1252.86 *	1319.29	0.65	0.24	0.11
MSD+CR	1681.09	1831.61	0.56	0.33	0.11
RR+CR	1564.10	1619.27	0.51 * **	0.33	0.16 * **
MSD+RR+CR	1225.35 * **	1406.97	0.48 * **	0.34	0.18 * **

Note: * ** , * * and * denote that the mean values for adopters of a CF option are significantly.
different from non-adopters at the 1%, 5% and 10% significance levels, respectively.
The yield values are winsorized at the 1st and 99th percentiles.
MSD=minimum soil disturbance; RR=residue retention; and CR=crop rotation.

of infested plants, which were implemented on about half of the plots. This deviates from previous studies that found that chemical control was the most widely used method of FAW control in Zambia and other SSA countries (Kansiime et al., 2019; Tambo et al., 2020a, 2020b). Chemical and botanical controls were applied on around one-third of the plots. The data show that the most commonly used chemical and botanical pesticides were cypermethrin and azadirachtin, respectively. Preventive cultural practices, such as timely planting, frequent weeding to remove alternative host plants and intercropping with non-host plants were also implemented on nearly half of the plots.

Table 1 also shows that on average, the sample households harvested roughly 1500 kg/ha of maize during the 2018/2019 cropping season. This is slightly higher than the national average of about 1300 kg/ha reported by MoA (2019), but is lower than the average yields (between 1700 kg/ha to 3000 kg/ha) in recent past years (FAOSTAT, 2020). Rainfall shortages and FAW attacks were among the main causes of the decrease in maize production in the country (MoA, 2019; FAO, 2020). A disaggregation of the maize yields according to the adoption of CF practices (Table 2) shows that with the exception of CR only, plots without a CF practice produced greater yields than those with CF practices, whether adopted in isolation or in combination. Notable is the statistically significant yield difference between the non-CF plots and the plots with the complete CF package (MSD+RR+CR), potentially pointing to lower yields from CF adoption. However, it should be noted that the results in Table 2 do not control for possible confounding factors, such as differences in plot characteristics, inputs and plot manager characteristics, and thus cannot be interpreted as yield effects of CF practices.

Table 2 also indicates that higher infestation levels of FAW were more prevalent on CF plots than on non-CF plots, based on farmers' own assessment of the severity of infestation. For instance, major FAW infestation was reported on 6% of non-CF plots, compared to 18% of the plots on which the full CF package was practiced. This may partly

Table 3
Probability of adoption of CF practices.

	RR only	CR only	MSD+RR	MSD+CR	RR+CR	MSD+RR+CR
Plot size	0.268 *	0.149	-0.009	0.164	0.251 * *	0.246 *
	(0.146)	(0.134)	(0.230)	(0.195)	(0.124)	(0.126)
Plot distance	0.070	0.064	0.046	-0.008	0.085 * *	0.095 * *
	(0.058)	(0.044)	(0.081)	(0.090)	(0.042)	(0.044)
Slope	0.015	-0.427 *	-0.187	0.459	0.397 *	0.055
	(0.329)	(0.255)	(0.405)	(0.401)	(0.238)	(0.259)
Tenure	1.848 * **	0.691 * *	1.375 * *	1.822 * *	2.377 * **	2.225 * **
	(0.570)	(0.346)	(0.694)	(0.798)	(0.423)	(0.499)
Female managed[a]	1.460 * **	0.090	0.851	-0.078	0.455	-0.147
	(0.484)	(0.319)	(0.574)	(0.515)	(0.311)	(0.342)
Jointly managed[a]	1.429 * **	-0.552 *	0.976 *	-0.194	0.461	0.288
	(0.469)	(0.307)	(0.524)	(0.475)	(0.284)	(0.304)
Age	-0.001	-0.007	-0.001	-0.009	-0.007	0.018 *
	(0.013)	(0.010)	(0.016)	(0.015)	(0.009)	(0.010)
Education	-0.033	-0.030	0.021	0.091	0.057	0.008
	(0.055)	(0.044)	(0.068)	(0.069)	(0.041)	(0.043)
Household size	-0.082	0.000	0.009	-0.100	-0.025	0.000
	(0.061)	(0.045)	(0.067)	(0.074)	(0.042)	(0.044)
Off-farm activity	-1.417 * **	-0.460 *	-1.296 * **	-1.163 * **	-1.240 * **	-1.139 * **
	(0.347)	(0.264)	(0.417)	(0.413)	(0.249)	(0.270)
Credit constrained	-0.513	-1.243 * **	-2.199 * **	-1.985 * **	-1.050 * **	-0.799 * **
	(0.356)	(0.281)	(0.590)	(0.597)	(0.267)	(0.301)
Asset index	0.089	0.026	-0.044	-0.058	0.035	0.098
	(0.131)	(0.101)	(0.157)	(0.159)	(0.096)	(0.103)
Livestock holding	-0.193 * **	-0.016	-0.099 *	-0.058	-0.044	-0.097 * **
	(0.067)	(0.026)	(0.056)	(0.042)	(0.024)	(0.028)
Distance to extension	0.011	0.023 *	-0.009	-0.028	0.008	-0.000
	(0.018)	(0.014)	(0.024)	(0.026)	(0.013)	(0.014)
Farmer group	0.440	0.890 * *	1.009	1.524 *	0.741 * *	1.061 * **
	(0.491)	(0.384)	(0.712)	(0.802)	(0.355)	(0.408)
Rainfall	-0.004 * **	-0.002 * *	-0.004 * *	-0.001	-0.001 *	0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
AEZ IIa[b]	0.564	0.743	-0.282	0.184	1.747 * **	0.995 * *
	(0.618)	(0.505)	(0.720)	(0.695)	(0.471)	(0.484)
AEZ III[b]	1.217	0.793	0.302	-1.484	-0.244	-2.692 * **
	(0.802)	(0.624)	(1.045)	(1.108)	(0.603)	(0.678)
Constant	0.913	1.158	0.883	-1.350	-0.900	-2.126
	(1.388)	(1.041)	(1.793)	(1.796)	(1.019)	(1.128)
No. of observation	1033	1033	1033	1033	1033	1033

Notes: Robust standard errors in parentheses. * **$p < 0.01$, * * $p < 0.05$, *$p < 0.1$
[a] The reference category is male-managed plots.
[b] The reference category is AEZ I.

Table 4
OLS estimates of the determinants of maize yield.

	Model 1		Model 2		Model 3	
	Coefficient	Robust S.E.	Coefficient	Robust S.E.	Coefficient	Robust S.E.
RR only	-220.778	212.159	-199.176	210.588	-102.548	207.005
CR only	356.743 *	192.509	335.424 *	192.221	341.991 *	190.616
MSD+RR	10.935	270.451	-5.940	269.818	40.364	263.658
MSD+CR	416.106	261.029	418.683	259.817	416.015	258.797
RR+CR	413.282 * *	170.926	420.093 * *	168.828	461.634 * **	167.693
MSD+RR+CR	260.138	183.664	267.656	181.604	258.316	179.577
Moderate infestation[a]			-238.248 * *	102.070	-271.825 * **	100.403
Major infestation[a]			-489.569 * **	105.663	-457.612 * **	107.762
Chemical control					495.199 * **	108.425
Botanical control					83.452	103.393
Cultural control					-53.532	111.766
Mechanical control					-173.086 *	97.810
Plot size	-102.839 * *	43.234	-99.304 * *	39.724	-103.395 * *	40.167
Plot distance	28.380 * *	13.002	27.044 * *	12.895	28.689 * *	12.398
Slope	92.054	89.580	95.809	89.313	74.270	88.440
Tenure	-312.591	197.373	-292.601	195.313	-253.870	194.561
Female managed[b]	3.684	124.067	15.278	124.602	38.056	123.923
Jointly managed[b]	71.351	113.199	79.361	113.476	83.881	112.165
Other pest shocks	-48.690	93.948	-47.632	93.339	1.127	108.629
Improved seed	357.825 * **	136.575	338.916 * *	136.814	318.820 * *	134.154
Fertilizer	0.116 * *	0.048	0.121 * *	0.047	0.110 * *	0.047
Manure	-125.835	110.035	-146.381	109.145	-149.694	107.424
Herbicide	1.241 * **	0.362	1.248 * **	0.357	1.101 * **	0.352
Hired labour	0.165	0.119	0.173	0.123	0.184	0.122
Age	-1.482	3.182	-1.273	3.170	-1.236	3.167
Education	-16.352	14.526	-18.093	14.449	-18.614	14.429
Household size	15.439	13.623	14.254	13.429	17.174	13.408
Off-farm activity	110.499	91.921	121.185	91.613	117.134	91.763
Credit constrained	-71.992	111.689	-45.658	112.705	-109.064	111.228
Asset index	141.362 * **	40.667	131.400 * **	39.754	115.538 * **	39.449
Livestock holding	1.651	10.780	0.956	10.627	-0.728	10.850
Distance to extension	-10.184 * **	3.724	-9.718 * **	3.724	-10.946 * **	3.764
Farmer group	210.725	135.120	206.061	134.326	177.568	132.365
Rainfall	1.027 * **	0.315	0.987 * **	0.313	1.070 * **	0.315
AEZ IIa[c]	94.378	142.720	133.958	143.656	105.570	147.555
AEZ III[c]	916.062 * **	256.566	843.148 * **	257.310	815.732 * **	255.918
Constant	-263.305	426.689	-93.637	430.225	-216.034	426.870
No. of observations	1033	1033	1033	1033	1033	1033

Notes: * **p < 0.01, * * p < 0.05, *p < 0.1. Robust standard errors in parentheses. The maize yield variable was winsorized at the 1st and 99th percentiles. As a robustness check, we also estimated the OLS models using a log-transformed maize yield variable. The results, which are available on request, are similar to those reported in Table 4.
Model 3: all the control variables are included; Model 2: no controls for FAW management strategies; Model 1: no controls for FAW management strategies and severity of infestation.
[a] The reference category is minor infestation.
[b] The reference category is male-managed plots.
[c] The reference category is AEZ I.

Table 5
Doubly robust estimates of yield effects of CF practices.

	Model 1		Model 2		Model 3	
	Treatment effect	Percentage effect	Treatment effect	Percentage effect	Treatment effect	Percentage effect
RR only	320.17	19.80	320.04	19.97	251.98	15.81
	(374.56)		(376.29)		(358.17)	
CR only	351.84 *	22.03	347.00 *	22.03	339.58 *	21.28
	(200.74)		(195.27)		(198.37)	
MSD+RR	-285.65	-17.12	-710.54	-42.13	-367.31	-21.84
	(588.67)		(857.82)		(600.27)	
MSD+CR	-262.26	-14.31	417.60	23.40	436.72	24.50
	(384.46)		(422.64)		(385.81)	
RR+CR	178.27	12.15	360.15 * *	27.83	294.21 *	21.54
	(179.31)		(150.95)		(158.17)	
MSD+RR+CR	-159.53	-9.41	-75.39	-4.69	84.05	5.31
	(321.81)		(299.49)		(247.96)	

Notes: * **p < 0.01, * * p < 0.05, *p < 0.1. Robust standard errors in parentheses. The maize yield variable was winsorized at the 1st and 99th percentiles. As a robustness check, we also estimated the OLS models using a log-transformed maize yield. The results, which are available on request, are similar to those reported in Table 5.
Model 3: all the control variables are included; Model 2: no controls for FAW management strategies; Model 1: no controls for FAW management strategies and severity of infestation.

explain why the adopters of CF practices generally recorded lower maize yields than their non-adopter counterparts. Once again, it cannot be concluded from this result that CF plots are more likely to be affected by FAW, as we have not accounted for possible plot-level heterogeneity such as investment in FAW control measures, which could prevent or limit the level of FAW infestation in the first place.

3.2. Determinants of CF adoption decisions

The multinomial logit estimation results of the factors explaining farmers' choice of the CF practices are presented in Table 3. There is considerable heterogeneity in the estimated coefficients across the CF options. Contrary to Ng'ombe et al. (2017) and Tambo and Mockshell (2018) but consistent with Ward et al. (2018), we find that larger maize area is significantly associated with a higher likelihood of adopting RR in isolation and in combination with CR, as well as the full CF package.

Results show that the full CF package and RR+CR are more likely to be practiced on plots that are far from the homestead. A plausible explanation is that homestead plots are more likely to receive alternative soil-improving inputs such as manure, which may decrease the likelihood of using CF practices on such plots. Moreover, in line with arguments about the potential trade-off between CF adoption and livestock raising (Giller et al., 2009), it is possible that crop residues on homestead plots are more likely to be used as fodder for livestock than those on distant plots.

Consistent with previous literature on soil conservation investment (Higgins et al., 2018; Tambo and Mockshell, 2018), we see that tenure security is a significant determinant of individual and joint adoption of the CF practices. This is expected since tenure-secure households may be more likely to care about the future benefits from their plots by investing in long-term soil restorative measures that can increase production, in line with the Marshallian inefficiency hypothesis. The gender of plot manager variables have a highly significant ($p < 0.01$) effect on the adoption of RR singly. Specifically, crop residues are more likely to be retained on plots managed by women, whether in isolation or together with men than on plots managed solely by men.

Among the household characteristics that significantly influence the adoption of CF techniques include access to off-farm employment and credit, livestock wealth and membership in farmer groups. Table 3 shows that having an off-farm job is significantly and negatively related to the uptake of the various CF options. A plausible explanation is that CF is perceived to be a labour-intensive technology package, thus making it less attractive to part-time farmers. It is also probably because income from off-farm activities can be invested in alternative and more expensive soil-improving inputs like fertilizer, and hence the less likelihood of adopting CF practices. In line with earlier research (Abdulai, 2016; Tambo and Mockshell, 2018), we see that credit-constrained households are significantly less likely to invest in CF practices, particularly the joint adoption of the practices. This is not surprising because credit can allow cash-constrained households to meet the costs involved in implementing CF practices, such as costs of specialized equipment (e.g., Magoye ripper) and complementary inputs like herbicides. Membership in farmer group, a proxy variable for social network or peer effect, is significantly linked to the use of CR individually and jointly with MSD and RR. This lends credence to the finding from a review of CA literature showing that social capital is a key driver of CA adoption in different settings worldwide (Knowler and Bradshaw, 2007). Livestock holding is negatively correlated with all the CF options, but has a statistically significant effect only on RR when adopted in isolation or concomitantly with MSD or MSD+CR. This resonates with the notion that the competing uses for crop residues is a key obstacle to the adoption of CA in Africa (Giller et al., 2009; Corbeels et al., 2014).

Results also suggest that higher rainfall is significantly related to a lower probability of adopting CF practices. Besides improving soil nutrition, CF techniques such as RR and MSD are touted as important soil moisture conservation measures; hence, they may be more attractive to households located in areas with low rainfall or frequent dry spells. We see that households located in AEZ III (high rainfall zone) are significantly less likely to adopt the full CF package (MSD+RR+CR) than those located in AEZ I (drought-prone zone), further confirming the importance of rainfall variability in CF adoption decisions. This result also corroborates the evidence from previous research in Zambia demonstrating that farmers adopt some of the CF practices as an adaptation measure to climate variability (Arslan et al., 2014; Kuntashula et al., 2014; Grabowski et al., 2016). Finally, we find that households located in AEZ II are more likely to adopt the full CF package as well as the RR+CR option, compared to those located in AEZ I. This is probably due to better awareness and knowledge of CF, as Eastern province (AEZ II) is the origin and centre of CF activities in Zambia (Arslan et al., 2014).

3.3. Determinants of maize yield

Table 4 reports the OLS estimates of the associations between the CF options and maize yield. In model 1, we only include controls for inputs use, plot and household characteristics. In model 2, we include plot-level variation in FAW infestation levels, in addition to the other control variables in model 1, while model 3 contains all the control variables, including the FAW management options used. Results show that only CR singly and its combination with RR significantly influence maize yield, with and without controls for FAW infestation and management strategies. In particular, conditional on household and plot characteristics, inputs, and FAW infestation and control measures, the CR only and RR+CR plots significantly out-yield the non-CF plots by 342 kg/ha and 462 kg/ha, respectively. Interestingly, the complete CF package variable shows the expected positive sign but is not significantly associated with higher maize yield.

Table 4 also shows that the severity of FAW infestation is significantly associated with reduced maize yield, as one would expect. For instance, compared to plots with minor infestation of FAW, plots with major infestation produced almost 460 kg/ha lower maize yield. Results suggest that among the FAW control measures, the use of chemical pesticides is the most effective in protecting yield. Chemical control significantly increases yield by nearly 500 kg/ha, corroborating the findings of Tambo et al. (2020a) who reported maize yield gains of about 90% from smallholder management of FAW using chemical pesticides. The negative and significant coefficient on the plot size variable suggests that maize production in our study area exhibits the well-known inverse farm size-productivity relationship (Barrett et al., 2010; Carletto et al., 2013).

Yields are higher on plots further from the homestead, which is possibly due to differences in soil conditions. The gender of plot manager variables do not significantly influence maize yield, suggesting that our results do not support the common notion that plots managed by women are less productive than those managed by men (FAO, 2011; Slavchevska, 2015). We observe that the use of modern farm inputs, such as improved seeds, herbicides and fertilizers significantly raise yields of maize. For example, adopters of improved maize seeds achieved about 320 kg/ha more yield than adopters of local varieties. Similarly, a 100 ZMW/ha investment in fertilizer and herbicide is significantly linked to about 12 kg/ha and 124 kg/ha increases in maize yield, respectively.

The results further show that the household demographic factors other than durable asset wealth are not significant determinants of yield. While proximity to extension services is generally not significantly correlated with the choice of CF practices, it is significantly associated with higher maize yield. Consistent with expectation, we find that higher rainfall leads to a significant increase in yield. There are also significant agro-ecological differences in yield, reinforcing the importance of rainfall in the performance of maize under FAW stress. For instance, households located in higher rainfall areas (AEZ III) obtained over 800 kg/ha gain in maize grain yield relative those located in areas of low and erratic rainfall (AEZ I). Taken together, this suggests that higher yields can be realised even in the face of FAW stress, provided there is a good amount of rainfall. Besides being vital for healthy plant growth, the amount of rainfall can affect the distribution, infestation rates and survival of FAW (Early et al., 2018). These results also concur with previous studies showing that the yield and economic performance of CA techniques differ across agro-ecological environments (Thierfelder et al., 2017).

3.4. *Yield effects of CF practices*

Before looking at the doubly robust estimates of the yield effects of CF practices, we first inspect whether or not the covariate balancing and overlap conditions of the CF adoption models are fulfilled. The balance diagnostic test results (Table A1 in the appendix) show insignificant chi-squared statistics; therefore, we cannot reject the null hypothesis that our CF adoption models balance the covariates by weighting (Imai and Ratkovic, 2014). Fig. A1 in the appendix also shows sufficient overlaps in the distribution of the propensity scores between various CF adopter categories and non-CF adopters, confirming a satisfaction of the overlap or common support condition. This indicates that conditional on relevant covariates, each maize plot has a positive probability of having and not having a CF practice. The results from the balancing and overlap diagnostics suggest high degrees of comparability between our CF adopter and non-adopter categories after weighting. Consequently, we can now examine the results of the doubly robust estimates of the effects of CF practices on maize yield, which are presented in Table 5.

The adoption of RR in isolation has a positive but statistically insignificant effect on maize yield, irrespective of the category of control variables included. On the contrary and consistent with OLS estimates above, the adoption of CR singly exerts a positive and statistically significant (albeit weak) effect on maize yield. The yield gain due to the adoption of CR singly ranges from 340 kg/ha to 352 kg/ha, depending on the control variables included. This is equivalent to about 22% yield advantage over the potential-outcome mean for the non-adopters of CF. We also find significant yield effects when RR and CR are adopted in tandem. The practicing of RR+CR enhances maize yield by 360 kg/ha (28%) when the severity of FAW infestation is controlled for and 294 kg/ha (22%) when both the severity of FAW infestation and the management strategies are taken into account. Given the significant maize yield effect of CR singly, but not RR singly, it is likely that the significant effect of RR+CR is largely driven by CR. Moreover, after including all the control variables (model 3), the joint adoption of RR and CR does not generate higher yield gains than the sole adoption of CR, possibly pointing to no major extra yield benefits to CR when it is supplementing with RR. As earlier explained, the yield advantage of CR could be due to the fact that rotation of maize with legumes improve soil health, which can support healthy plant growth, thereby helping the maize plants to withstand FAW attack and ultimately result in increased yield. Additionally, crop rotation helps to break pest cycles and prevent the build-up of pests.

The results in Table 5 also suggest that MSD+RR, MSD+CR and MSD+RR+CR do not significantly influence maize yield, even after controlling for adoption decisions and other determinants of yield. Thus, none of CF packages that includes MSD (a key component of CF) provides a significant yield benefit in the face of FAW invasion. The treatment effect estimates of some of the CF practices are even negative (albeit statistically insignificant), suggesting lower yields compared to non-adoption. This is in contrast to Baudron et al. (2019) who found that MSD significantly decreased FAW damage in maize fields in Eastern Zimbabwe.

Overall, our results are in line with findings from previous research indicating that the full adoption of packages of CF practices may not necessary produce the greatest outcome (Pannell et al., 2014; Ng'ombe et al., 2017); and thus, the farmers' decision to adopt components of the CF technology package seems rational. The results are also in line with Arslan et al. (2015) who found no significant effect of MSD on maize yield in smallholder agriculture in Zambia, but differ in terms of the significant yield effect of CR in our case. All in all, our findings suggest that among the CF options practiced by smallholders in Zambia, only CR singly or when combined with RR may have the potential to increase maize yield under FAW stress; and adopters of the other CF packages may not be significantly better or worse off than non-adopters.

However, it should be emphasised that these results are based on cross-sectional data and estimation techniques, which precluded us from accounting for potential selection bias due to unobserved heterogeneity and from examining the dynamics and long-term yield effects of the CF practices in the presence of FAW infestation. Hence, further research using alternative methods (such as panel data methods) would be useful to confirm our findings and improve the understanding of the extent to which the CF practices can mitigate FAW-induced yield loss.

As also noted earlier, we were unable to estimate the yield effect of the adoption of MSD singly due to limited observations ($n = 15$). One could argue that excluding these few MSD only observations from the analysis may create a sample selection bias. It could also be argued that the MSD+RR and MSD+CR estimates are limited by lack of statistical power, given that the plots under these two CF options were only about 3.5% each. Hence, as a robustness check, we combined the MSD only, MSD+RR and MSD+CR variables into one variable (called combined MSD practices) and re-estimated the yield effects of the CF categories. The OLS and doubly robust estimates in Table A2 in the appendix suggest no significant effect of the combined MSD practices on maize yield, further confirming the above findings on the lack of significant yield advantages from MSD-related practices under FAW stress. The remaining results are similar to those reported in Tables 4 and 5, where we dropped the MSD only variable and separated the MSD+RR and MSD+CR variables.

Finally, it should be mentioned that while the focus of the current study was on the effectiveness of CF practices in reducing yield loss under FAW stress, there are several other compatible agro-ecological approaches (e.g., fertilisation, field margins and weed management) that can be used to sustainably manage FAW in smallholder farming systems (Harrison et al., 2019; Hruska, 2019). For instance, Midega et al. (2018) found that a climate- adapted push-pull strategy was effective in controlling FAW in maize in East Africa. Some of these agro-ecological options could also be tested or promoted for FAW management in Zambia.

4. Conclusion

Conservation farming (CF) is being extensively promoted in sub-Saharan Africa with the goal of increasing smallholder productivity while conserving natural resources. In the wake of the outbreak of the highly destructive FAW pest in Africa and Asia, CF has been hypothesised to have the potential to mitigate yield loss by providing favourable microclimate for natural enemies, by disrupting FAW life cycle, and by supporting healthy plant growth, thereby better withstanding FAW infestation (Prasanna et al., 2018; Harrison et al., 2019). Using recent data from 1048 smallholder maize plots across the major maize-growing areas in Zambia, this study examined the extent to which the implementation of CF practices can offset the negative yield effects of FAW. In particular, we examined: (1) the factors determining smallholders' use of three CF practices, either separately or in tandem; (2) whether CF is able to raise maize yields even in periods of FAW outbreak; and (3) the heterogeneous effects of CF technology packages on smallholder maize yields under FAW stress.

The data showed that partial implementation of the CF practices is common among Zambian smallholders. Only 26% of the sample plots were under the full CF package, consisting of MSD, RR and CR. Regression results indicated that the key factors inhibiting the implementation of the CF practices include tenure insecurity, livestock raising, credit constraints, off-farm employment, and agro-climatic conditions. We found suggestive evidence that CR, when adopted in isolation or in combination with RR, significantly (albeit weakly) increased maize yield under FAW stress. Specifically, after controlling for the severity of FAW infestation, inputs use and other determinants of maize yield, the practicing of CR only and RR+CR enhanced maize yield by 340–352 kg/ha and 294–360 kg/ha, respectively. Conversely, none of the MSD-related practices (including the full CF package) had a significant effect on maize yield. We also found that high-rainfall environments and the use of improved seeds and agrochemicals are the most robust determinants of smallholder maize yields in the face of FAW invasion.

Overall, our analyses suggest that certain components of CF can mitigate FAW-induced yield loss in the short-term. However, this would require further investigation. The data used in this study were collected just two years after the outbreak of FAW in Zambia, and it is unknown how long CF have been practiced on the sample plots. The cross-sectional nature of the data allowed us to examine only the short-term yield effects of CF under FAW stress. Some previous studies have suggested that the yield responses of crops to CF practices are slow, with a potential lag of up to five or more cropping seasons before significant yield gains are observed (Giller et al., 2009; Thierfelder et al., 2017). Hence, additional research using panel data would be necessary to further understand the extent to which the CF practices can reduce the risk of FAW infestation and increase yield in the long-term.

Our findings also imply that to maximise maize yield under FAW stress in the short run, the implementation of the crop rotation component of CF needs to be complemented by the use of modern inputs such as improved seeds and pesticides. However, considering reports that some of the pesticides used against FAW in Zambia are highly hazardous to human health and the environment, coupled with the limited use of personal protective equipment (Kansiime et al., 2019; Tambo et al., 2020b), efforts should be geared towards the promotion of safer and environmentally friendly alternatives such as biopesticides and agro-ecological approaches, as well as the development of maize varieties that are resistant to FAW.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

See Table A1 and A2, Fig. A1.

Table A1
Test of covariate balancing.

	Chi^2	P-value
RR only vs. non-adopters	5.13	0.9974
CR only vs. non-adopters	13.21	0.8279
MSD+RR vs. non-adopters	0.45	1.0000
MSD+CR vs. non-adopters	3.87	0.9991
RR+CR vs. non-adopters	13.58	0.6967
MSD+RR+CR vs. non-adopters	16.84	0.4654

Table A2
Effects of CF practices on maize yield (combined MSD practices).

	OLS estimates			Doubly robust estimates		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
RR only	-208.362	-184.268	-89.626	320.17	320.04	251.98
	(211.204)	(209.653)	(205.939)	(374.56)	(376.29)	(358.17)
CR only	364.280 *	341.911 *	348.830 *	351.84 *	347.00 *	339.58 *
	(192.157)	(191.815)	(190.261)	(200.74)	(195.27)	(198.37)
RR+CR	421.711 * *	429.818 * *	472.188 * **	178.27	360.15 * *	294.21 *
	(170.075)	(167.85)	(166.875)	(179.31)	(150.95)	(158.17)
MSD+RR+CR	267.928	276.731	234.164	-159.53	-75.39	84.05
	(182.581)	(180.482)	(199.059)	(321.81)	(299.49)	(247.96)
Combined MSD practices	215.673	216.092	268.861	252.10	247.87	389.22
	(203.493)	(200.777)	(178.517)	(253.52)	(243.15)	(267.40)

Notes: * **p < 0.01, * * p < 0.05, *p < 0.1. Robust standard errors in parentheses. The maize yield variable was winsorized at the 1st and 99th percentiles. As a robustness check, we also estimated the OLS models using a log-transformed maize yield. The results, which are available on request, are similar to those reported in Table A2.
Model 3: all the control variables are included; Model 2: no controls for FAW management strategies; Model 1: no controls for FAW management strategies and severity of infestation.

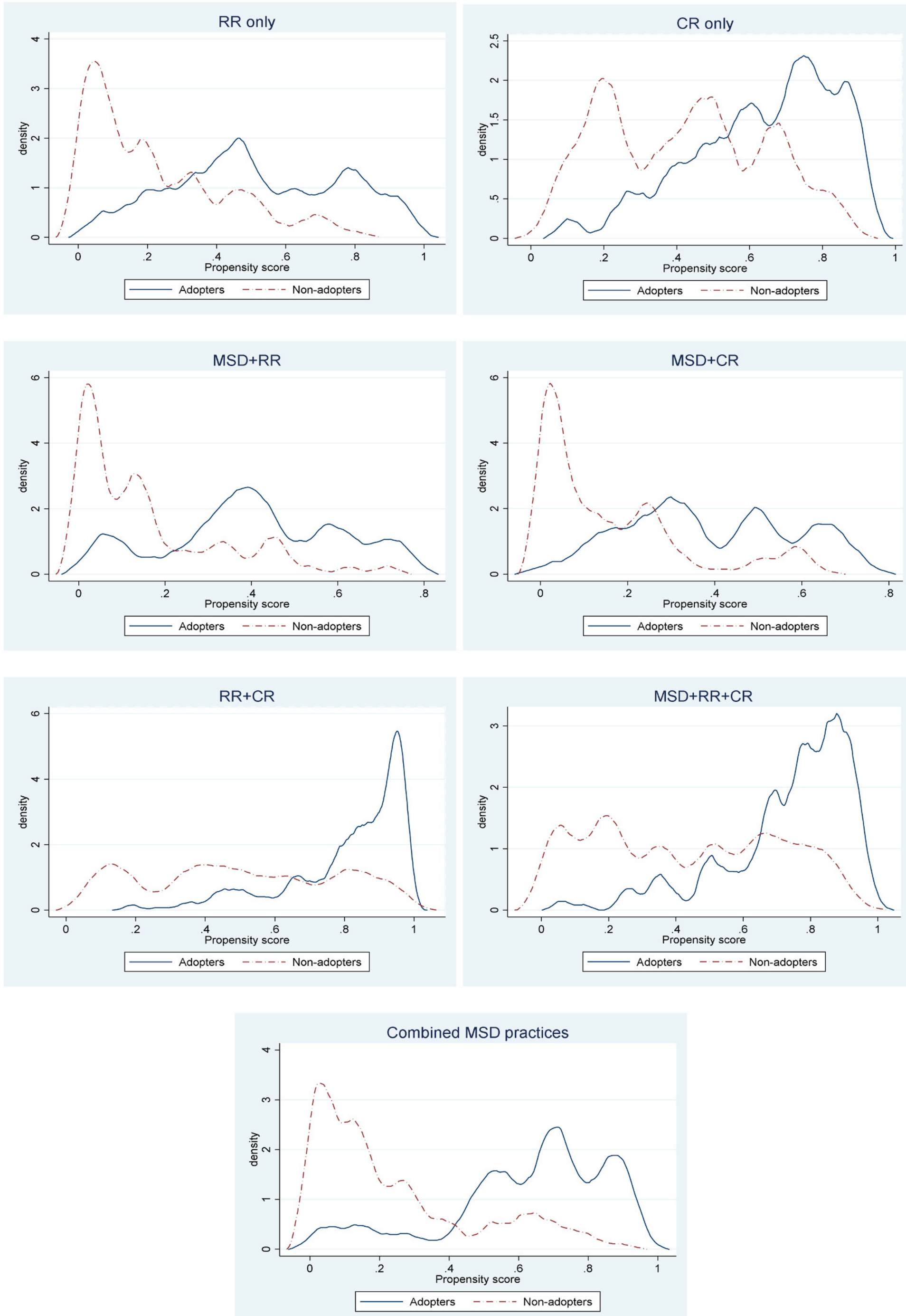

Fig. A1. Kernel density distribution showing overlap between adopters and non-adopters of CF practices.

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