Staple crop pest damage and natural resources exploitation: fall army worm infestation and charcoal production in Zambia

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Abstract

Sub-Saharan Africa (SSA) is home to the highest rates of deforestation in the world, pushing the research community to understand its drivers. One driver may be negative agricultural shocks that drive households to consume natural resources as a coping mechanism. This paper uses primary household panel data from Zambia to estimate the effect of the introduction of an agricultural pest, fall armyworms (FAW) on charcoal production. We exploit exogenous variation in the intensity of exposure to FAW across households and years to identify their effect and find a positive and significant effect of FAW on charcoal production and deforestation. We find that FAW in the village increases the probability of producing charcoal by 3.48 percentage points, from 22 percent to 25 percent. The results also indicate that when methods to mitigate FAW damage such as reducing the share of maize, migration for off-farm employment opportunities and chemical spraying are available, farmers are less likely resort to charcoal production as a coping strategy. Effects are robust to linear including region-specific time trends and instrumental variables for FAW presence. The results suggest that policy interventions to mitigate agricultural production shocks could also have the benefit of reducing charcoal production and deforestation.

1 Introduction

Climate change is an existential threat and limiting deforestation is a critical climate mitigation strategy. Forests are a vital carbon sink and deforestation is a significant source of Greenhouse Gases (GHGs) (Fearnside, 2000; Houghton et al., 2000). Deforestation is recently on the rise, particularly in Sub-Saharan Africa (SSA), driven in large part by charcoal production. (Sparovek et al., 2012; Bare, Kauffman, and Miller, 2015). Many smallholder maize farmers also produce charcoal to purchase farm inputs such as seeds, fertilizers and pesticides for the upcoming agricultural season (Kalipeni et al., 2009). A study by Mulenga, Hadunka, and Richardson (2017) finds a correlation between low agricultural productivity and fuelwood production. However, the authors do not separate the effects of charcoal and firewood in their analysis which are distinct products [1]. Little work estimates the causal effect of agricultural production shocks on charcoal production, and how this is affected by the availability of other coping strategies.

Farmers can employ several coping strategies during a bad agricultural season such as: migration, crop diversification, off-farm employment, and charcoal production (Eriksen, Brown, and Kelly, 2005; Osei, 2017; Hänke and Barkmann, 2017). Farmers use the income from charcoal production as a safety net during a crop failure or other economic shocks (Brobbey et al., 2019; Ndegwa et al., 2016; Mulenga, Hadunka, and Richardson, 2017). Prior studies on the relationship between charcoal production and agricultural shocks are based on cross-sectional data, and the specifications often have endogeneity issues. In this study, we use a specific exogenous agricultural shock - the introduction of fall armyworms (FAW) - to estimate its effects on charcoal production.

Fall armyworms are a relatively new crop pest in Zambia, first reported in 2016 (Durocher-Granger et al., 2020). To estimate the effect of FAW exposure on charcoal production we use a panel dataset of 1,200 farmers over 4 years. We then further estimate what factors can exacerbate of mitigate the link between FAW and charcoal production.

This study provides insight into how farmers respond to a new pest shock and

[1] It is much less common for people to sell firewood, while charcoal is widely sold along roadsides and in towns

how coping mechanisms can affect natural resources management. It contributes to the broad literature on deforestation and agricultural productivity/production. [Most of these studies argue that there is a positive relationship between agricultural productivity and deforestation (Abman and Carney, 2020; Chibwana, Jumbe, and Shively, 2013; Doggart et al., 2020). Other studies have found a negative relationship between agricultural productivity/production and deforestation (Mulenga, Hadunka, and Richardson, 2017; Labarta, White, and Swinton, 2008; Zulu and Richardson, 2013). However, all these studies use positive agricultural shocks to show the relationship between agricultural productivity/production and deforestation.] This study is among the few to analyze the impact of an negative agricultural shock on a natural resource (forests).

This paper also estimates the impact of a negative shock on deforestation as a coping mechanism in the presence of other coping mechanisms. Most studies that study the effect of agriculture on deforestation use deforestation satellite data (Geoghegan et al., 2001; Cardille and Foley, 2003; Vance and Geoghegan, 2002). However, satellite data lacks the spatial granularity to pick up selective tree harvesting associated with charcoal production. Additionally, the common deforestation dataset (Hansen et al., 2013) is not well calibrated to non-tropical forests. In this paper, we use primary household data on their charcoal production.

We find that the presence of FAW in a village increases the probability of producing charcoal by 3.48 percentage points, from 22 percent to 25 percent. The result is robust to a linear fixed effects models that includes household characteristics and district-year fixed effects. Further, the results also indicate that when methods to mitigate FAW damage such as reducing the share of maize, migration for off-farm employment opportunities and chemical spraying are available, farmers are less likely resort to charcoal production as a coping strategy. The findings are consistent with previous studies which find that charcoal is more labor intensive and less profitable compared to crop production (Hänke and Barkmann, 2017; Mwampamba, Owen, and Pigaht, 2013; Stassen, 2015). Thus, farmers would prefer producing crops over charcoal during a normal agricultural season. Farmers would also prefer changing cropping patterns to mitigate the effect of FAW act as a substitute for charcoal.

Given that FAW and other agricultural pests outbreaks are becoming more prevalent with climate change (Gregory et al., 2009; Paini et al., 2016), this study highlights an additional cost of climate change as it drives farmers to consume natural resources as a coping strategy. Second, this paper highlights which other strategies can help mitigate the link between negative agricultural production shocks and deforestation. These findings can help policy makers and resource managers identify and support households who are more likely to produce charcoal when faced with an agricultural production shock.

2 Background

80 percent of the countries in the world most affected by deforestation are located in Africa (Semazzi and Song, 2001). Most of the African countries with high deforestation are in the SSA region. Zambia has one of the highest rates of deforestation and forest degradation in SSA, with most estimates indicating of between 250,000 - 300,000 hectares of forest loss per year and a deforestation rate of approximately 6 percent (Zulu and Richardson, 2013; Mabeta, Mweemba, and Mwitwa, 2018; Kalaba, 2016; Ngoma et al., 2021; Phiri, Morgenroth, and Xu, 2019). A number of factors have been identified as drivers of deforestation, with charcoal and fuel wood production among the most prominent (Mulenga, Tembo, and Richardson, 2019; Mwitwa and Makano, 2012; Chidumayo et al., 2002).

Charcoal production is likely to continue being a major cause of deforestation in Zambia. Increased demand for charcoal is caused by high electricity tariffs, erratic and unreliable electricity supply, and lack of other sources of energy (Mulenga, Hadunka, and Richardson, 2017). On the supply side, charcoal is a source of income for rural households. Many smallholder farmers use charcoal as an alternative source of income during negative production shocks (Mulenga et al., 2014; Zulu and Richardson, 2013).

Fall army worms are a voracious pest which can attack a crop at any stage in its development but usually appears in the early stages with potential to cause complete crop failure (Harrison et al., 2019; Donatelli et al., 2017). The pest has ravaged staple maize fields and has caused significant reduction in yields in SSA since first reported in 2016. According to the Zambia Vulnerability Assessment Report of 2018 by the Disaster Management and Mitigation Unit (DMMU), estimated that more than 130,000 hectares of maize were destroyed by the FAWs during the 2016/17 agricultural season causing the government to spend millions of dollars in pesticides and other control measures (Province, 2012).

Huge losses in crops and expected incomes would make farmers who reported FAW infestations to be more likely to engage in other income generating activities to supplement their crop income in the next agricultural season. A readily available option for supplementing farm income is natural resource exploitation, particularly forest-based activities such as harvesting wild fruits, mushrooms, honey, and charcoal production. These can either be for home consumption, sale, or both. Charcoal, in particular, remains a common sources of forest income among rural smallholder farming households in Zambia (Mulenga et al., 2014; Brobbey et al., 2019; Zulu and Richardson, 2013).

FAW are a possible cause of production shocks as they are likely to continue causing crop damage in the foreseeable future. The magnitude of the FAW shock would shift some of the household's labor and resources toward charcoal production. However, how farmers shift their labor between both types of production is unknown.

A number of studies have been conducted to understand the relationship between maize production/productivity and charcoal production (Mulenga, Hadunka, and Richardson, 2017; Smith, Hudson, and Schreckenberg, 2017). Mulenga, Hadunka, and Richardson (2017) is one of the few studies to rigorously address the relationship between agricultural productivity and charcoal production. The authors find a negative relationship between maize yields and likelihood of charcoal production in Zambia. However, the results do not attribute yield loss to a particular factor such as an insect pest shock. A more nuanced understanding of how different production shocks are associated with charcoal production helps identify interventions to address over exploitation of natural resources. This paper analyses the nuance by determining the nature and magnitude of the relationship between

FAW infestation of maize fields and smallholder farmers' likelihood of participation in charcoal production. In addition, in the event of an FAW infestation, we assess the strategies that farmers use to mitigate this risk.

3 Study site

The study sites included 12 randomly selected districts in Zambia[2]. These districts are Mkushi, Mumbwa, Mpongwe, Masaiti, Lundazi, Petauke, Mbala, Mungwi, Chinsali, Mufumbwe, Solwezi, Choma and Namwala. Respondents were randomly selected across all the districts. On average, the same number of households were sample from each district. We further randomly selected agricultural camps within the districts. An agricultural camp is defined as a small unit within the agricultural sector where farmers are grouped around agricultural extension service provision in groups called cooperatives (Alamu et al., 2018). A cooperative is a small group of farmers living in the same locality (camps) that come together to help each other to have better price bargains, access to resources (agricultural inputs) and extension services. Cooperatives is the best way in which the government can be able to reach farmers and provide inputs and extension services (Bijman and Wijers, 2019; Blekking et al., 2021). Even though the cooperatives are heterogeneous, the members within the same cooperatives usually have access to resources (inputs, pesticides) are similar times Finally, we randomly selected households within the agricultural camps and villages.

4 Data sources

The data comes from a large panel survey of smallholder farmers across Zambia called the Household Income Consumption and Production Survey (HICPS). The survey was conducted in June and July of 2016, 2017, 2018 and 2019 covering the 2015/16, 2016/17, 2017/18 and 2018/19 agricultural seasons. The HICPS sampled about 1,200 smallholder households in 12 districts of Zambia and collected data on socioeconomic,

[2]The selected districts are shaded in Figure 2 of the appendix

demographic characteristics, production activities, income sources and insect pest infestation, charcoal/firewood production and sales (aggregated monthly), expenditure from charcoal sales (how the money from charcoal sales spent). The survey was a cooperation by the University of Illinois, Indiana University, Princeton University, the University of Zambia and Zambia Agricultural Research Institute.

The HICPS defines FAW infestation intensity as the proportion of the farmer's crop in the field that was damaged by FAW. Based on the farmer's responses, enumerators categorized the infestation in three categories: if the farmer reported that the infestations destroyed less than 25 percent of their crop then that would be categorized as low level of infestation intensity; reports of crop damage of 25-50 percent were be categorized as severe medium (moderate) infestation intensity; and damages of over 50 percent were regarded as severe infestation intensity. The survey also asked if and when the households produced charcoal during their agricultural production season.

To plot the pre-trends, we use the deforestation rates data from the Global Forest Change dataset by the university of Maryland. Further, rainfall is obtained from the Climate Hazards center InfraRed Precipitation with Station data (CHIRPS) repository and the temperature data is from the Moderate Resolution Imaging Spectroradiometer (MODIS).

5 Charcoal and FAW theoretical model

5.1 Basic Model

We start by assuming each household is trying to maximize utility from its production and that there are no savings such that $y_i = c_i$. Each household is able to produce either an agricultural output or charcoal. Each one has its own production function f and g, respectively. We also assume that the agricultural good is the numeraire so has a price of 1, and the price of the charcoal is p.

There are two states of the world, s_p and s_{np} in which the household must consider: one in which a pest infects its crops which happens with probability α and one without pest with probability $1 - \alpha$. The pests affect only the agricultural output and not the production of charcoal.

The household must choose how much labor they will allocate to the production of either charcoal and agricultural goods. We normalize the time they can allocate for labor to be 1, such that the time they spend in agricultural work is l_a and the time they spend in charcoal production is $1 - l_a$.

Households then maximize the following equation:

$$\max_{l_a} y = \alpha f(l_a, s_p) + p \cdot g(1 - l_a) + (1 - \alpha)[f(l_a, s_{np}) + p \cdot g(1 - l_a)]$$

Now let's assume no functional form, with some minor changes to account for it. We are going to have the inputs (land and trees) as part of the production functions. Additionally, let's assume there's diminishing marginal product of labor in both production functions ($f_l < 0, g_l < 0$) and that the capital inputs and the labor are complements ($f_{l,k} > 0, g_{l,t} > 0$). With the same first order conditions we get:

$$\rightarrow \alpha f_l(l_a, k, s_p) + (1 - \alpha) f_l(l_a, k, s_{np}) - p \cdot g_l(1 - l_a, t) = 0$$

Let's also assume that under the bad state that the production of the agricultural good becomes a fraction σ of the production in the good state. That captures the possible intensity of the pest. This also implies that:

$$\rightarrow \alpha\sigma f_l(l_a, k, s_{np}) + (1 - \alpha) f_l(l_a, k, s_{np}) - p \cdot g_l(1 - l_a, t) = 0$$

$$\rightarrow f_l(l_a, k, s_{np})[(1 - \alpha) + \alpha\sigma] = p \cdot g_l(1 - l_a, t)$$

$$\rightarrow f_l(l_a, k, s_{np}) = \frac{p}{1 - \alpha \cdot (1 - \sigma)} \cdot g_l(1 - l_a, t)$$

Therefore, we can see from the equilibrium equation, that if the household decides to produce charcoal, it must be the case that the *marginal product of labor in agriculture* is equal to a constant times the *marginal product of labor in charcoal production.* Some basic analysis we can gather from the equation above are:

1. If the price of charcoal (p) increases, the right hand side (RHS) of the equation, the marginal product of labor in the agricultural sector on the left hand side (LHS) must increase. Since the production functions exhibit diminishing marginal product of labor that implies that an increase in charcoal price will lead to a **decrease** in the labor supplied in the agricultural sector.

2. If the pest infestation (α) increases then the RHS of the equation becomes larger, which by the same logic implies lower labor used in the agricultural sector.

3. If the impact of the pests increases (σ) then the RHS of the equation becomes larger, so a decrease in labor in the agricultural sector.

4. If the household has more land (k) then since labor and land are complements, that increases the labor used on the agricultural sector.

5. Similarly, if the household has more trees (t) then since labor and trees are complements of the charcoal production that leads to a decrease in the supply of labor in the agricultural sector and an increase in the labor supplied to charcoal.

5.2 Model with outside opportunities (coping strategies)

Now the household can choose to allocate their labor over three different sectors: agriculture (l_a), charcoal production (l_c), and outside options ($1 - l_a - l_c$). The outside option, like the charcoal, doesn't depend on the state of the world and we assume it only depends on the the labor hours invested on it (since most of the work would be wage employment). Therefore, the new maximization problem is as follows:

$$\max_{l_a, l_c} y = \alpha[f(l_a, s_p)] + (1 - \alpha)[f(l_a, s_{np})] + p \cdot g(l_c) + p_2 \cdot h(1 - l_a - l_c)$$

Where $h(\cdot)$ is the production function associated with the outside labor, and p_2 is possible income relative to the agricultural production. We also assume the same conditions as in the previous model in which in the bad state the agricultural production is a fraction σ of the production of the good state. Solving the maximization problem for l_a and l_c yields the following two equations:

1.
$$f_{l_a}(l_a, k, s_{np}) = \frac{p_2}{1 - \alpha \cdot (1 - \sigma)} \cdot h_{l_a}(1 - l_a - l_c)$$

2.
$$g_{l_c}(l_c, t) = \frac{p_2}{p} \cdot h_{l_c}(1 - l_a - l_c)$$

3. Combining 1 and 2 gets:
$$\frac{f_{l_a}(l_a, k, s_{np})}{g_{l_c}(l_c, t)} = \frac{p}{1 - \alpha \cdot (1 - \sigma)} \cdot \frac{h_{l_a}(1 - l_a - l_c)}{h_{l_c}(1 - l_a - l_c)}$$

Equation 1 is identical to the one described in model 2 since the outside opportunities come in the maximization equation the same as the charcoal production did in Model 2.

Equation 2 indicates that increasing the relative income from the outside options to charcoal (p_2/p increases), then people would choose less l_c and work more on the outside option.

6 Charcoal dynamics

6.1 Charcoal production process

Charcoal production involves a tedious process of clearing of forest or woodland whose trees are converted into the charcoal biomass which can be used as a source of energy (Chidumayo and Gumbo, 2013). The most common way of making a kiln (surface earth-mound) is buying digging a pit/hole and the filling the pit/hole with wood and then this is covered with mud to form a surface earth-mound. This way, the surface earth-mound limits the amount of oxygen reaching the burning logs thus preventing the total burning of the wood to ashes in the process obtaining the biomass (carbonization) (Girard et al., 2002; Demirbas et al., 2016).

6.2 Charcoal production labor and timing

A normal agricultural season in most parts of the SSA usually begins in November and farmers start planting by the end of that month (Umar, 2014; Vorlaufer et al., 2017). The farmers start reporting the FAW invasions on the maize plant gets planed in November because at that time most of the maize would have would emerged and FAW would have started ravaging them (Babu et al., 2019; Supartha et al., 2021; Prabhakar et al., 2020). Typically, harvest of crops especially maize is done in July and this usually done by hand (Adnan et al., 2017; Awal, Koshi, and Ikeda, 2006). Depending on the intensity of FAW experienced by farmers that reported FAW, the farmers could possibly experience low crop complete crop failure. When farmers experience low yields or crop failure, the incomes of farmers are affected bearing in mind that these the major and possibly only source of income for these rural farmers is agriculture. This income shock just after harvest forces farmers to produce charcoal as an income safety-net (Kiruki et al., 2020; Brobbey et al., 2019; Mburu, Kung'u, and Muriuki, 2015). Charcoal is produced during the dry season between September and October just before the farmers begin planting. The reason for this timing is that the money for charcoal is important in procuring agricultural inputs for the in preparation of the being of planting in November (Zackrisson, Nilsson, and Wardle, 1996; Jones, Ryan, and Fisher, 2016; Smith, Hudson, and Schreckenberg, 2017). Given that charcoal is produced in the dry season just before planting when farmers are supposed to be clearing the land and gardening, it affects the temporal distribution of labor from land preparation which is supposed to be the main activity in the season, thus causing labor competition between land clearing and charcoal production which can also delay farmers' agricultural season (Labarta, White, and Swinton, 2008; Zulu and Richardson, 2013) (Labarta, White, and Swinton, 2008; Zulu and Richardson, 2013) (See figure 12 in the appendix for the production timing).

7 Empirical Approach

7.1 Identification strategy/approach

To identify the causal effect of FAW on charcoal production, our analysis exploits the variation in FAW infestations across households. We leverage the diffusion of FAW, which is based on exogenous weather variables and not on farmer characteristics (somewhat random), and conduct an average treatment effect (ATE) analysis using a difference-in-differences estimation with the panel data. The key assumption to the difference-in-differences approach is that in the absence of FAW, the households that reported having produced charcoal and those that did not have to be balanced across observables and unobservables, such that any difference that subsequent arises between the two groups, can be attributed to the FAW infestations (parallel trend assumption). To show the pre-trends, we use the the rate of deforestation from 2014 - 2019.

To extract the deforestation data we create a buffer of 4 km around the households coordinates which is on the average furthest distance of their landholdings. We then overlay the deforestation raster layer to extract the deforestation around the farmer's landholdings (where the farmers are likely to produce charcoal). We plot the means of households' deforestation that have at least reported having FAW at least once against those that never reported it. We then calculate the difference and the standard errors.

One of the major concerns of using satellite data, including the Global Forest Change data, is that it suffers from accuracy issues (Galiatsatos et al., 2020; Miller, 2016; Martone et al., 2018). For that reason, we use charcoal production which is producer based since it less likely to have accuracy issues compared to satellite data and thus, it is a good proxy for deforestation. In order to use the charcoal production as a proxy for deforestation, one needs to understand that charcoal production involves cutting down the entire tree and then heaping them to create a kiln which is later burnt under controlled amount of air (Njenga et al., 2014; Branch and Martiniello, 2018; Tunde, Adeleke, and Adeniyi, 2013) see Figure 6 in the appendix. The deforestation caused by charcoal can be proxied by satellite data.

We then carry out a correlation test to measure the dependency between charcoal production and deforestation. The results reveal a strong correlation between deforestation and charcoal production, with a correlation coefficient of 0.71. We further test this assumption using a balanced table (data does not extend before 2015/16).

As a robustness check for the parallel trend assumption, we carry out a leads test following the approach used by Autor (2003). We test whether households who produced charcoal and those who did not were different before FAW invasions.

$$Y_{it} = \gamma_s + \lambda_t + \sum_{k=l+1}^{z} \beta_k D_{it}(t = q + k) + X_{it}\delta + \varepsilon_{it} \tag{1}$$

For this, we include the lags and leads(future) of FAW instead of FAW. Where Y_{it} is the likelihood to produce charcoal, l is the 'leads' which is basically the current FAW infestations which in this study is the 'future FAW' in that it captures FAW in November-April compared to harvesting of charcoal in October before planting in that same agricultural (planting usually starts in November). For instance, this year's agricultural season,production begins November 2021- April 2022. For the lead l, the decisions to produce charcoal around October 2022 is basically from the FAW infestations in the same agricultural season (April - November). As for the lag, z, which affects the farmers decisions to produce charcoal in the current year based on the previous year's infestations, the possible crop failure from FAW leads to charcoal production starting October 2022 is from the previous agricultural season which between November 2020 - November 2021 (see figure 3 in the appendix). β_k is the coefficient for the kth lead or lag. The assumption for this test is that $\beta_k = 0, \forall k < 0$ which means all the coefficients on all leads of the treatment should be zero.

One may worry that FAW infestations are determined by farmer characteristics and not exogenous factors such temperature, wind and rainfall. To address this concern, we demonstrate the exogeneity of the FAW by regressing the FAW on the growing degree-days (GDD) for the FAW for each of the geographic location of the households. In calculating the GDD I follow the procedure by Fraisse and Paula-Moraes (2018). The formula is as follows;

$$GDD = \max\left(\left[0, \frac{\text{Tmax} + T\min}{2} - T\ base\ _1\right]\right)$$

Where $Tmax$ is the maximum average temperature for that day and the $Tmin$ is the minimum temperature for the particular day. $Tbase_1$, is the base is the optimal temperature that FAW thrive in which is 10 degrees Celsius (Fraisse and Paula-Moraes, 2018). To understand how much of the variation in infestation severity is determined by the GDD we check the correlation between the two variables. The motivation for this is to demonstrate that the FAW infestations are possibly determined by weather factors and not farmer characteristics. We specify the regression equation as follows:

$$FAW_{it} = \gamma_1 Temp_{it} + \rho Rain_{it} + \lambda_t + \psi_{it} \tag{2}$$

Where $Temp_{it}$ is the the growing degree days (temperature) that influence the activity of FAW and its square, ρ is rainfall its square and λ_t are the district and year FE and ψ_{it} is the error term.

7.2 Econometric model

To estimate the effects of FAW on household participation in charcoal production, We employ a correlated random effects (CRE) probit model. The most common panel probit model with a time invariant and time varying error component is random effects probit model. However, a potential problem with this estimator is the assumption that covariates are independent of the time invariant error. In the event that one suspects correlation, that can be modelled with the Mundlak device that models the time invariant error as a function of the means of time varying covariates. Through the Mundlak device, the random effects probit estimation will have the coefficients that margin out the time invariant error on the time varying variables. For this reason, random effects probit model would be superior for the non-linear models to linear fixed effects model (Chamberlain, 1982).

For the full sample in this study, we specifically employ a CRE probit given that our panel data set is unbalanced and non-linear as the dependent variable (household participation in charcoal/firewood production) takes on a value of one (1) if a household participated and zero otherwise. In the first year the charcoal variable is binary but in the subsequent years, quantity of charcoal production which is a continuous variable for the quantity produced. The estimated model is as follows:

$$P\left(y_{it}=1 \mid \mathbf{x}_{it}, FAW_{it}, c_i\right)=\Phi(\beta FAW_{it-1}+c_i\ +\mathbf{x}_{it}^{\prime}\gamma+\delta_{it}+u_{it}), t=1,\ldots,T \qquad (3)$$

$\boldsymbol{\beta}$ is the variable of interest which indicates the severity of FAW. We test for serial correlation is tested because the data have an annual temporal dimension using the Durbin-Watson (DW) test (Durbin and Watson, 1971). We lag the FAW variable by a year because the decision to participate in charcoal production is mainly dependent on the intensity of FAW in the previous season. For example, if a farmer is affected by FAW this season and loses the crop, the decision to produce charcoal will be in the following year as they start preparing for the agricultural season and they need some income to buy the inputs. c_i captures the time invariant unobservable characteristics of the households that can affect their participation in charcoal production and may also be correlated with some explanatory variables. Φ is the Cumulative Distribution Function (CDF) of the standard normal distribution function and $\mathbf{X}_{it}$ is a vector of covariates which include rainfall, temperature, agriculture production, and household characteristics. δ_{it} are the means of time varying variables and u_{it} represents an idiosyncratic error term.

As a robustness check, we consider a linear probability model (FE) with fixed effects (FE) estimation as specified in equation (3).

$$Y_{it}=\sigma_t+\beta FAW_{it-1}+\gamma\mathbf{X}_{it}+\mu\mathbf{Z}_i+\alpha_i+\varepsilon_{it} \qquad (4)$$

Y_{it} is a binary variable that takes the value of 1 if the household participates in charcoal production and 0 otherwise. $\mathbf{X}_{it}$ is a set of predictor variables that vary over time, $\mathbf{Z}_i$ are a set of predictors that do not vary over time, α_i combined effect on y of all unobserved variables that do not change over time, ε_{it} is the error term.

We estimate the effect of FAW intensity on the quantities of charcoal produced with the following Tobit regression:

$$Q^*_{it} = \beta' \gamma_{it-1} + \phi_{it} \tag{5}$$

$$Q_{it} = \begin{cases} Q^*_i, & \text{if } y^*_{ii} < 1 \\ 1, & \text{otherwise} \end{cases} \qquad i = 1, \dots, N \text{ and } t = 1, \dots, T \tag{6}$$

Where i is the household and t defines the time. Q_{ij} is the quantity of charcoal produced by household i in time t, $\boldsymbol{\beta}$ is the variable of interest which indicates the severity of FAW. The sample used only includes observations that reported charcoal production. We employ the random effects Tobit regression model. The random effects ensure that our estimates are not biased by incidental parameters, a problem with Tobit with fixed effects (Fernández-Val and Weidner, 2016). This is mainly because the distribution of dependent variable (quantity of charcoal produced), conditional on the explanatory variables is Normal, with uniform variance.

Given that in this study we use a panel data, the error term is defined as follows:

$$\phi_{it} = \lambda_i + u_{it} \tag{7}$$

Where λ_i is the unobservable individual effects and u_{it} is the unobservable individual and random effects. The individual effects λ_i is the individual random effects as it is randomly picked from the probabilistic distribution (Samut and Cafrı, 2016).

We then explore farmer's heterogeneous effects on charcoal production. We regress likelihood to participate in charcoal production on farmer characteristics such as the asset index, access to credit, landholding size etc, and also the interaction of farmer characteristics with FAW severity variable using the CRE framework as specified in equation 3. Understanding how individual characteristics have an effect on charcoal production is of relevance.

Furthermore, we explore various coping strategies that farmers use when affected by FAW. We regress the FAW_{it} on the various coping mechanisms such as inter-cropping, migration, crop diversification, off-farm jobs (piece-work) and maize share on the outcome variable as specified in equation (3).

Lastly, we investigate the effect of the coping strategies on the farmer likelihood to participate in charcoal production as using the CRE framework as specified in equation (3). The problem with this regression is that charcoal production is a coping strategy that farmers use when attacked FAW, which is endogenous. The endogeneity arises from the possible simultaneity when deciding among the available coping strategies to employ. For example, in instance where the household decides to migrate when affected by FAW, then that household cannot also chose to do piece-works at the same time. To address the potential endogeneity concern, we employ an instrumental variable (IV) technique. We use the availability of other coping strategies in a camp as the exogenous measure i.e., the camp level average of the sum of each farmer's coping strategy except the observed household. We follow the procedure by Papke and Wooldridge (2008) where they employ a correlated random effects approach with instrumental variables, in both the linear and nonlinear models. We leverage the variation of coping strategies across the agricultural camps in constructing the instrument. We specify the instrument as follows;

$$Z_{it} = \left[\sum_{i=1}^{i=j} CS_{it} \right] /n - 1 \tag{8}$$

We then regress these coping strategy instruments (as specified in equation 8) on likelihood to produce charcoal separately as a reduced form (RF) using equation (3). The instrument should not correlated with the outcome (likelihood to produce charcoal) of the regression other than through the endogenous variable (household coping strategy). For the exclusion criteria, we argue that that average coping strategies do not directly affect household outcomes. However, there are challenges to that assumption - i.e. if neighboring coping strategies generate spillovers in economic outcomes (not just in coping strategies), then that would violate the exclusion criterion.

Furthermore, for the instrument Z_i to be valid, it also needs to be highly correlated with the household coping strategies i.e. $E[Z_i \cdot \varepsilon_i] = 0$. We test for weak instruments and whether the household's coping strategies are correlated the neighboring farms' coping strategies within the camps. To satisfy the exclusion restriction, the likelihood that the household is practicing any of the coping strategies must be randomly distributed over space. The average camp coping strategies should only determine an individual household's likelihood to participate in charcoal production through affecting that household's likelihood of the household using the coping strategies itself.

The problem with the equations above is that the variable of interest, FAW intensity, is based on self-reporting which may suffer from measurement error. Further, one might worry that this measurement error is not random; more observant farmers may be more likely to report FAW and may also likely have higher maize yields. One may be concerned that if we do not instrument for the self-reported FAW infestations, our estimates of the effect of FAW on charcoal production will be biased.

To further address endogeneity concerns, we use the fact that FAW intensity for the *ith* farm is correlated with the presence of FAW on the neighboring farm, j. As a robustness check, we control for the possible mismeasurement error in reporting by using the average of the sum farmers' responses on FAW intensity at camp level for the household in a particular camp minus the observed household as specified in equation 8 (these camps households are from specific camps which are heterogeneous). We then regress the instrument on the likelihood of producing charcoal using the RF approach as in equation 3. The exclusion restriction states that if the probability to detect FAW in one's field is randomly distributed over space, then the average camp infestation level should only determine the individual's decision to participate in charcoal production through affecting that household's likelihood of being infested itself. To show that the mis-measurement error is randomly distributed over space, I plot the individual deviation from the camp average over space. We then test for weak instruments on both the intensity and binary instrument and from the first stage regression to assess if the household's stated infestation intensities are correlated with the FAW intensities of the neighboring farms in the camp.

8 Descriptive Statistics

To test whether households affected by FAW infestations are more likely to produce charcoal we create a map of households that reported severe FAW infestation (those reported reported more than 50 percent crop loss) and overlay the shapefile layer of the households that reported charcoal production. We concentrate on households that reported severe infestations to avoid having a clutter of households on a map which would make the visualization of the relationship between FAW and charcoal production difficult (see Figure 4 in the appendix). Additionally, the households with severe FAW are more likely to produce charcoal compared to those who experienced less severe infestation. Figure 4 shows that households that produced charcoal also reported having severe FAW infestation. This suggests a correlation between FAW and charcoal production.

Over the years the charcoal market has provided consumers, especially urban households, with affordable source of energy at relatively stable prices (Zulu and Richardson, 2013). Figure 5 in the appendix, shows the average prices of charcoal for the 2016-17 and 2017/18 agricultural season. The graph shows the charcoal prices have been somewhat stable within and across years. The consistency of charcoal prices are corroborated in the literature of Ellegård, Nordström, et al. (2003) and Chomitz and Griffiths (2001). Production of charcoal is not driven by the demand or prices, but instead by other factors. The farmers' decisions to produce charcoal is not influenced by the prices but on the marginal product of labor for agricultural sector and farmer characteristics. When the marginal productivity of labor in agriculture is low, the farmers would move their labor to other coping mechanisms such as charcoal with a higher marginal productivity and this decision is not influenced by the prices of charcoal (see the theoretical model).

We show that the intensity in FAW varies across years and districts (see Figure 7 in the appendix). In some districts the intensities were higher during the first year and reduced in the following year and then increased in the final year. For others they increased across the years.

With regards to the pre-trends in Figure 1, we find that the deforestation rates seem lower in places where FAW are not reported. However, there is no statistical difference in deforestation rates between households who reported to have had FAW at least once and those who did not. The difference is less than is less than 0.1 percent and the standard error 0.15 percent and thus, we can conclude there is no difference between the treatment group than the comparison group in regards to deforestation rates prior to the FAW infestation. We use the deforestation rate as a proxy for charcoal production as it allows to show pre-trends before 2015. It works as deforestation and charcoal production have a strong correlation (see Table 13 in the appendix). The leads test results (see, Table 9 in the appendix), indicate that the coefficient for the lead of the treatment to be zero. This entails that the households that produced charcoal and those that did not were not different before the invasion of FAW. This further supports the differences-in-difference (Diff-in-Diff) parallel trend assumption.

It is also worth noting that at baseline, all of the farmers have access to forests nearby. However, charcoal production as a risk management tool was only available to some farmers in some regions (camps) (see Figure 4 appendix)

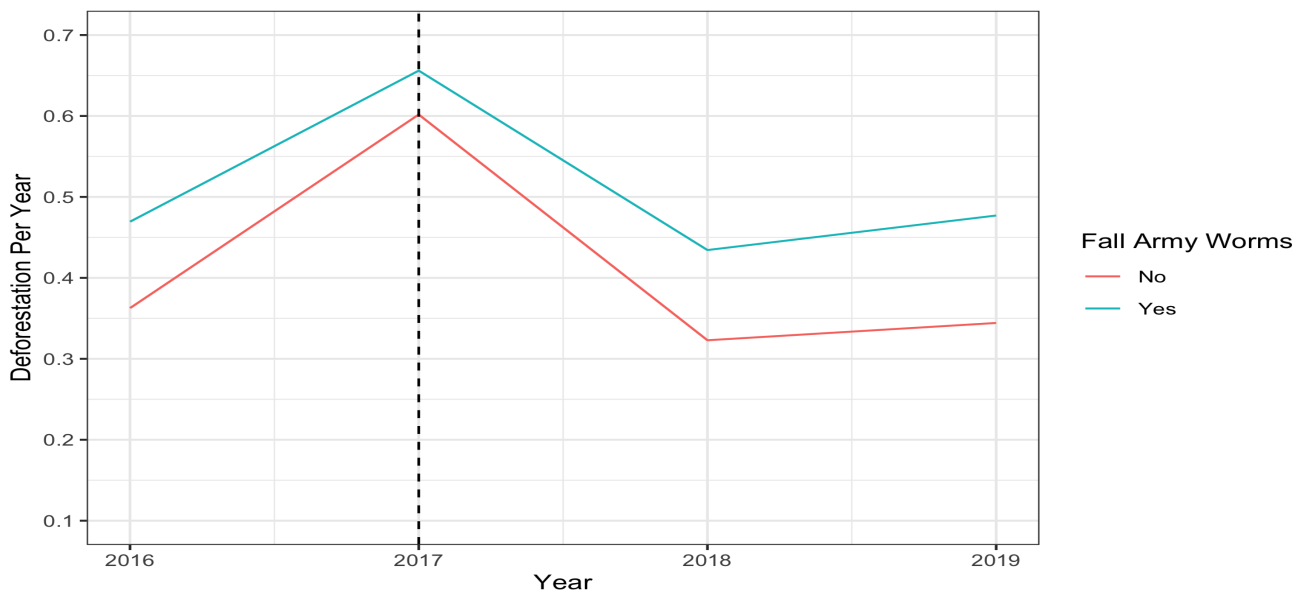

Figure 1: Deforestation rates trends. **Source: Author's work from Global Forest Change** (University of Maryland)

The results from show that temperature (degree growing days) and rainfall (weather variables) determine the severity of FAW and not farmer characteristics. From Table 1 We find that GDD and rainfall have significant effect on the intensity of FAW Which is not the case for farmer characteristics. From the table 1 we can also see that weather variables are the largest determinant of variation in the severity of FAW and not necessarily farmer characteristics. The F-test results, from comparing two models one with weather variables and the other with weather variables and farmer characteristics shows no significant difference between the two models.

Table 1: Effects of temperature on FAW

VARIABLES	(1) FAW intensity	(2) FAW intensity
Temperature	-0.3086*	-0.3195*
	(0.1864)	(0.1877)
Square of temperature	0.00415	0.00434*
	(0.00267)	(0.00269)
Rainfall	-0.00229*	-0.00258**
	(0.00089)	(0.00091)
Square rainfall	1.06e-06**	1.14e-06**
	(3.63e-07)	(3.68e-07)
Land cultivated (ha)		-0.00116
		(0.00275)
Education		-0.0114
		(0.0108)
Household size		0.0075
		(0.00461)
Gender (Male = 1)		0.0402
		(0.0454)
Year FE	Y	Y
District FE	Y	Y
R-squared	**0.364**	**0.366**
Observations	2,478	2,478

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

In Table 2, we present the balance table from the 2015/16 agricultural season (baseline season) between groups and test for the difference in means using the normalized differences similar to the approach in the study done by Friedman et al. (2016). Table 2 shows that the FAW produced treatment and control groups balanced along most characteristics. However, we find difference in rainfall between the two groups. We find that farming households with FAW infestations received relatively less rainfall, with an average of 931.29 mm, compared to households with no FAW 960.51 mm. The difference is not economically relevant, however, we still control for it in our models.

Table 2: Baseline (2015/16 agricultural season) Means and Balance

	Means (SD)		Normalized differences
	No FAW	FAW	No FAW vs with FAW
	(1)	(2)	(3)
Age (years)	46.6	45.319	0.018*
	(15.589)	(14.592)	
Gender (1 = male)	0.835	0.808	0.0142
	(0.371)	(0.393)	
Education	3.313	3.116	0.107
	(1.827)	(1.489)	
Charcoal	0.166	0.224	-0.0391
	(0.372)	(0.417)	
Total landholding	4.46	4.77	-0.115
	(9.74)	(6.049)	
Cultivated land	2.334	2.464	-0.134
	(2.402)	(2.414)	
Maize yield	1515.577	1601.981	0.218
	(1797.449)	(1508.622)	
Total income	7129.986	7436.039	0.178
	(13891.93)	(13897.2)	
Rainfall	931.291	960.517	0.401*
	(141.141)	(159.616)	
Access to credit	0.722	0.73	0.00947
	(0.448)	(0.444)	
Asset index	117.305	77.842	0.069
	(530.63)	(4.122)	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

9 Results

9.1 Main results

For this paper the CRE model is our preferred model. We employ the CRE model because of concerns about the population suffering from incidental parameters problem if a fixed effects model was used. In this study, we focus on the average partial effects, which represent the change in participation likelihood resulting from a change in the intensity while controlling for the covariates at their means. The estimates from Table 3 column 3 indicate that the intensity of FAW increases the likelihood of participation in charcoal production by 3.48 percentage points. Even though this study is different from the study by Mulenga, Hadunka, and Richardson (2017) which broadly estimates the relationship between agricultural productivity and charcoal production, the marginal effects are very similar. As a robustness check we show that FAW severity increases almost the same across all the intensity categories (See table 10 in the appendix).

The results are consistent with Mulenga, Hadunka, and Richardson (2017). A possible explanation is that FAW damage has a direct negative effect on maize yields. Losses in yields could be interpreted as the differences in productivity and/or production due to the availability of income and other inputs possibly influence the size of the yield losses which is also dependent on the intensity of FAW in the previous agricultural since and all that can be translated as agricultural productivity and/or production. Therefore, households who were affected by FAW in the previous season may have lower maize yields compared to those that did not get affected by FAW. Lower yields leads households to be financially constrained to buy more productive inputs such as certified seeds. And thus, since FAW affects the decision to participate in charcoal production through agricultural productivity/or production, it makes sense that our results are consistent with the findings by Mulenga, Hadunka, and Richardson (2017).

In terms of land, results show that cultivated land has a significant negative influence on the household's participation in charcoal production. As shown in the model, labor and land are complements and more land leads to higher allocation of labor by the households towards the agricultural sector which reduces the likelihood of households participating in charcoal production. This land (arable) is defined as the portion of land under the direct control of the household in accordance to the stipulated of the norms of the customary tenure system (Hichaambwa and Jayne, 2012). Although it may seem like Zambia has plenty of uncultivated land, access to land for the rural poor is still a problem. In Zambia, land is controlled under the customary land tenure system where the traditional leaders own the rights to the land and thus, the production of charcoal is constrained by land availability (Munshifwa and Botswana, 2003).

Table 3: Effects of FAW on charcoal production using the CRE model

VARIABLES	(1) Coefficient	(2) Average Partial effects
Lag FAW	0.0888*	0.0348***
	(0.1366)	(0.00533)
Land cultivated (ha)	-0.1026**	-0.00017**
	(0.0346)	(0.00074)
Education	-0.00832	-0.00427
	(0.03354)	(0.00305)
Household size	-0.01894	-0.00125
	(0.0130)	(0.0013)
Gender (Male = 1)	0.3114**	0.01552
	(0.1443)	(0.01293)
Weather controls	Y	Y
Observations	2,478	2,478

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note: Controlled for weather variables in the form of rainfall, temperature and their squared terms (weather controls)

We then further explore effects of FAW on quantity of charcoal produced using a random effects Tobit regression model. It is important to note that the number of observations are lower compared to Table 3 as some households while saying they produced charcoal did not specify a quantity. The results are shown in Table 4. In column 2 we present the effect of the FAW intensity on quantity of charcoal produced and in column 3, we control for covariates as specified in equation 3. Both sets of regressions control for district and year fixed effects. The results indicate that as the intensity of FAW increases, households' charcoal production increases by 1343 kilograms (kgs). According to a study by Malimbwi and Zahabu (2008), a tree of 32 cm diameter at breast height (dbh) on average produces only 80 kgs of charcoal which is sells for approximately K90 at current prices (4 dollars). A back of the envelope calculation estimates that farmers are likely to cut down approximately 16 trees when the intensity of FAW intensity increases. The results indicate that a significant quantity of trees are cut down for charcoal production by a single household affected by FAW (see figure 6 in the appendix to see the amount of trees from just a single medium sized kiln).

Table 4: Effects of FAW on quantity of charcoal produced

	(1)	(2)
VARIABLES	QChar(kg)	QChar(kg)
Lag FAW	1965.639	1343.62*
	(2003.717)	(345.28)
Controls	No	Yes
Year FE	Yes	Yes
District FE	Yes	Yes
Observations	1,634	1,572

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Note: Controlled for weather variables in the form of rainfall, temperature and their squared terms and household characteristics

9.2 Robustness checks

We analyze the effects of FAW on the likelihood of charcoal production using a linear probit model (LPM), the effect of insecticide spraying on FAW and camp average FAW infestations as robustness checks. Column 2 of Table 5 presents the LPM estimates with district and year fixed effects while controlling for several household characteristics. The estimates from the LPM are very similar to the estimates from the CRE model in

Table 3. One might be concerned that households that may have sprayed are less likely to participate in charcoal production than those who did not and that can potentially bias the results. In column 3 we specify the CRE model similar to equation 3. In addition to controlling for household characteristics and district and FE effects we control for the household spraying and its interaction with FAW. The results remain consistent even with controlling for spraying.

In column 4, we control for measurement error in farmer self-reports using the average prevalence of the FAW at camp level as both a measure of threat in and of itself, and as an instrument for self-reporting as specified in equation 8 using the CRE framework . The results from the weak instrument test indicate that the F-statistics from the first regression was 34.43 which is greater than 10. The Wald test indicates that the maximum amount that the instruments might be biased from weak instruments is 4 percent. Given this maximum amount of bias is relatively low, reject the null hypothesis of weak instruments. With such high F-statistics, the choice of the instrument is statistically strong as it is in line with the literature The results are consistent with the self reported results in column 2. Further, we regress the treatment (FAW intensity variable) as a categorical variable (dummies). The results in table 10 in the appendix section are consistent with the main results where we regress the treatment as a continuous variable.

Table 5: Robustness checks on the effect of FAW on charcoal production

VARIABLES	(1) Charc (=1 if yes)	(2) Charc (=1 if yes)	(3) Charc (=1 if yes)
Lag FAW	0.0322***	0.0395***	
	(0.00534)	(0.00529)	
Ave campFAW			0.0378**
			(0.0117)
Spray		-0.01286*	
		(0.00842)	
Spray*LagFAW		-0.00149	
		(0.00151)	
Land cultivated (ha)	-0.00012	-0.00016	-0.00008
	(0.00071)	(0.00074)	(0.00074)
Education	-0.00637	-0.00386	-0.00662**
	(0.00309)	(0.00306)	(0.00308)
Household size (Labor)	-0.00196	-0.00115	-0.00182
	(0.00132)	(0.0013)	(0.00141)
Gender (Male=1)	0.01862	0.0155	0.0212*
	(0.01299)	(0.0129)	(0.0129)
Weather controls	Y	Y	Y
District FE	Y		
Year FE	Y		
Observations	2,478	2,478	2,478

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note: Controlled for weather variables in the form of rainfall, temperature and their squared terms (weather controls)

9.3 Farmer heterogeneous effects

We further explore the effect of baseline farmer characteristics on charcoal production and then we explore the effects those characteristics when farmers are affected by FAW. The results from Table 6 indicate that farmers with access to credit are less likely to participate in charcoal production. In terms of land for cultivation we find that farmers with larger land are less likely to participate in charcoal production when affected by FAW. This is because as the household increases (clearing) the cultivated land they allocate more labor in agriculture and since labor and land are complements, increasing land increases labor in the agricultural sector which in turn increases agriculture production and thus reduces charcoal production. This is consistent with our theoretical model.

With regards to capital, we find that capital increases the marginal productivity of labor in agriculture and thus reduces the likelihood a household will produce charcoal. We define capital as the household assets that are used in the agricultural production such as an axe, machetes, etc that can be used for both agriculture and charcoal production. In the presence of FAW infestation, the marginal productivity of capital in agriculture becomes less and as such that the households reduces the labor used in the agricultural sector and thus increasing the likelihood of households participating in charcoal production. This result is consistent with the theoretical model. This could be because during FAW invasions farmers divert some of their capital to buying insecticides against FAW which is consistent with the theory. Further, the results indicate that farmers that reported having capital are less likely to participate in charcoal production. We then evaluate potential effects of distance on the likelihood of charcoal production.

We find that distance to the nearby trees which can be used for charcoal reduces the likelihood of households to engage in charcoal production. This is consistent with the study by (Malimbwi et al., 2000) which found that distance to the suitable trees that can be used for charcoal as increased over time which due to the depletion of the trees for charcoal production. However, in the presence of FAW invasions, the distance has an insignificant effect on reducing the likelihood of farmers participating in charcoal production. This could be attributed to the low marginal productivity of labor for agriculture during FAW invasions and thus farmers will still find charcoal production productive regardless of the distance and thus less likely to not to produce charcoal. This is in line with the analysis of the theory where we show that as the number trees reduce (distance to trees increase) given that labor and trees are complements of the charcoal production, then there will be an increased supply of labor in agriculture and less in charcoal production and hence the reduction of labor for charcoal production.

Lastly, the results indicate that the assets index does not play a significant role in reducing the likelihood of participation in charcoal production. What plays a significant role is capital because given that in most cultures the asset index is used as a sign of prestige and can not be used for liquidity even in times of crop failure and even if it can be used as liquidity and would reduce the effects of FAW, it is rarely used compared to capital.

9.4 Coping strategies when affected by FAW

We analyze how farmers cope with having been affected by FAW in the previous agricultural season. The results from Table 7 indicate that farmers affected by FAW reduce the amount of land allocated to maize. The results are expected as FAW prefer to attack maize or any crop in the grass family such as sorghum. In order to hedge against FAW infestation, the farmers reason then reduce the maize share in the presence of the pest. As farmers reduce their maize share (portion of the field dedicated for maize production), they increase the number of other crops they are planting, thus increasing crop diversification. Crop diversification involves the cultivation of a variety of crops in a mixed cropping method (Mofya-Mukuka and Hichaambwa, 2018). However, in this paper, crop diversification involves the shift from the producing more of the staple crop to the production of non-staple crops. We observe this effect in Column 3, where households affected by FAW in the previous agricultural season are 2.2% more likely to have reported crop diversification.

In column 2, we find that farmers that reported having higher FAW intensities are 23.3 percent more likely to spray insecticides than households that reported lower FAW

Table 6: Farmer heterogeneous effects

VARIABLES	(1) Charc (=1 if y)	(2) Charc (=1 if y)	(3) Charc (=1 if y)	(4) Charc (=1 if y)	(5) Charc (=1 if y)
Lag FAW	0.0159**	0.01408*	0.01395**	0.01145	0.0141**
	(0.00789)	(0.00797)	(0.00611)	(0.00834)	(0.00789)
Acess to credit (1= Yes)	-0.0198**				
	(0.00919)				
Access to credit *FAW	-0.00606				
	(0.00519)				
Land cultivated (ha)		0.00020			
		(0.00032)			
Land cultivated *FAW		-0.000034			
		(0.00062)			
Capital			-0.01201***		
			(0.00304)		
Capital* FAW			0.01395**		
			(0.00249)		
Distance to trees				-0.0227**	
				(0.00837)	
Distance to trees* FAW				-0.001074	
				(0.00155)	
Asset Index					-0.000753
					(0.00516)
Asset_Index* FAW					-9.49e-07
					(6.45e-07)
Observations	2,478	2,478	2,345	2,478	2,478

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

severity. The results indicate that spraying is the most used and effective and most used coping strategy which is also consist with the findings by Kumela et al. (2019) (see the appendix for detailed information). In column 4 the results also indicate that farmers migrate to areas that may not have been affected by FAW. The estimate indicates that farmers who were previously affected by FAW are 3% more likely to migrate from their original household. A possible explanation is that farmers are worried about the recurrence of FAW and as a result seek to live in an area not affected by FAW. Another possible mechanism, is that instead of migrating the households seek off-farm work. In column 5 the result indicates that farmers affected by FAW are 2.3% more likely to engage in off-farm work. Given that FAW might affect the households' income, members of it would then look for other job possibilities to compensate for the loss of income.

Table 7: FAW on coping strategies employed by farmers

VARIABLES	(1) Maize share	(2) Spraying (=1 if yes)	(3) Crop diversification (=1 if yes)	(4) Migration (=1 if yes)	(5) Off-farm work (=1 if yes)
Lag FAW	-0.0153*	0.233***	0.0226**	0.0301***	0.0233*
	(0.00643)	(0.0441)	(0.00856)	(0.00708)	(0.0125)
Weather controls	Yes	Yes	Yes	Yes	Yes
Observations	2,468	2,473	2,478	2,478	2,173

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note: Controlled for weather variables in the form of rainfall, temperature and their squared terms (weather controls)

9.5 Effect of coping strategies on charcoal production

The reduced form results from Table 8 show that not all the coping strategies that farmers employ when attacked by FAW reduce the likelihood of participating in charcoal production. Our robust Hausman test indicated he presence of time-invariant unobserved heterogeneity correlated with the explanatory variables. This is important as it shows that random-effects estimator would be inconsistent (Cameron and Trivedi, 2005). Further, the Kleibergen-Paap underidentification test results show that the instruments are significantly correlated with the endogenous explanatory variables. The weak instrument test for all the coping strategies indicate that the F-statistics from the first regression was all greater than 10. The Wald test which indicates that the maximum amount that the instruments might be biased from weak instruments as below 5 percent for all the coping strategies except crop diversification. With all the F-statistics greater than 10, we can conclude that the instruments are statistically strong (see table 11 and 12 in the appendix section for the first stage regression results). All our instruments appear to be relevant when tested across various diagnostic tests. The results indicate that in areas (camps) where there's migration, it reduces the likelihood of participation in charcoal production. A study by Yang et al. (2016) finds that as the migration or local off-farm employment has no negative effect on grain (maize) technical efficiency of grain production and as such does not affect the household food security. Thus, during crop failure the household opportunity cost of agricultural production reduces and with possible off-farm wages increases, and bearing in mind that the technical efficiency is not negatively affected by this, then it becomes relatively easy for households to migrate for off-farm employment and thus, less likely to produce charcoal. With regards to increased maize share, we use the inverse of the maize share to ease the interpretation of our results. We find that decreasing the maize share during FAW invasions the likelihood of farmers participating in charcoal production bearing in mind that maize is the most preferred crop by FAW. The farmers then increase their crop production by planting other crops (non-staple) which are usually less affected by FAW invasions such as beans, sweet potatoes, pumpkins etc. However, maize is an important cash crop and staple food for most countries in the SSA. When households have a FAW invasion even when in the presence of other food crops, household will still require their daily intake of nshima (maize cake) (Chapoto et al., 2010; Dorosh, Dradri, and Haggblade, 2009; Mason et al., 2011) which would potentially push them towards the production of charcoal in order to supplement the possible shortage caused by reducing maize share as a coping mechanism for FAW infestation. This is also in line with a study by Mzyece (2020) which shows that crop diversification from staple to a non-staple crop is more likely to result in reduction in agricultural productivity and profitability which was driven by forgone efficiency benefits from economies of scale. Our result indicates that as households reduce the production of maize (maize share) they are less likely to participate in charcoal production or forest degradation. I argue that this depends on the presence or absence of FAW. In the absence of FAW, increasing agricultural production (maize) is likely to cause a reduction in charcoal production and forest degradation since farmers will have enough of the cash crop/staple food. This result contradicts a number of studies that find that increasing agricultural production lead to a increases in forest degradation (Abman and Carney, 2020; Chibwana, Jumbe, and Shively, 2013; Doggart et al., 2020). We argue that the effect of agricultural production/productivity on forest degradation can either be negative or positive depending on the shock. Studies that find a positive relationship use positive shocks in their analysis as opposed to our study which uses a negative agricultural shock (FAW infestation).

Table 8: Coping strategies on Charcoal production

VARIABLES	(1) Charc
Inv_ Maize share	-0.00853
	(0.0454)
Inv_ Maize share * FAW	-0.0119
	(0.00963)
Crop diversification	0.0629
	(0.0400)
Crop diversification * FAW	0.00907
	(0.00594)
Migration	-0.111*
	(0.0585)
Migration * FAW	-0.0296
	(0.0355)
Off farm work	-0.0103
	(0.0231)
Off farm work * FAW	0.0370***
	(0.0141)
Spray	-0.00541
	(0.0147)
spray_FAW	-0.0281***
	(0.00909)
Weather controls	Yes
Observations	2,327

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note: Controlled for weather variables in the form of rainfall, temperature and their squared terms (weather controls)

10 Conclusion

Increasing rates of deforestation are a major concern in Sub-Saharan Africa in recent years. A important cause of deforestation is charcoal production. Charcoal production has been widely seen as an income safety net to cushion households against negative income shocks during crop failure. In this paper, We explicitly compare the effect of adopting charcoal production as a coping strategy when alternative strategies are available. We further quantify the effect of the invasion of FAW on charcoal production, deforestation, and the likelihood of farmers' participation in charcoal production. We find that FAW in the village increases the probability of producing charcoal by 3.48 percentage points, from

22 percent to 25 percent. We also find that as the intensity of FAW increases, farmers are more likely to produce 1343 kilograms (kgs) of charcoal which translates to 16 trees that are cut which is a huge piece of deforested land. (see figure 6 in the appendix of deforested land that uses half the size of normal trees required for charcoal).

Our results also indicate that spraying chemical insecticides is the most widely used coping strategy. I find that reducing the maize share in a farmers' field and migration significantly reduce the likelihood of farmers participating in charcoal production. Crop diversification significantly increases the likelihood farmers participating in charcoal production as it reduces the amount of staple food produced. Without main staple foods, households still need some income to buy maize meal (staple) and thus increase the likelihood of participating charcoal production.

Our results shed new light on the impact of a new agricultural pest (FAW) on natural resources (forest) and the mechanisms that leads to natural resource degradation. In a resource constrained economy like Zambia it is imperative that the mechanism is fully understood so the government can focus on effective mechanisms that reduce farmers' likelihood to participate in natural resource degradation.

From a policy-making perspective, the results show that if the objective of the policy makers is to reduce natural resource degradation (deforestation), then the policy makers must focus on interventions that decrease the maize share and maize production in general when households are affected by FAW. Policy should be aimed at crop diversification to produce substitutes of the staple crop such as cassava. Policy makers could also help the farmers by making chemical insecticides more available and ensuring some off-farm employment opportunities. Studies have shown crop diversification is an important mitigation mechanism against FAW (Malo and Hore, 2020; Ojuu, Kyamanywa, and Odong Lapaka, 2021; Harrison et al., 2019). However, these studies do not explicitly mention if the diversification is towards the increase in the production of other substitute staple crops or non-staple crops. Our results indicate that crop diversification towards non-staple crops during insect pest infestation can actually increase charcoal production.

References

Abate, Teo, Arnold van Huis, and JKO Ampofo (2000). "Pest management strategies in traditional agriculture: an African perspective". *Annual review of entomology* 45.1, pp. 631–659.

Abman, Ryan and Conor Carney (2020). "Agricultural productivity and deforestation: Evidence from input subsidies and ethnic favoritism in Malawi". *Journal of Environmental Economics and Management* 103, p. 102342.

Adnan, Adnan A, Jibrin M Jibrin, Alpha Y Kamara, Bassam L Abdulrahman, Abdulwahab S Shaibu, and Ismail I Garba (2017). "CERES–Maize model for determining the optimum planting dates of early maturing maize varieties in Northern Nigeria". *Frontiers in plant science* 8, p. 1118.

Alamu, Emmanuel Oladeji, Therese Gondwe, Juliet Akello, Nancy Sakala, Grace Munthali, Mweshi Mukanga, and Busie Maziya-Dixon (2018). "Nutrient and aflatoxin contents of traditional complementary foods consumed by children of 6–24 months". *Food science & nutrition* 6.4, pp. 834–842.

Autor, David H (2003). "Outsourcing at will: The contribution of unjust dismissal doctrine to the growth of employment outsourcing". *Journal of labor economics* 21.1, pp. 1–42.

Awal, MA, H Koshi, and T Ikeda (2006). "Radiation interception and use by maize/peanut intercrop canopy". *Agricultural and forest meteorology* 139.1-2, pp. 74–83.

Babu, S Ramesh, RK Kalyan, Sonika Joshi, CM Balai, Mahla Mahla, and P Rokadia (2019). "Report of an exotic invasive pest the fall armyworm, Spodoptera frugiperda (JE Smith) on maize in Southern Rajasthan". *J. Entomol. Zool. Stud* 7, pp. 1296–1300.

Bare, Matthew, Craig Kauffman, and Daniel C Miller (2015). "Assessing the impact of international conservation aid on deforestation in sub-Saharan Africa". *Environmental Research Letters* 10.12, p. 125010.

Bijman, Jos and Gea Wijers (2019). "Exploring the inclusiveness of producer cooperatives". *Current opinion in environmental sustainability* 41, pp. 74–79.

Blekking, Jordan, Nicolas Gatti, Kurt Waldman, Tom Evans, and Kathy Baylis (2021). "The benefits and limitations of agricultural input cooperatives in Zambia". *World Development* 146, p. 105616.

Branch, Adam and Giuliano Martiniello (2018). "Charcoal power: The political violence of non-fossil fuel in Uganda". *Geoforum* 97, pp. 242–252.

Brobbey, Lawrence Kwabena, Christian Pilegaard Hansen, Boateng Kyereh, and Mariéve Pouliot (2019). "The economic importance of charcoal to rural livelihoods: Evidence from a key charcoal-producing area in Ghana". *Forest Policy and Economics* 101, pp. 19–31.

Cameron, A Colin and Pravin K Trivedi (2005). *Microeconometrics: methods and applications*. Cambridge university press.

Cardille, Jeffrey A and Jonathan A Foley (2003). "Agricultural land-use change in Brazilian Amazonia between 1980 and 1995: Evidence from integrated satellite and census data". *Remote Sensing of Environment* 87.4, pp. 551–562.

Chamberlain, Gary (1982). "Multivariate regression models for panel data". *Journal of econometrics* 18.1, pp. 5–46.

Chapoto, Antony, Jones Govereh, Steven Haggblade, and Thomas S Jayne (2010). *Staple food prices in Zambia*. Tech. rep.

Chibwana, Christopher, Charles BL Jumbe, and Gerald Shively (2013). "Agricultural subsidies and forest clearing in Malawi". *Environmental Conservation* 40.1, pp. 60–70.

Chidumayo, Emmanuel N and Davison J Gumbo (2013). "The environmental impacts of charcoal production in tropical ecosystems of the world: A synthesis". *Energy for Sustainable Development* 17.2, pp. 86–94.

Chidumayo, EN, I Masialeti, H Ntalasha, and O Kalumiana (2002). "Charcoal potential in southern Africa–Final Report for Zambia". *INCODEV, Stockholm Environment Institute, Stockholm.*

Chomitz, Kenneth M and Charles Griffiths (2001). "An economic analysis and simulation of woodfuel management in the Sahel". *Environmental and Resource Economics* 19.3, pp. 285–304.

Davis, T, R Day, R Early, J Godwin, P Gonzalez-Moreno, M Kansiime, and M Kenis (2018). "Fall armyworm: impacts and implications for Africa".

Demirbas, Ayhan, Waqar Ahmad, Rami Alamoudi, and Manzoor Sheikh (2016). "Sustainable charcoal production from biomass". *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 38.13, pp. 1882–1889.

Doggart, Nike, Theron Morgan-Brown, Emmanuel Lyimo, Boniface Mbilinyi, Charles K Meshack, Susannah M Sallu, and Dominick V Spracklen (2020). "Agriculture is the main driver of deforestation in Tanzania". *Environmental Research Letters* 15.3, p. 034028.

Donatelli, Marcello, Roger D Magarey, Simone Bregaglio, L Willocquet, Jérémy PM Whish, and Serge Savary (2017). "Modelling the impacts of pests and diseases on agricultural systems". *Agricultural systems* 155, pp. 213–224.

Dorosh, Paul A, Simon Dradri, and Steven Haggblade (2009). "Regional trade, government policy and food security: Recent evidence from Zambia". *Food Policy* 34.4, pp. 350–366.

Durbin, James and Geoffrey S Watson (1971). "Testing for serial correlation in least squares regression. III". *Biometrika* 58.1, pp. 1–19.

Durocher-Granger, Léna, Tibonge Mfune, Monde Musesha, Alyssa Lowry, Kathryn Reynolds, Alan Buddie, Giovanni Cafà, Lisa Offord, Gilson Chipabika, Marcel Dicke, et al. (2020). "Factors influencing the occurrence of fall armyworm parasitoids in Zambia". *Journal of Pest Science*, pp. 1–14.

Ellegård, A, M Nordström, et al. (2003). "Deforestation for the poor?" *Renewable Energy for Development* 16.2, pp. 4–6.

Eriksen, Siri H, Katrina Brown, and P Mick Kelly (2005). "The dynamics of vulnerability: locating coping strategies in Kenya and Tanzania". *Geographical Journal* 171.4, pp. 287–305.

Fearnside, Philip M (2000). "Global warming and tropical land-use change: greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation". *Climatic change* 46.1, pp. 115–158.

Fernández-Val, Iván and Martin Weidner (2016). “Individual and time effects in nonlinear panel models with large N, T”. *Journal of Econometrics* 192.1, pp. 291–312.

Fraisse, Clyde W and Silvana V Paula-Moraes (2018). “Degree-days: growing, heating, and cooling”. *EDIS* 2018.2.

Friedman, Willa, Michael Kremer, Edward Miguel, and Rebecca Thornton (2016). “Education as liberation?” *Economica* 83.329, pp. 1–30.

Galiatsatos, Nikolaos, Daniel NM Donoghue, Pete Watt, Pradeepa Bholanath, Jeffrey Pickering, Matthew C Hansen, and Abu RJ Mahmood (2020). “An assessment of global forest change datasets for national forest monitoring and reporting”. *Remote Sensing* 12.11, p. 1790.

Geoghegan, Jacqueline, Sergio Cortina Villar, Peter Klepeis, Pedro Macario Mendoza, Yelena Ogneva-Himmelberger, Rinku Roy Chowdhury, BL Turner Ii, and Colin Vance (2001). “Modeling tropical deforestation in the southern Yucatan peninsular region: comparing survey and satellite data”. *Agriculture, Ecosystems & Environment* 85.1-3, pp. 25–46.

Girard, Philippe et al. (2002). “Charcoal production and use in Africa: what future?” *Unasylva (English ed.)* 53.211, pp. 30–34.

Goergen, Georg, P Lava Kumar, Sagnia B Sankung, Abou Togola, and Manuele Tamò (2016). “First report of outbreaks of the fall armyworm Spodoptera frugiperda (JE Smith)(Lepidoptera, Noctuidae), a new alien invasive pest in West and Central Africa”. *PloS one* 11.10, e0165632.

Gregory, Peter J, Scott N Johnson, Adrian C Newton, and John SI Ingram (2009). “Integrating pests and pathogens into the climate change/food security debate”. *Journal of experimental botany* 60.10, pp. 2827–2838.

Hänke, Hendrik and Jan Barkmann (2017). “Insurance function of livestock, Farmers coping capacity with crop failure in southwestern Madagascar”. *World Development* 96, pp. 264–275.

Hansen, Matthew C, Peter V Potapov, Rebecca Moore, Matt Hancher, Svetlana A Turubanova, Alexandra Tyukavina, David Thau, Stephen V Stehman, Scott J Goetz, Thomas R Loveland, et al. (2013). “High-resolution global maps of 21st-century forest cover change”. *science* 342.6160, pp. 850–853.

Harrison, Rhett D, Christian Thierfelder, Frédéric Baudron, Peter Chinwada, Charles Midega, Urs Schaffner, and Johnnie Van Den Berg (2019). “Agro-ecological options for fall armyworm (Spodoptera frugiperda JE Smith) management: Providing low-cost, smallholder friendly solutions to an invasive pest”. *Journal of Environmental Management* 243, pp. 318–330.

Hichaambwa, Munguzwe and Thomas S Jayne (2012). *Smallholder commercialization trends as affected by land constraints in Zambia: what are the policy implications?* Tech. rep.

Houghton, Richard A, DL Skole, Carlos A Nobre, JL Hackler, KT Lawrence, and W H Chomentowski (2000). “Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon”. *Nature* 403.6767, pp. 301–304.

Jones, Daniel, Casey M Ryan, and Janet Fisher (2016). “Charcoal as a diversification strategy: The flexible role of charcoal production in the livelihoods of smallholders in central Mozambique”. *Energy for Sustainable Development* 32, pp. 14–21.

Kalaba, Felix Kanungwe (2016). “Barriers to policy implementation and implications for Zambia’s forest ecosystems”. *Forest Policy and Economics* 69, pp. 40–44.

Kalipeni, E, I Kakoma, YO Sanogo, K Fawcett, and RE Warner (2009). “Biodiversity Conservation and Natural Resources Management in Africa”.

Kiruki, Harun M, Emma H van der Zanden, Patrick Kariuki, and Peter H Verburg (2020). “The contribution of charcoal production to rural livelihoods in a semi-arid area in Kenya”. *Environment, Development and Sustainability* 22.7, pp. 6931–6960.

Kumela, Teshome, Josephine Simiyu, Birhanu Sisay, Paddy Likhayo, Esayas Mendesil, Linnet Gohole, and Tadele Tefera (2019). “Farmers’ knowledge, perceptions, and management practices of the new invasive pest, fall armyworm (Spodoptera frugiperda) in Ethiopia and Kenya”. *International Journal of Pest Management* 65.1, pp. 1–9.

Labarta, Ricardo A, Douglas S White, and Scott M Swinton (2008). “Does charcoal production slow agricultural expansion into the Peruvian Amazon rainforest?” *World Development* 36.3, pp. 527–540.

Mabeta, Joshua, Bruno Mweemba, and Jacob Mwitwa (2018). “Key drivers of biodiversity loss in Zambia”. *Policy.*

Malimbwi, RE, E Zahabu, GC Kajembe, and EJ Luoga (2000). “Contribution of charcoal extraction to deforestation: experience from CHAPOSA Research Project.”

Malimbwi, Roger E and Eliakimu M Zahabu (2008). “Woodlands and the charcoal trade: the case of Dar es Salaam City”. *Research and development for sustainable management of semiarid miombo woodlands in East Africa. Working Paper* 98, pp. 93–114.

Malo, Mousumi and Jayita Hore (2020). “The emerging menace of fall armyworm (Spodoptera frugiperda JE Smith) in maize: A call for attention and action”. *J. Entomol. Zool. Stud* 8, pp. 455–465.

Martone, Michele, Paola Rizzoli, Christopher Wecklich, Carolina González, José-Luis Bueso-Bello, Paolo Valdo, Daniel Schulze, Manfred Zink, Gerhard Krieger, and Alberto Moreira (2018). “The global forest/non-forest map from TanDEM-X interferometric SAR data”. *Remote sensing of environment* 205, pp. 352–373.

Mason, Nicole M, Thomas S Jayne, Cynthia Donovan, Antony Chapoto, et al. (2011). “Are Staple foods becoming more expensive for urban consumers in Eastern and Southern Africa? Trends in food prices, marketing margins and wage rates in Kenya, Malawi, Mozambique, and Zambia”. *The food and financial crises in sub-Saharan Africa: origins, impacts and policy implications. CABI Publishing, UK. p*, pp. 154–188.

Mburu, Benson Kamau, James Biu Kung’u, and John Njagi Muriuki (2015). “Climate change adaptation strategies by small-scale farmers in Yatta District, Kenya”. *African Journal of Environmental Science and Technology* 9.9, pp. 712–722.

Miller, James (2016). “Examining the Hansen Global Forest Change (2000-2014) dataset within an Australian local government area”.

Mofya-Mukuka, Rhoda and Munguzwe Hichaambwa (2018). “Livelihood effects of crop diversification: a panel data analysis of rural farm households in Zambia”. *Food Security* 10.6, pp. 1449–1462.

Mulenga, Brian P, Protensia Hadunka, and Robert B Richardson (2017). “Rural households’ participation in charcoal production in Zambia: Does agricultural productivity play a role?” *Journal of forest economics* 26, pp. 56–62.

Mulenga, Brian P, Robert B Richardson, Gelson Tembo, and Lawrence Mapemba (2014). “Rural household participation in markets for non-timber forest products in Zambia”. *Environment and Development Economics* 19.4, pp. 487–504.

Mulenga, Brian P, Solomon T Tembo, and Robert B Richardson (2019). “Electricity access and charcoal consumption among urban households in Zambia”. *Development Southern Africa* 36.5, pp. 585–599.

Munshifwa, Ephraim K and Gaborone Botswana (2003). “The Draft Zambian Land Policy (1999)”.

Mwampamba, Tuyeni H, Matthew Owen, and Maurice Pigaht (2013). “Opportunities, challenges and way forward for the charcoal briquette industry in Sub-Saharan Africa”. *Energy for Sustainable Development* 17.2, pp. 158–170.

Mwitwa, J and A Makano (2012). “Preliminary charcoal production supply and demand assessment in Eastern and Lusaka Provinces”. *Lusaka, Zambia: United States Agency for International Development.*

Mzyece, Agness (2020). “The strategic value of crop diversification in Zambia”. PhD thesis. Kansas State University.

Ndegwa, Geoffrey, Dieter Anhuf, Udo Nehren, Adrian Ghilardi, and Miyuki Iiyama (2016). “Charcoal contribution to wealth accumulation at different scales of production among the rural population of Mutomo District in Kenya”. *Energy for Sustainable Development* 33, pp. 167–175.

Ngoma, Hambulo, Johanne Pelletier, Brian P Mulenga, and Mitelo Subakanya (2021). “Climate-smart agriculture, cropland expansion and deforestation in Zambia: Linkages, processes and drivers”. *Land Use Policy* 107, p. 105482.

Njenga, M, N Karanja, H Karlsson, R Jamnadass, M Iiyama, J Kithinji, and Cecilia Sundberg (2014). "Additional cooking fuel supply and reduced global warming potential from recycling charcoal dust into charcoal briquette in Kenya". *Journal of cleaner production* 81, pp. 81–88.

Ojuu, David, Samuel Kyamanywa, and Thomas Odong Lapaka (2021). "Influence of wetland borders on prevalence of fall armyworm and wasps in maize-soybean cropping system in Eastern Uganda". *International Journal of Pest Management*, pp. 1–9.

Osei, S (2017). "Climate Change Adaptation Constraints among Smallholder Farmers in Rural Households of Central Region of Ghana". *West African Journal of Applied Ecology* 25.2, pp. 31–48.

Paini, Dean R, Andy W Sheppard, David C Cook, Paul J De Barro, Susan P Worner, and Matthew B Thomas (2016). "Global threat to agriculture from invasive species". *Proceedings of the National Academy of Sciences* 113.27, pp. 7575–7579.

Papke, Leslie E and Jeffrey M Wooldridge (2008). "Panel data methods for fractional response variables with an application to test pass rates". *Journal of econometrics* 145.1-2, pp. 121–133.

Phiri, Darius, Justin Morgenroth, and Cong Xu (2019). "Long-term land cover change in Zambia: An assessment of driving factors". *Science of The Total Environment* 697, p. 134206.

Prabhakar, Mathyam, Kodigal A Gopinath, Nakka Ravi Kumar, Merugu Thirupathi, Uppu Sai Sravan, Golla Srasvan Kumar, Gutti Samba Siva, Guddad Meghalakshmi, and Sengottaiyan Vennila (2020). "Detecting the invasive fall armyworm pest incidence in farm fields of southern India using Sentinel-2A satellite data". *Geocarto International*, pp. 1–16.

Province, Lusaka (2012). "Zambia". *Socio-economics Discussion Paper*.

Samut, Pınar Kaya and Reyhan Cafrı (2016). "Analysis of the efficiency determinants of health systems in OECD countries by DEA and panel tobit". *Social Indicators Research* 129.1, pp. 113–132.

Semazzi, Fredrick HM and Yi Song (2001). "A GCM study of climate change induced by deforestation in Africa". *Climate Research* 17.2, pp. 169–182.

Smith, Harriet Elizabeth, Malcolm D Hudson, and Kate Schreckenberg (2017). "Livelihood diversification: The role of charcoal production in southern Malawi". *Energy for Sustainable Development* 36, pp. 22–36.

Sparovek, Gerd, Göran Berndes, Alberto Giaroli de Oliveira Pereira Barretto, and Israel Leoname Fröhlich Klug (2012). "The revision of the Brazilian Forest Act: increased deforestation or a historic step towards balancing agricultural development and nature conservation?" *Environmental Science & Policy* 16, pp. 65–72.

Stassen, Hubert E (2015). *Current issues in charcoal production and use.* CRC Press: Boca Raton, FL.

Supartha, I WAYAN, I WAYAN Susila, Mahaputra IGF Sunari AAAAS, IKW Yudha, and PA Wiradana (2021). "Damage characteristics and distribution patterns of invasive pest, Spodoptera frugiperda (JE Smith)(Lepidoptera: Noctuidae) on maize crop in Bali, Indonesia Biodiversitas J". *Biol. Divers* 22.

Tunde, AM, EA Adeleke, and EE Adeniyi (2013). "Impact of charcoal production on the sustainable development of Asa Local Government Area, Kwara State, Nigeria". *African Research Review* 7.2, pp. 1–15.

Umar, Bridget Bwalya (2014). "A critical review and re-assessment of theories of smallholder decision-making: a case of conservation agriculture households, Zambia". *Renewable Agriculture and Food Systems* 29.3, pp. 277–290.

Vance, Colin and Jacqueline Geoghegan (2002). "Temporal and spatial modelling of tropical deforestation: a survival analysis linking satellite and household survey data". *Agricultural economics* 27.3, pp. 317–332.

Vorlaufer, Tobias, Thomas Falk, Thomas Dufhues, and Michael Kirk (2017). "Payments for ecosystem services and agricultural intensification: Evidence from a choice experiment on deforestation in Zambia". *Ecological Economics* 141, pp. 95–105.

Yang, Jin, Hui Wang, Songqing Jin, Kevin Chen, Jeffrey Riedinger, and Chao Peng (2016). "Migration, local off-farm employment, and agricultural production efficiency: evidence from China". *Journal of Productivity Analysis* 45.3, pp. 247–259.

Zackrisson, Olle, Marie-Charlotte Nilsson, and David A Wardle (1996). "Key ecological function of charcoal from wildfire in the Boreal forest". *Oikos*, pp. 10–19.

Zulu, Leo C and Robert B Richardson (2013). "Charcoal, livelihoods, and poverty reduction: Evidence from sub-Saharan Africa". *Energy for Sustainable Development* 17.2, pp. 127–137.

11 Appendix

11.1 FAW control practices

Famers in Zambia use various methods to mitigate FAW infestations, with 61 percent of the farmers reporting chemical spray being their main method of control which is slightly less than the 62 percent reported by Davis et al., 2018 for the previous agricultural season (see Figure 8 in the appendix). Our findings are consistent with the finding by Kumela et al., 2019 done in Kenya and Ethiopia but in contrast to a study by Abate, Huis, and Ampofo, 2000 in the Sahel region of Africa that found that smallholder farmers do not mainly use insecticides to control for FAW but rather use cultural methods. The higher use of pesticides could be due to the fact that following the sudden invasion of FAW, the Zambian government supplied farmers with free insecticides. According to our study, the second most popular methods was a cultural (traditional) method which involves the hand-picking egg masses with 31 percent of the farmers reporting having used as method of control. This is consistent with findings by Davis et al., 2018. Studies have shown that farmers perceive the use of chemical pesticide to control FAW as ineffective in controlling the pest (Kumela et al., 2019). Our analysis equally shows that the majority of the farmers (86 percent) reported that the use of chemical pesticide was ineffective (see Figure 9 in the appendix). One concern is whether the insecticides are being applied appropriately. Spraying by farmers is usually done during the day when FAW are inactive as they are nocturnal for this reason some farmers may regard as ineffective even when it is just their wrong spraying timing (Kumela et al., 2019). According to Goergen et al., 2016 the insecticides are only effective on younger larva and late spraying may not be ineffective. Figure 10 (in the appendix) shows the reason why some farmers don't use insecticides on their crops. Most (59 percent) reported that they couldn't afford the insecticides. Even though the cost of insecticides in Zambia is usually subsidized, a farmer is expected to spend an average a farmer spent USD 6.5/ha on pesticide treatments alone i.e without subsidy (Davis et al., 2018). This is already too high for an average Zambian farmer to afford. A further 23 percent of the farmers reported that they did not spray because they had no access to the insecticides.

Table 9: Effects of FAW on Charcoal as a categorical variable (Robustness check)

	(1)
VARIABLES	Charc (=1 if yes)
Lag_FAW	0.0327***
	(0.00536)
Lead_FAW (current FAW)	-0.00634
	(0.00495)
Land cultivated (ha)	0.000049
	(0.00074)
Education	-0.00649*
	(0.00309)
Household size (Labor)	-0.00182
	(0.00132)
Gender (Male=1)	0.0185
	(0.0129)
Weather controls	Yes
Observations	2,158

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 10: Effects of FAW on Charcoal as a categorical variable (Robustness check)

VARIABLES	(1) Charc (=1 if yes)
1. Lag_Low intensity	0.0480***
	(0.0116)
2. Lag_Moderate intensity	0.0855***
	(0.0134)
3. Lag_High intensity	0.123***
	(0.0124)
Land cultivated (ha)	0.000372
	(0.000754)
Education	-0.00593**
	(0.00287)
Household size (Labor)	-0.00173
	(0.00127)
Gender (Male=1)	0.0197
	(0.0122)
Weather controls	Yes
Observations	2,325

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

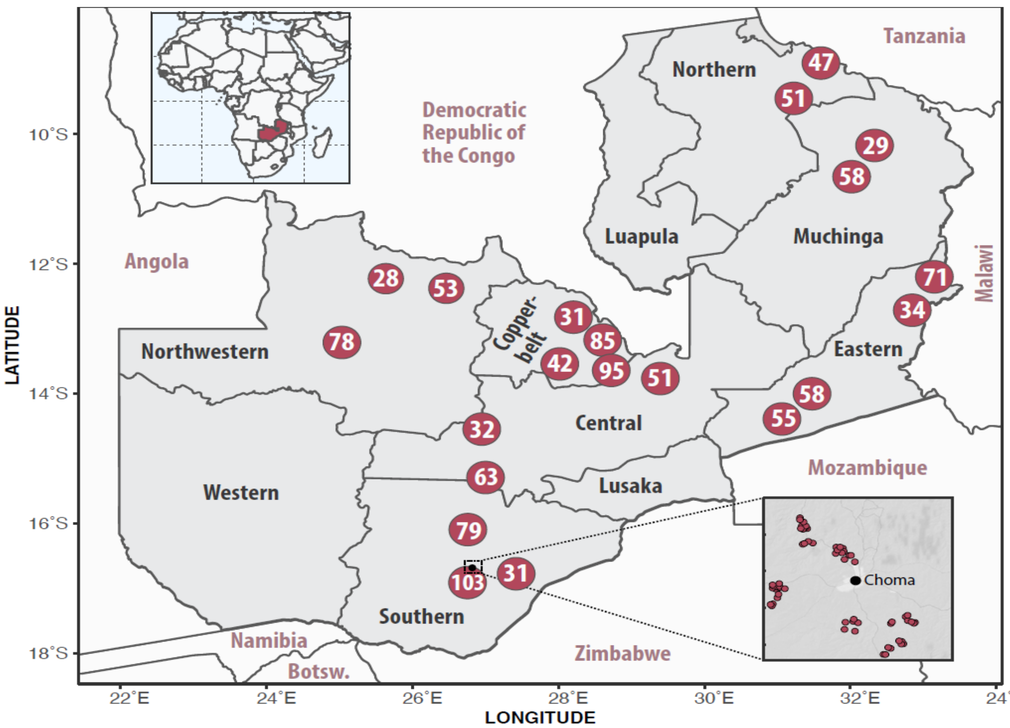

Figure 2: The shaded regions area are the districts that were randomly selected for the study. Source: Author's work from the HICPS data

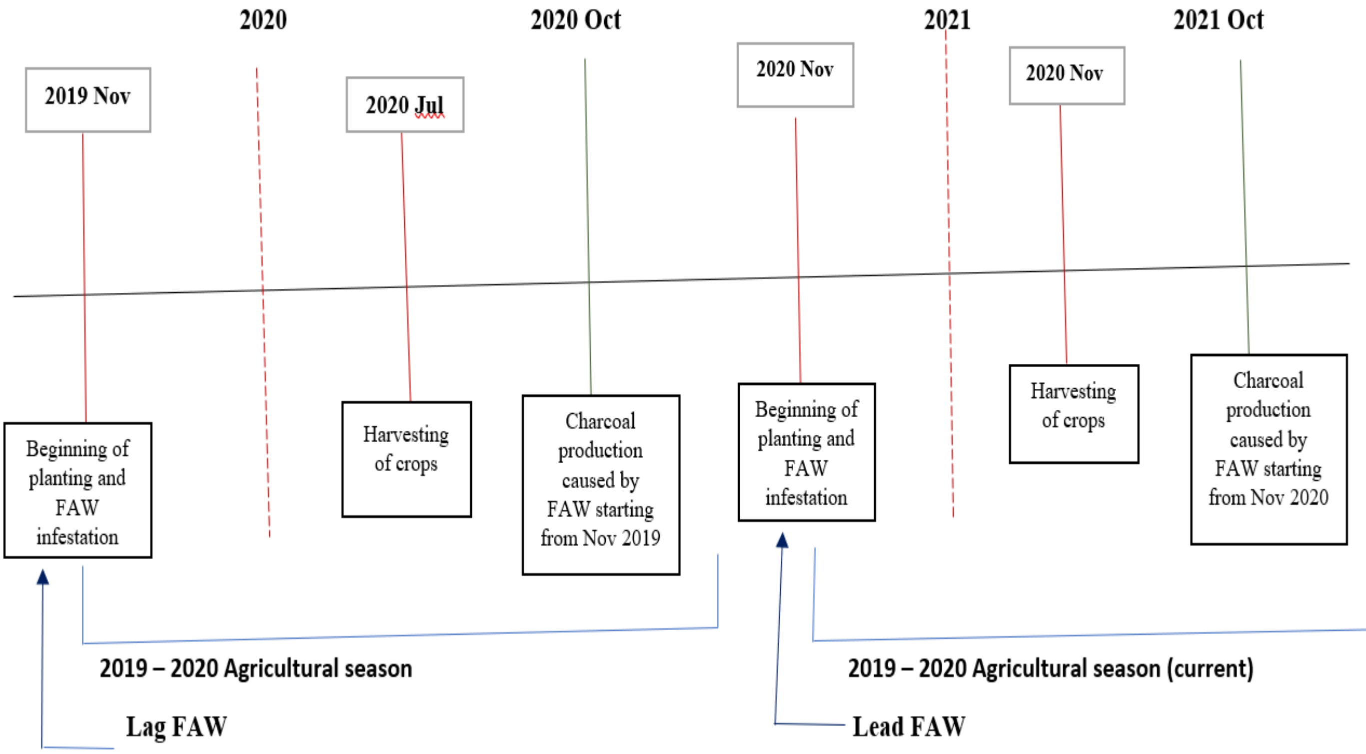

Figure 3: Agricultural seasons and FAW leads and lags **Source: Author's work from the field work**

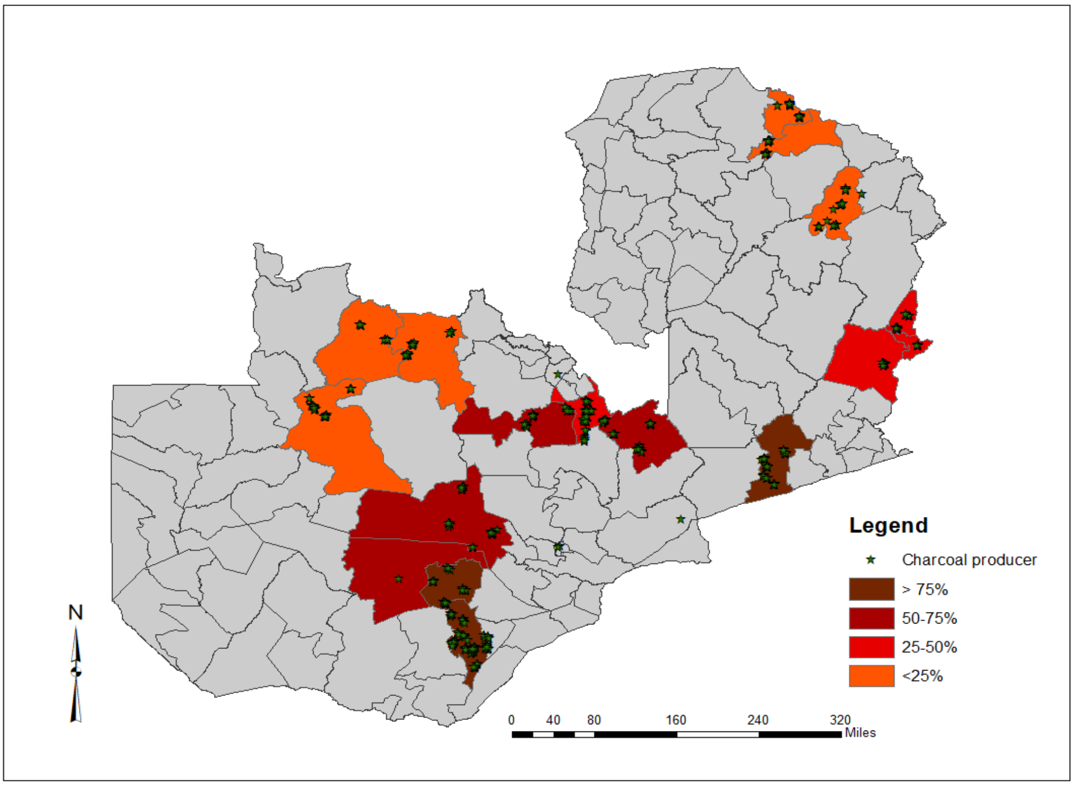

Figure 4: FAW infestations and charcoal production. **Source: Author's work from the HICPS data**

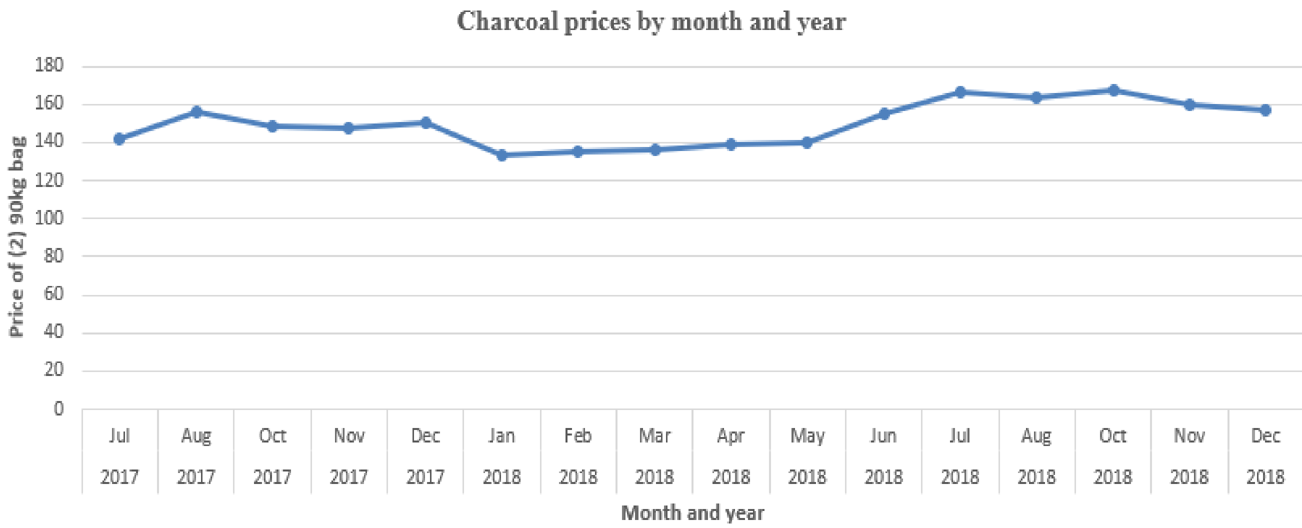

Figure 5: Charcoal prices across time. **Source: Author's work from the HICPS data**

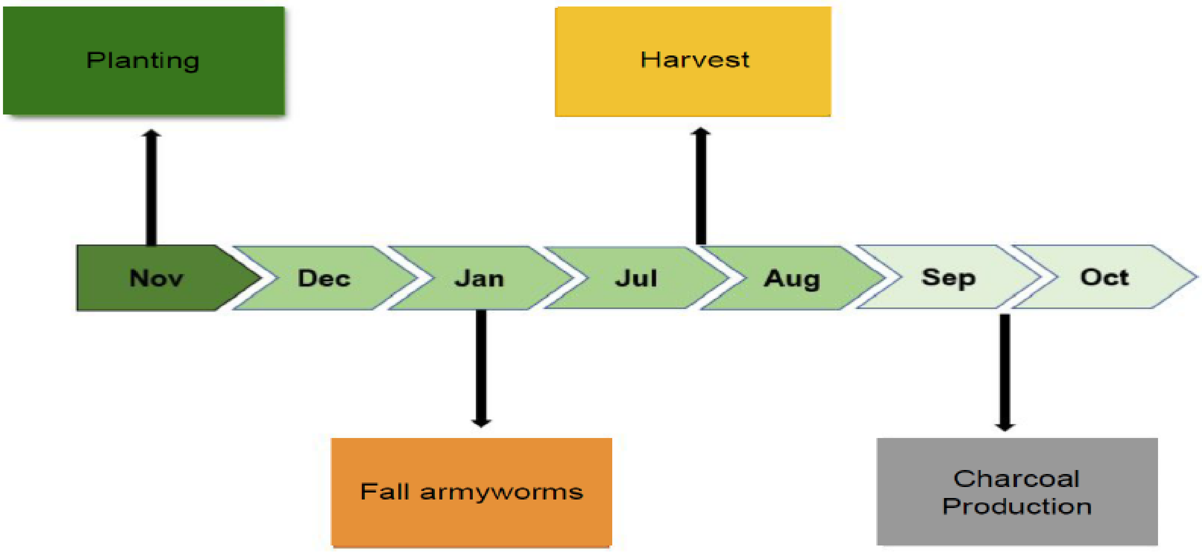

Figure 6: Charcoal production and FAW timing. **Source: Author's work from the HICPS data**

Table 11: First stage of Coping strategies on Charcoal production

VARIABLES	(1) Charc (=1 if yes)
Maize share	-0.06755**
	(0.02459)
Maize share * FAW	-0.00168
	(0.01283)
Crop diversification	-0.02171
	(0.02006)
Crop diversification * FAW	0.03211
	(0.00788)
Migration	0.00890
	(0.01967)
Migration * FAW	-0.00213
	(0.01407)
Off farm work	0.00583
	0.01139)
Off farm work * FAW	0.01311
	(0.00926)
Spray	-0.00739
	(0.00821)
Spray * FAW	-0.00179
	(0.00147)
Weather controls	Yes
Observations	2,327

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 12: First stage of coping strategies on charcoal production diagnostics results

VARIABLES	Maize share	Spraying	Crop diversification	Migration	Off-farm work
F-test	17.41	294.26	88.97	12.43	14.54
	(0.00310)	(0.0213)	(0.00397)	(0.00325)	(0.0125)
Robust Hausman test (χ^2)	57.45	43.65	34.43	33.54	28.76
	(0.016)	(0.0711)	(0.0134)	(0.0145)	(0.0123)

Table 13: Effects of Charcoal on deforestation

	(1)
VARIABLES	Deforestation rate
Charc (=1 if yes)	0.397***
	(0.078)
Year FE	Yes
HH FE	Yes
Weather controls	Yes
Observations	2,158

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Figure 7: The medium sized charcoal kiln with with small sized trees. **Source: Author's work from the field work**

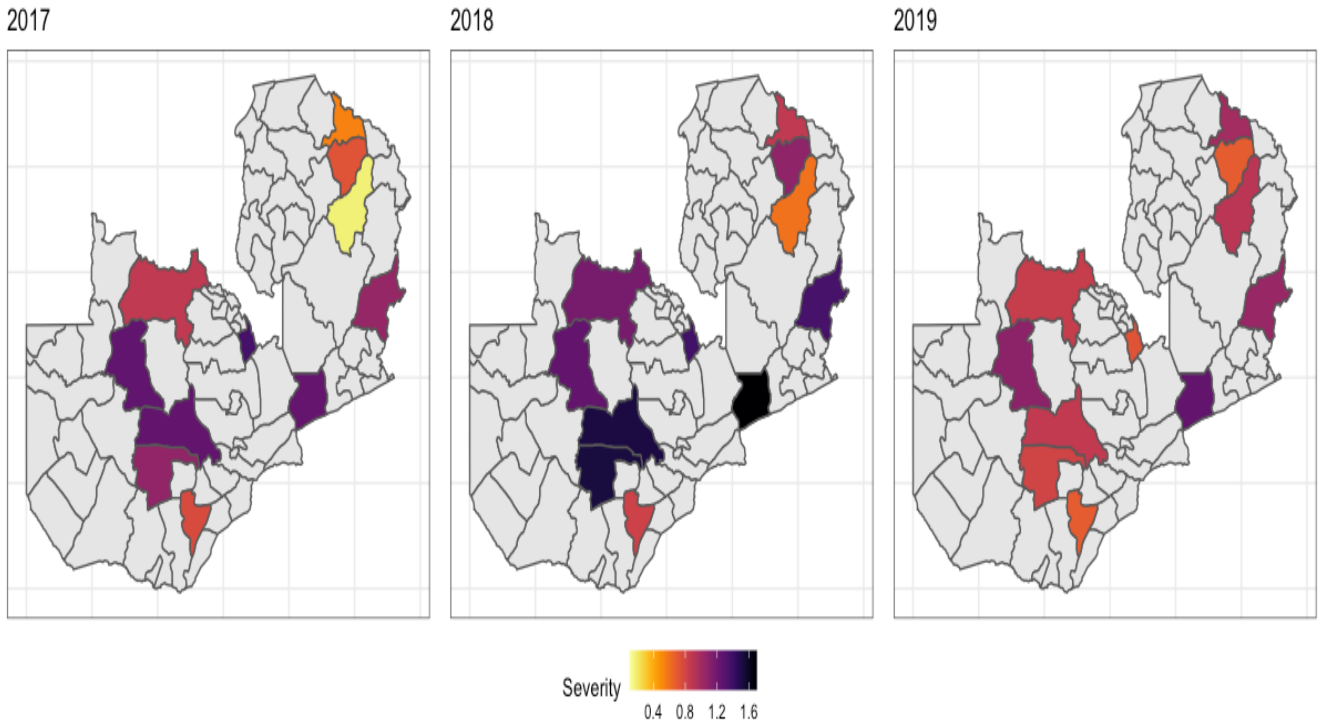

Figure 8: FAW infestations intensity across years and district. **Source: Author's work from the HICPS data**

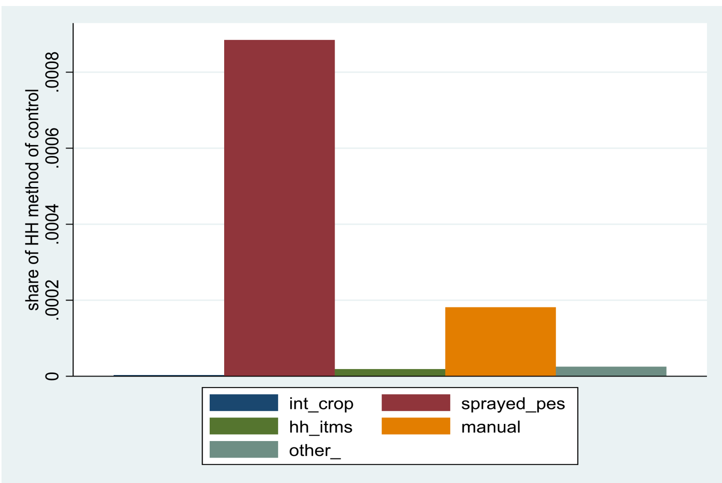

Figure 9: Methods of Control of FAW. **Source: Author's work from the HICPS data**

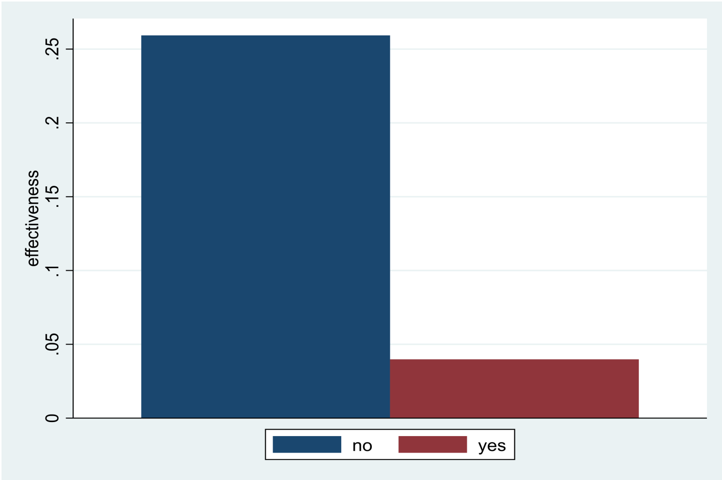

Figure 10: Effectiveness of the insecticide. **Source: Author's work from the HICPS data**

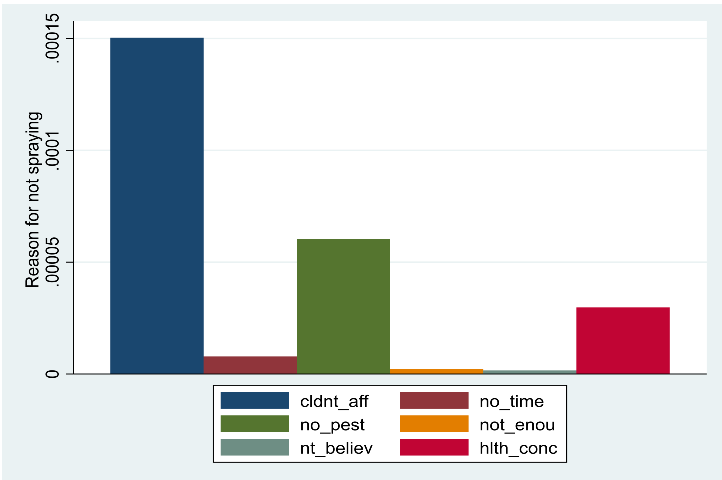

Figure 11: Reason for not spraying. **Source: Author's work from the HICPS data**