The Economic, Food Security, and Health Effects of Fall Armyworm in Ethiopia

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1. Introduction

Maize is a staple food for more than 300 million Africans (Badu-apraku et al., 2007; Matova et al., 2020). Despite the importance, its production is constrained by several biotic and abiotic factors that contribute to the sub-Saharan Africa (SSA)'s pervasive food insecurity. For a long time, stemborers and Striga weed were the main maize pests in SSA, a combination known to cause complete maize production failure (De Groote, 2002). The recent invasion (since 2016) of maize by the fall armyworm (FAW), *Spodoptera frugiperda,* hereafter referred to as FAW, has exacerbated the already fragile food systems and food security in the region (De Groote et al., 2020; FAO, 2019; Hruska, 2019; Njuguna et al., 2021; Otim et al., 2021). Farm-level estimates in some SSA countries show that FAW causes maize yield losses of between 11% and 67% (Baudron et al., 2019; Day et al., 2017; De Groote et al., 2020; Kassie et al., 2020; Kumela et al., 2019; Rwomushana et al., 2018; Overton et al., 2021).

Infestation by FAW also causes additional costs due to the use of insecticides and the need for labor to control the pest (Kansiime et al., 2019; Kassie et al., 2020; Tambo et al., 2019; Yang et al., 2021). The application of insecticides is the primary FAW control strategy in SSA countries (Harrison et al., 2019). This inevitably has impacts beyond abating maize production losses; insecticides pollution can have adverse effects on the environment, biodiversity, and health of the producers and consumers (Gautam et al., 2017; Lai, 2017; Midingoyi et al., 2019; Pingali, 2001; Rwomushana et al., 2018). Furthermore, FAW invasions can affect trade, income, and food consumption due to reductions in maize supply. FAW invasions can also increase health expenditure arising from exposure to insecticides, and affect the performance of businesses along the maize value chain, such as maize input suppliers and contributors to the livestock feed sector (Chapman et al., 2017; Early et al., 2018; Jeger et al., 2017). Unless effective control strategies are implemented, the pest will continue to cause massive destruction to maize and affect the livelihoods of millions of people in SSA. Implementing such control strategies requires updates on the current impact of FAW on the economy, food security, and health (human and environmental).

Despite FAW's importance, there are limited studies on its impact on production, on the cost of control including the cost of insecticides, and on the unintended negative consequences of insecticide use on human and environmental health. Using survey data from Ghana and Zambia, Day et al. (2017) and Rwomushana et al. (2018) extrapolated production losses due to FAW for twelve SSA countries. Country-specific studies are crucial, because the effects of FAW vary across and within countries due to differences in agro-ecology and farm and farmer characteristics. De Groote et al. (2020) show that losses caused by the FAW vary by agro-ecological zones. Many of the existing studies do not capture the large degree of agro-ecological and socioeconomic heterogeneity of smallholder farmers in SSA, because the studies rely on limited geographical areas (Baudron et al., 2019; Kassie et al., 2020; Koffi et al., 2020; Kumela et al., 2019). Many of these studies also use data collected at the early stages of the FAW invasion. The real impacts of FAW infestation may take time to become evident as the infestation varies from season to season. The arrival of the FAW has changed the dynamic of existing farming system constraints to maize production, leading to a new status quo (Hailu et al., 2021).

Invasion by FAW has significantly increased insecticide use in most of the invaded regions (Kassie et al., 2020; Yang et al., 2021). Majority of studies have focused on the efficacy of insecticide for the management of FAW in the invaded regions (Deshmukh et al., 2020; Sisay et al., 2019b), but the increased use of insecticides for FAW control is affecting the health of farmers. In Ghana and Zambia for instance, farmers have reported sickness after applying insecticides recommended for controlling FAW (Rwomushana et al., 2018). However, no systematic study to document the health effects and their socioeconomic impact has been made.

In this paper, we present evidence on the economic and health cost of FAW. Particularly, we estimate the pest's effect on maize production, food security, and the effect of insecticide use on public and environmental health. The evidence will help to prioritize investment in FAW management strategies that simultaneously reduce losses and maintain ecological balance. As secondary objectives, we endeavor to understand farmers' current FAW control measures and the effectiveness of these, and the support that communities receive in combating the pest. Since the accuracy of production loss estimates depends on farmers' knowledge of the pest (Prasanna et al., 2018), we examine farmers' awareness of and knowledge about FAW.

To measure FAW's effect on maize production and achieve the secondary objectives, we combined agroecology-based community surveys with nationally representative datasets collected by Ethiopia's Central Statistical Agency (CSA). We covered 150 villages/communities and 1,100 farmers distributed across 30 districts of maize-growing agro-ecological zones. We also collected data from 180 agricultural experts in these communities to validate the results. The community and expert opinion survey data helped us to triangulate yield losses to avoid over/underestimation, because we recorded community-level yield losses validated through focus group discussions (FGDs). This also reduced data collection costs and saved time as we did not need to interview farmers individually (De Groote et al., 2020). The datasets from the CSA's Agricultural Sample Survey show a good picture of maize production in Ethiopia. On average, the data covers 17,833 maize-growing farmers across the country. We developed a simple arithmetic formula to quantify maize production losses at the national level. Using secondary data obtained from the Ministry of Agriculture, we applied the environmental impact quotient (EIQ) approach to quantify adverse health risks and the environmental effects of insecticides used to manage FAW (Grant, 2020; Kovach et al., 1992).

We report four key results. First, 97% and 88% of the farmers interviewed were aware of and identified FAW, respectively. Knowledge of farmer's awareness of FAW is vital to estimating its effects accurately. Second, FAW has a considerable socioeconomic impact in Ethiopia that varies by agro-ecology. From 2017 to 2019, the country lost 0.67 million tonnes of maize production, worth US$ 200 million (0.08% of the Gross Domestic Product). This lost maize could have met the maize consumption requirement of 4 million food-insecure households. Third, farmers perceived the effectiveness of most current control measures as below average, contributing to large direct and indirect losses. Fourth, FAW has a negative spillover effect on biodiversity and the human population. In the short term, the application of insecticides to control FAW has greater toxic effects on the environment than on humans. However, in the long-term, it can aggravate food insecurity by killing beneficial insects and contaminating other essential natural resources.

Overall, our findings present a cautionary note about the impacts of FAW. Lack of appropriate control measures against FAW combined with other production constraints can lead to high economic losses to society and monetary expenditures associated with managing this pest. Although the food security cost is not high at the household level (60 kg per year per affected farmer), the economic and biodiversity losses are high at the national level. For example, from 2017 and 2019, the country lost US $ 204 million worth of income due to maize production losses and chemicals purchases. However, if the pest persists, it can cause food security and poverty problems in the long run by reducing marketed surplus and income (Kassie et al., 2020).

The rest of the article is structured as follows: in Section 2, we outline study areas and data sources; in Section 3, we describe the estimation approaches used to measure production losses due to FAW, and the impact of insecticides on human and environmental health; we present and discuss the results in Section 4; finally, we make concluding remarks in Section 5.

2. Study areas and data sources

2.1. Study areas

In Ethiopia, FAW is a threat to over 9 million maize-growing farm households. It was first observed in 2017 (Legesse, 2017) and is currently one of the most destructive maize pests in the country. Maize is an economically important and strategic food security crop covering 20% of cultivated land and accounting for 30% of the total cereal production (CSA, 2019). It provides the largest share of calories (22%) for most Ethiopians (Dorosh and Minten, 2020). It is also the most productive cereal crop in the country, with an average yield of 4 tonnes/ha (CSA, 2019).

This study covers the major maize-producing districts and agro-ecological zones of Ethiopia. We used the sampling frame prepared by the Sustainable Intensification of Maize-Legume Cropping Systems in Eastern and Southern Africa (SIMLESA) project of the International Wheat and Maize Improvement Center (CIMMYT) (Jaleta et al., 2018). The SIMLESA survey was designed to represent the key maize-producing agro-ecological zones of Ethiopia. It covered 225 maize-producing villages in 39 districts in Amhara, Benishangul Gumuz, Oromia, Southern Nations and Nationalities (SNNP), and Tigray Regional States. In our study, we cover 30 districts and 150 villages. We dropped seven districts in the Oromia Regional State due to security reasons and excluded the Benishangul Gumuz and Tigray Regional States for logistical reasons. The three remaining Regional States (Amhara, Oromia, and SNNPR) jointly produce more than 86% of the country's maize, as reported in Table 1 (CSA, 2019).

[Table 1 here]

The study villages and their corresponding agro-ecological zones, represented by the CIMMYT's maize mega-environments (MMEs), are represented in Figure 1. The MMEs are homogenous production environments defined based on agro-climatic conditions (Bellon et al., 2005; Sonder, 2016) and classified using maximum rainfall and temperature. Rainfall and temperature and rainfall are key parameters that affect not only maize production but also the biology and spread of the FAW (Kasoma et al., 2020; Ramirez-Cabral et al., 2017).

[Figure 1 here]

Among the communities we surveyed, 71 are classified as wet upper mid-altitudes, 48 are in the highlands, 28 fall in the dry mid-altitudes, two are found in the wet lower mid-altitudes, and one is in the dry lowlands. Over the study period, nearly 96% of the maize production in the country came from three major MMEs: the wet upper mid-altitudes (45%), the highlands (39%), and the dry mid-altitudes (12%). The remainder of the country's maize production came from the wet lower mid-altitudes, wet lowlands, and dry lowlands, each contributing nearly 1% (see Table 1).

2.2. Data sources and collection

We used data from three sources: first, we used primary community and expert opinion survey datasets collected for this study using FGDs between June and July 2020 from 150 communities. On average, seven farmers participated per FGD, making 1100 farmers (10% women) in total. The expert opinion survey involved 180 agricultural experts, of whom 150 were development agents who worked with the farmers, and 30 were experts who worked in the districts' agriculture offices. We used a structured questionnaire that covered various topics, including farmers' awareness and knowledge of FAW, the percentage of farmers affected by FAW, control strategies, attainable yield, actual yield, and yield losses due to FAW. We collected data on the percentage of farmers affected by FAW in their respective villages, and the yield losses due to FAW in 2017, 2018, and 2019 production season. To understand farmers' levels of FAW awareness and knowledge, we asked each FGD participant two questions: (1) Are you aware of the FAW? and (2) Can you identify the FAW from these pictures? (See Figure 2).

Second, we used the agricultural sample survey datasets for the 2017, 2018, and 2019 main seasons. These datasets are nationally representative household survey data collected by the Ethiopian Central Statistical Agency (CSA, 2019).

Third, we used insecticide data collected by the authors from the Ministry of Agriculture (MoA, 2020).

[Figure 2 here]

To measure the effect of FAW, we combined the community survey data with the CSA data, from which we obtained the total maize area and the number of maize-growing farmers in the country CSA datasets. We identified the agro-ecological zones for each survey community by overlaying their coordinates with the global maize mega-environments' shapefile. Because we did not have access to the farmers' coordinates in the CSA survey, we used the centroids of the CSA's survey areas to identify the key MMEs. Finally, we used region, zone, district, and MMEs as unique identifiers to combine the two datasets.

3. Estimation approach

3.1. Measuring maize production losses

Maize yield loss is the difference between attainable yield without the presence of FAW and actual yield in the presence of FAW (De Groote et al., 2020). However, FAW is not the only cause of yield loss. Several other factors contribute to yield loss, including abiotic factors (e.g., drought and soil fertility) and other biotic factors (e.g., diseases, stemborers, and locusts). Results may be biased if farmers are asked directly to estimate yield loss due to FAW alone without considering the potential yield loss attributable to other production constraints. To mitigate this problem, we first asked farmers to compute the actual maize yield in the community in the presence of all production constraints, including FAW. Secondly, we asked them to estimate the attainable yield in the absence of production constraints. Thirdly, we asked farmers to quantify FAW's contribution and that of other production constraints to the yield gap, which is the difference between the attainable and actual yields.

We calculated the total production loss (PL_i) due to FAW using equation (1) as follows:

$$PL_i = \sum_i^k A_i \times [(Y_a - Y) \times L_i] \times (N_{hi} \times F_{ai}) \quad (1)$$

where the index i represents agro-ecological zones; k denotes the number of agro-ecological zones; A_i is the average land size (ha) devoted to maize in that zone; Y_a is the attainable yield without the presence of production stresses, including FAW (tonnes/ha); and Y is the actual yield in the presence of FAW and other production stresses (tonnes/ha). L_i is the proportion of the average yield losses attributed to FAW (%); N_h is the number of maize-growing households; and F_{ai} is the proportion of farmers affected by FAW. We obtained the values for Y_a, Y, L_i and F_{ai} from the community survey data, while the values of A_i and N_{hi} were from the CSA datasets (Table 2).

[Table 2 here]

Although farmers and government incur management costs, we focused on production losses (PL_i) because we did not have full management cost data. However, we report the chemical costs and measure the impacts of chemical spraying on human health and the environment, as discussed in the next section.

3.2. Measuring the impacts of insecticides on environmental and human health

The sudden invasion of FAW has alarmed the government, whose response has been to deploy the massive spraying of insecticides as emergency measure in FAW-affected maize fields. Over the study period, the government distributed 457,427 liters of insecticides and sprayed on 1.5 million ha of maize (see Table 8). The direct cost of pesticides to the government was about US $ 4 million. This does not include the insecticides that farmers purchased themselves, or the costs of surveillance and management, on which no data are available.

While insecticides are used to boost crop productivity, they have unintended consequences on human and environmental health. The use of insecticides poses a risk to human health, water quality, food safety, aquatic species, and beneficial insects (Arias-Estévez et al., 2008; Athukorala et al., 2012; Kouser and Qaim, 2015; Leach and Mumford, 2008; Liu et al., 1995; Mullen et al., 1997; Skevas et al., 2013). To measure the risks to human health and the environment caused by pesticides used to control FAW, we used the environmental impact quotient (EIQ) (Grant, 2020; Kovach et al., 1992). The EIQ has three components: producer, consumer, and environmental effects. The producers' and consumers' effects measure the potential health impact of direct exposure to insecticides, and food and water contaminated with insecticides. Insecticides like chlorpyrifos have been shown to harm the cognitive development of children, while others have been linked to cancer (Liu and Schelar, 2012). The environmental effects of insecticides include threat to the potential effects on fish, birds, bees, and other beneficial insects, and potential leaching. Although the EIQ uses arbitrary weights to measure the effects of the insecticides, it has been used in other studies as there is no easily available alternative to EIQ at present (Kniss and Coburn, 2015; Kouser and Qaim, 2015; Midingoyi et al., 2019; Sharma and Peshin, 2016). In any event, it is important to consider the health and environmental effects (Midingoyi et al., 2019). For the detailed computation of EIQ, we refer readers to Kovach et al. (1992) and Grant (2020).

4. Results and discussion

4.1. Farmers awareness of damage caused by FAW and knowledge in identifying FAW

We found that 97% of the FGD participants in Ethiopia were aware of FAW. Moreover, 88% of the farmers in the FGDs correctly identified the FAW from the pictures shown (Table 3), slightly more than those in Kenya (82%) (De Groote et al., 2020). There were relatively fewer farmers in the wet upper mid-altitude and highland MMEs that correctly identified FAW than farmers in other agro-ecological zones. These two agro-ecological zones contribute more than 80% of the country's maize production, suggesting that the extension system may need to provide additional capacity-building activities for farmers.

[Table 3 here]

4.2. Farmers' FAW control strategies

Farmers' assessment of the effectiveness of FAW control strategies varied by agro-ecology (Figure 3). Farmers in the wet lower mid-latitude and dry lowland agro-ecological zones named a few control methods. We asked farmers to score their effectiveness on a scale from zero (minimum) to ten (maximum). Insecticides received an average score of six (Figure 3 Panel A). The effectiveness of chemicals remained the highest (Figure 3, Panels B-F). Cultural (e.g., rotation, and fallow) and biological (e.g., caring for the striped earwig species during field management) pest control techniques received a score of five. The effectiveness of botanical extracts (e.g., neems) and mechanical control (e.g., killing larvae of the pest) received below-average scores. The FGD participants gave a low effectiveness score (two) for agro-ecological approaches (e.g., cropping systems such as intercropping), which are being promoted to control FAW in Ethiopia and elsewhere (Harrison et al., 2019; Matova et al., 2020; Njuguna et al., 2021; Salato and Crozier, 2017). This result is in line with Kassie et al. (2020), who found that intercropping (maize-legume) had little impact on controlling maize production losses due to FAW in southern Ethiopia. However, an experimental study in Uganda showed that intercropping was more effective than monocropping in controlling FAW and stemborers (Hailu et al., 2018). A systematic study of intercropping, differentiated by country and agro-ecology, may determine its effectiveness.

[Figure 3 here]

4.3. External support for FAW control

We asked the FGD participants to assess if the community they belonged to had received external support for controlling FAW. We also asked whether the support had increased, decreased, or remained the same. The support included training in FAW management, provision of credit, free insecticides, and spraying equipment. Farmers may be able to receive support from the regional and federal governments, Agricultural Research Systems, and development organizations. More than half of the communities (61%) had not received any support (Table 4). For 6% of the communities, support had remained the same, suggesting that farmers had received continuous support since the first occurrence of FAW in their respective communities. About 21% of the communities reported that external support for FAW control had increased. On the other hand, 11% of the studied communities reported that their communities had received external support, but it had decreased over time. The absence or low level of support may have contributed to higher production losses.

[Table 4 here]

4.4. Farmers affected by FAW

The map in Figure 4 shows the distribution of the affected farmers by agro-ecology. The FGD results indicated that FAW affected 40% of maize farmers (Table 5), while the expert opinion interviews estimated that 51% of the farmers were affected (Table A1, Appendix). In the wet lower mid-altitudes, which contain 3% of all maize farmers (Table A2, Appendix), farmers were the most affected (59%). In the dry lowlands, where 4% of maize farmers are located, FAW affected 17% of them. For the other agro-ecological zones, the proportion of farmers affected by FAW was close to the country's average at 40%. The total number of farmers affected by FAW over the study period was 3.7 million per annum.

[Table 5 here]
[Figure 4 here]

4.5. Maize yield losses due to FAW

The FGD participants estimated that 36% of maize yield losses could be attributed to FAW (Table 6). This estimate was close to the agricultural experts' estimate of 32% (Table A1, Appendix). The map in Figure 5 shows the distribution of the yield losses by agro-ecology. In the wet mid-altitudes and highland agro-ecological zones, losses were close to the country's average of 36%. However, yield losses in the dry lowlands were higher than the country's average. This was perhaps because of the limited support farmers had received for

FAW control in this zone (Table 4), the resulting limited use of control strategies (Figure 3), and the absence of hosts other than maize. The variability in yield loss could be due to several factors including farming practices, natural enemies' availability, and climatic factors (Harrison et al., 2019). Several studies have established the role of climatic factors in FAW incidence. The combined effect of natural enemies including predators and parasitoids could be up to 60% effective in controlling FAW if these natural enemies were conserved (Sisay et al., 2019b, 2018). Heavy downpours can reduce FAW by washing away neonates and affecting the flight capability of adult moths. Soil health in terms of soil moisture and fertility enhance plant vigor, which, in turn, protects crops against heavy damage (Baltzer et al., 2012; Wyckhuys and Oõneil, 2007). In future, a detailed study would be warranted, to understand the factors driving differences across agro-ecological zones. While a direct comparison might not be suitable, as yield losses depend on several factors (agro-ecology, farm management, years of data collection, estimation approach, etc.), our estimates of yield loss are lower than those reported by De Groote et al. (2020) in Kenya.

[Table 6 here]

[Figure 5 here]

4.6. Production losses: economic and food security implications

This sub-section reports the total maize production losses computed using equation (1), presented by agro-ecological zones (Table 7) and administrative regions (Table A4, Appendix). In 2017, we estimate that Ethiopia lost 0.18 million tonnes of maize to FAW (Table 7). The production loss increased from 0.22 million tonnes in 2018 to 0.25 million tonnes in 2019. The increase in loss over time could be attributable to changes in the proportion of farmers affected (Table 5), the percentage yield losses (Table 6), the number of maize farmers (Table A2, Appendix), and maize land size (Table A3, Appendix). The highest production losses are in the wet upper mid-altitude, highland, and dry mid-altitude agro-ecological zones. The production losses are small compared to the first estimates by Day et al. (2017) and Rwomushana et al. (2018). For 2017, our estimate was 7% of the 2.74 million tonnes of maize production loss in

Ethiopia estimated by Day et al. (2017). Similarly, our estimated losses were 13% of the 1.67 million tonnes of maize loss in 2018 estimated by Rwomushana et al. (2018).

Over the study period, total production loss was 0.67 million tonnes (0.22 million tonnes per year). The total loss was US $ 200 million worth of maize (Table 7), equivalent to 0.08% of the country's Gross Domestic Product ($US 262 billion) from 2017 to 2019 (World Bank, 2020). Alternatively, the losses were equivalent to 3% of the total foreign direct investment (US $7,327 million) in 2017 and 2018 alone (FAO, 2019). Using the 152 kg per capita consumption of maize in Ethiopia (Muricho et al., 2014), the quantity of maize lost could have met the per capita maize consumption of over 50% (4.3 million) of the country's chronically food-insecure (8.5 million people) (IPC, 2020).

The economic and food security costs are high at the national level as the per capita maize production loss is 60 kg per year (0.22 million tonnes divided by 3.7 million affected framers). At household-level, Kassie et al. (2020) find no significant effect of FAW on per capita maize consumption. However, if the pest persists, it can have food security and poverty implication at the household level by reducing marketed surplus and income (Kassie et al., 2020).

[Table 7 here]

4.7. Human and environmental effects of insecticides used for FAW control

Four insecticides are used in Ethiopia to reduce the impact of the pest (Table 8). According to the World Health Organization (WHO), malathion is slightly hazardous while the rest of the chemicals are moderately hazardous (WHO, 2009). According to the Leach and Mumford (2008) toxicity-level classification, all these insecticides have a high toxicity impact on the environment (e.g., by killing beneficial insects). Malathion, diazinon, and dimethoate carry a considerable risk for the environment, as shown by the high EIQ values (Table 8). Synthetic insecticides are important management options in FAW control, but repeated application increases the accumulation of insecticides in the environment and raises major concern, as demonstrated by the high EIQ values. Furthermore, resistance to major classes of synthetic insecticides in the native regions of this pest is another problem. The efficacy of a synthetic insecticide-based management strategy is not guaranteed, as the FAW has developed resistance to many active ingredients from different classes of insecticides (Gutiérrez-Moreno et al., 2019; Otim et al., 2021; Özkara et al., 2016; Yu, 1991). This suggests the need for resistance management as a vital component of integrated pest management. The risk impact on human health is relatively low, given the relatively low value of EIQ for consumers and producers. However, repeated exposure to small doses of insecticides can lead to long-term effects in humans. This calls for a judicious and appropriate use of synthetic insecticides to successfully manage FAW and sustain the increased productivity of maize in Ethiopia and elsewhere in Africa. Previous reports show that Ethiopia is home to many natural enemies of the FAW (Sisay et al., 2019a). The adverse impacts of these insecticides on non-target and beneficial organisms and the environment might also explain pest incidence variations and yield loses because of the negative impact of insecticides on biological control agents. Our results suggest the importance of control strategies that effectively suppress the pest without compromising the natural environment. These may include biopesticides (Akutse et al., 2019), predators and parasitoids (Laminou et al., 2020; Sisay et al., 2019a), and the push-pull technology (Harrison et al., 2019; Midega et al., 2018).

[Table 8 here]

5. Conclusions

The FAW has received a great deal of attention from researchers, growers, private sector, policymakers and development partners since it has threatened the agriculture sector's performance and the livelihoods of the population of SSA. However, there is little evidence on the country-wide economic effects of FAW and its implications for food security. Despite the increasing use of insecticides to control FAW, its effects on the environment and human health have not been studied. In this paper, we present the first comprehensive estimate of the impact of FAW on maize production, food security, and health in Ethiopia, contributing to the few existing studies in SSA. We used primary community survey data combined with a nationally representative agricultural household survey to achieve our objectives. The community survey provided good estimates of community-level yield losses, while the agricultural household survey provided a good picture of maize production in Ethiopia.

Combining the two survey datasets enabled us to estimate the heterogeneous impacts of the FAW on maize production in the country.

The first finding is that FAW caused production losses of 0.67 million tonnes of maize, equivalent to 2.54% of the maize production (25.96 million tonnes) over the study period. The total production loss was US $ 200 million worth of maize (0.08% of the country's GDP). At the current 152 kg per capita consumption of maize in the country, the maize lost to the FAW could have met the maize consumption requirement of over 4 million food-insecure people. In the long run, together with other co-existing production constraints, FAW can put the livelihoods of many poor people at risk and may reverse the gains already made in productivity and poverty reduction that the country has achieved over the last three decades. The second main finding is that controlling the pest using pesticides is contributing to environmental damage or degradation, thus threatening sustainable food production. The third finding is that the results vary substantially by agro-ecology, which is vital for prioritizing investment.

A key implication of these findings is that developing and promoting affordable, accessible, ecologically friendly control strategies must be facilitated to control the pest sustainably. Our analysis does not reflect the total impact of FAW due to limited data. Firstly, we did not capture the full management costs, such as insecticides and labor costs, involved in controlling the pest. Secondly, although we indicate the toxicity of insecticides for the environment and human health, the chemical application's health and environmental costs are not factored into the analysis. We, therefore, recommend that future studies should (1) consider both the direct and indirect effects of the pest and its control to reflect its overall cost; and (2) introduce effective, healthy, and environmentally friendly management strategies for FAW and conduct comprehensive evaluations of their effectiveness. It is important to generate evidence on the full impact of FAW and to develop and promote ecologically sustainable control strategies.

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Tables and Figures

Table 1. Area under maize cultivation and production by agro-ecological zones

	Cultivated land (millions of ha)			Production (millions of tonnes)		
Agro-ecological zones	2017	2018	2019	2017	2018	2019
Wet upper mid-altitudes	0.85	0.97	0.85	3.74	4.27	3.78
Wet lower mid-altitudes	0.05	0.03	0.03	0.14	0.09	0.09
Dry mid-altitudes	0.34	0.29	0.34	1.00	0.88	1.37
Wet lowlands	0.01	0.03	0.03	0.04	0.11	0.13
Dry lowlands	0.04	0.04	0.02	0.08	0.05	0.07
Highlands	0.69	0.85	0.82	2.95	3.59	3.59
Total	1.98	2.20	2.08	7.95	8.98	9.03

Source: CSA's agricultural sample survey

Table 2. Attainable yield, actual yield, and average land size, 2017-2019

	Attainable yield (tonnes/ha)- (Y_a)	Actual yield (tonnes/ha)- (Y)	Yield losses due to FAW and other stresses (tonnes/ha)- ($Y_a - Y$)	Average land size (ha)- (A_i)	Number of farmers (millions) (N_{hi})
Agro-ecological zones	A	B	C=A-B	D	E
Wet upper mid-altitudes	4.02	2.76	1.26	0.12	3.41
	(0.10)	(0.08)	(0.05)	(0.08)	(0.015)
Wet lower mid-altitudes	5.08	3.73	1.35	0.08	0.32
	(0.90)	(0.82)	(0.15)	(0.01)	(0.006)
Dry mid-altitudes	4.40	2.86	1.54	0.14	1.29
	(0.13)	(0.13)	(0.07)	(0.01)	(0.013)
Dry lowlands	3.10	2.47	0.63	0.10	0.33
	(0.12)	(0.16)	(0.11)	(0.02)	(0.007)
Highlands	4.13	2.88	1.25	0.11	3.80
	(0.14)	(0.11)	(0.06)	(0.06)	(0.014)
Average	4.11	2.82	1.29	0.12	9.28
	(0.07)	(0.06)	(0.03)	(0.04)	(0.007)

Note: Standard errors in parenthesis.

Sources: columns A and B are from the community survey data; columns D and E are from the CSA's agricultural sample survey.

Table 3. Farmers awareness and knowledge of FAW (%)

Agro-ecological zones	Awareness of FAW (%)	Correctly identified FAW (%)
Wet upper mid-altitudes	92	70
Wet lower mid-altitudes	100	100
Dry mid-altitudes	99	88
Dry lowlands	100	100
Highlands	92	80
Average	97	88

Source: Community survey

Table 4. FAW control support to communities

External support:	Wet Upper Mid-altitudes	Wet Lower Mid-altitudes	Dry Mid-altitudes	Dry Lowlands	Highlands	Average
Not at all	61	100	63	0	61	61
Increased	21	0	30	0	18	21
Same	7	0	0	100	5	6
Decreased	10	0	5	0	15	11
Do not know	2	0	1	0	0	1
Total	100	100	100	100	100	100

Source: Community survey

Table 5. Proportion of farmers affected by FAW (%)

Agro-ecological zones	2017	2018	2019	Average
Wet upper mid-altitudes	36.40	39.64	39.71	38.60
	(2.51)	(2.49)	(2.28)	(1.40)
Wet lower mid-altitudes	55.00	55.00	67.50	59.17
	(20.00)	(25.00)	(27.50)	(11.21)
Dry mid-altitudes	44.02	41.71	45.27	43.68
	(4.73)	(5.07)	(4.96)	(2.82)
Dry lowlands	20.00	12.50	17.50	16.67
	(0.00) [a]	(2.50)	(2.50)	(1.67)
Highlands	37.95	42.39	44.75	41.67
	(3.58)	(4.06)	(4.07)	(2.25)
Average	38.07	40.68	42.13	40.30
	(1.86)	(1.97)	(1.89)	(1.10)

Note: Standard errors of the mean are reported in parenthesis; [a] the standard errors are zero because FGD participants provided 20% loss for all data points

Source: Community survey

Table 6. Yield losses due to FAW (%)

Agro-ecological zones	2017	2018	2019	Average
Wet upper mid-altitudes	34.37	34.71	35.82	34.97
	(2.14)	(1.96)	(2.05)	(1.18)
Wet lower mid-altitudes	35.00	32.50	35.00	34.17
	(5.00)	(2.50)	(5.00)	(2.01)
Dry mid-altitudes	38.78	41.21	43.46	41.17
	(3.78)	(3.47)	(3.15)	(1.99)
Dry lowlands	80.00	80.00	80.00	80.00
	(0.00) [a]	(0.00) [a]	(0.00) [a]	(0.00) [a]
Highlands	33.20	36.43	34.20	34.61
	(3.13)	(2.69)	(2.75)	(1.65)
Average	35.13	36.64	36.96	36.25
	(1.61)	(1.45)	(1.48)	(0.87)

Note: Standard errors in parenthesis; [a] the standard errors are zero because FGD participants provided 80% loss for all data points

Source: Community survey

Table 7. Estimated total maize production losses

	Loss (millions of tonnes)			Loss (millions of $US) [¥]		
MMEs	2017	2018	2019	2017	2018	2019
Wet upper mid-altitudes	0.064	0.080	0.084	15.21	22.35	28.53
Wet lower mid-altitudes	0.007	0.004	0.006	1.52	0.89	1.73
Dry mid-altitudes	0.049	0.047	0.073	13.33	14.94	24.87
Wet lowlands	0.002	0.005	0.005	0.55	1.37	1.53
Dry lowlands	0.002	0.002	0.002	0.75	0.58	0.46
Highlands	0.057	0.089	0.095	14.22	25.24	32.28
Total	0.182	0.228	0.265	45.59	65.38	89.40

[¥] We use producer prices to estimate the value of production losses. The exchange rate was 26.87 ETB/$US in 2017, 27.43 ETB/$US in 2018, and 29.23 ETB/$US in 2019.

Source: authors' computation based on community survey and CSA's agricultural sample survey

Table 8. Human health and environmental impacts of insecticides use to control FAW

				Components of field use EIQ			
Insecticides	Active ingredient (%)	Application rate (liter/ha)	Quantity (liters)	Average EIQ	Consumer effects	Producer effects	Ecological effects
Malathion	50	2	114,529	23.80	3.80	7.70	49.60
Diazinon	60	1	256,914	22.60	1.30	3.50	63.00
Dimethoate	40	1	25,488	11.50	3.90	3.50	26.90
Chlorpyrifos	48	0.5	60,496	5.50	0.40	1.20	14.90

Source: authors' computation based on MoA's pesticides data (MoA, 2020)

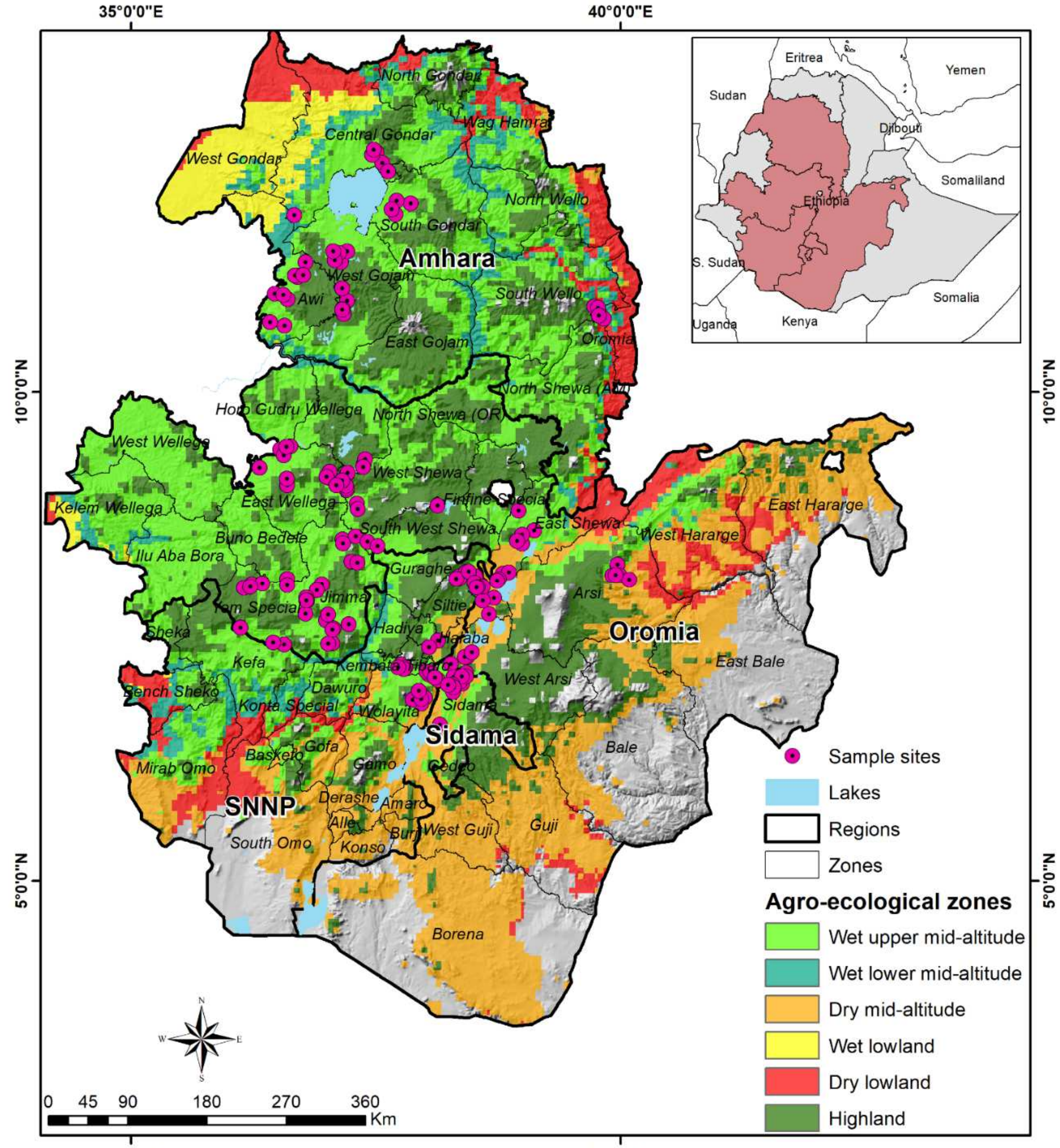
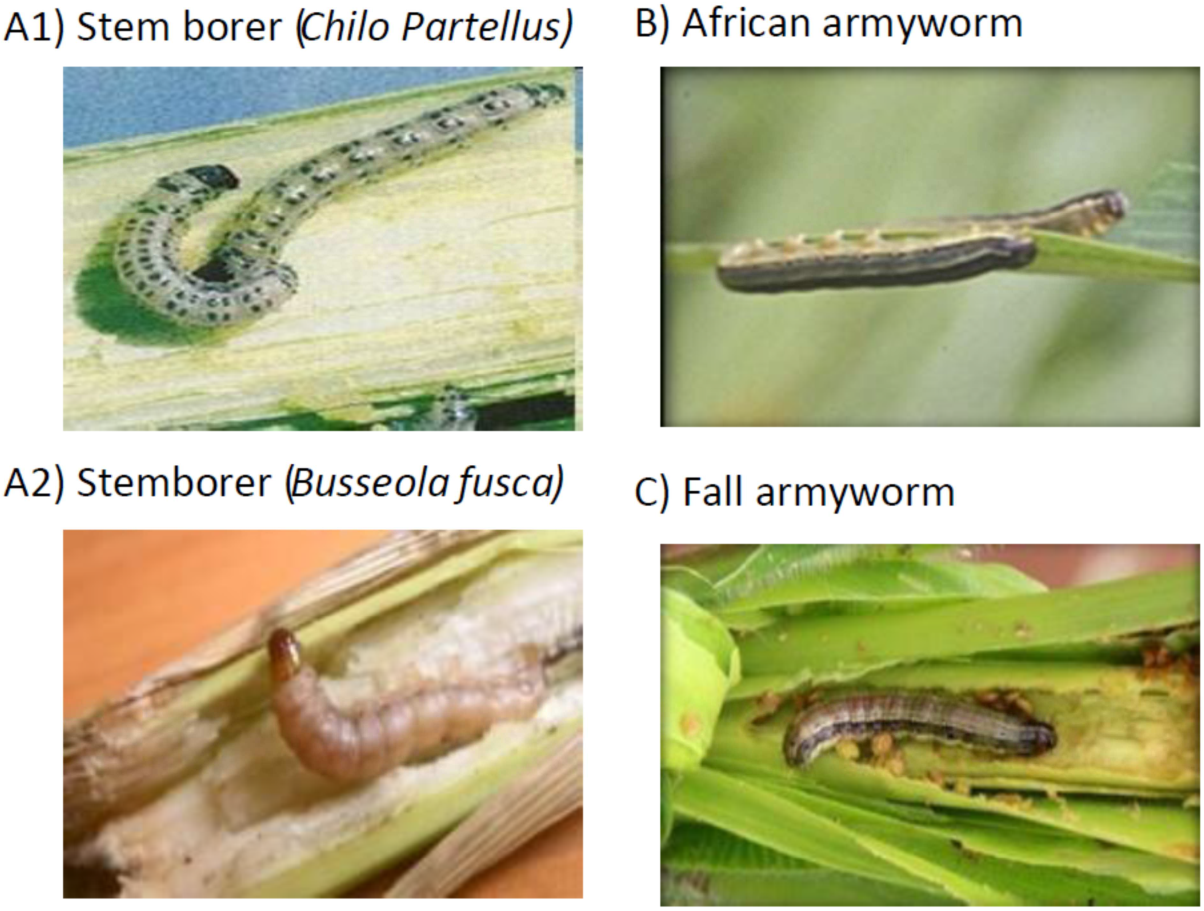


Figure 1. The study areas and the location of sample communities within maize mega-environments



A1) Stem borer (*Chilo Partellus)*

B) African armyworm

A2) Stemborer (*Busseola fusca)*

C) Fall armyworm

Figure 2. Pictures of lepidopterous insect pests shown to farmers: A) stemborers (either Chilo partellus (A1), or Busseola Fusca (A2); B) African armyworm; and C) fall armyworm

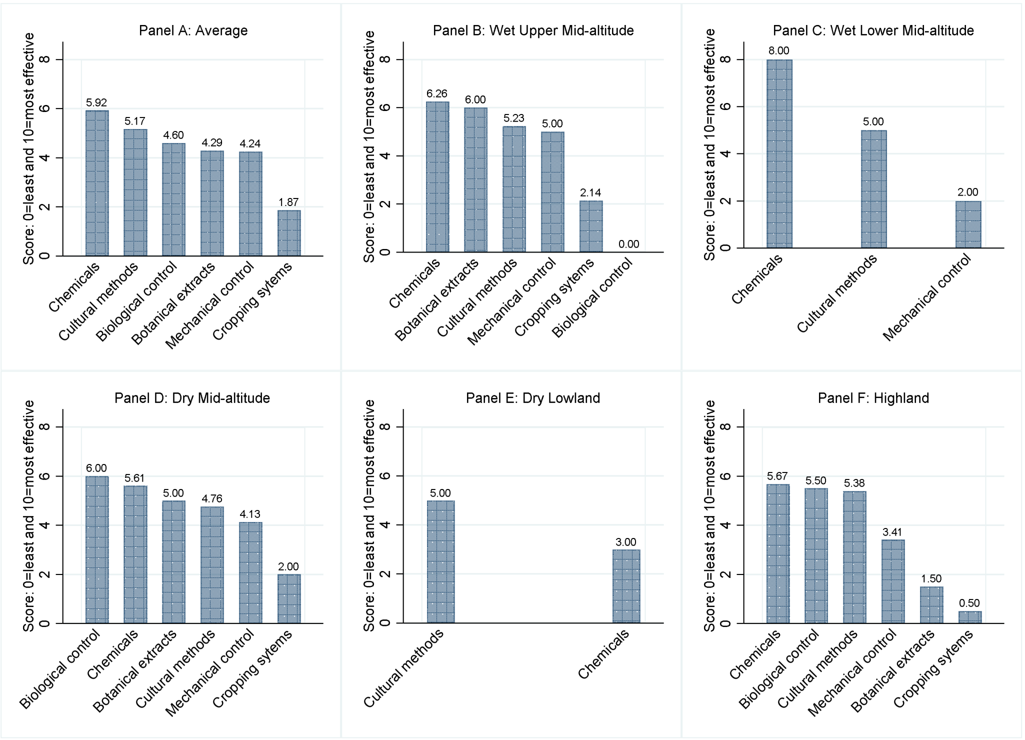


Figure 3. Farmers’ FAW control strategies by agro-ecological zones

Source: Community survey

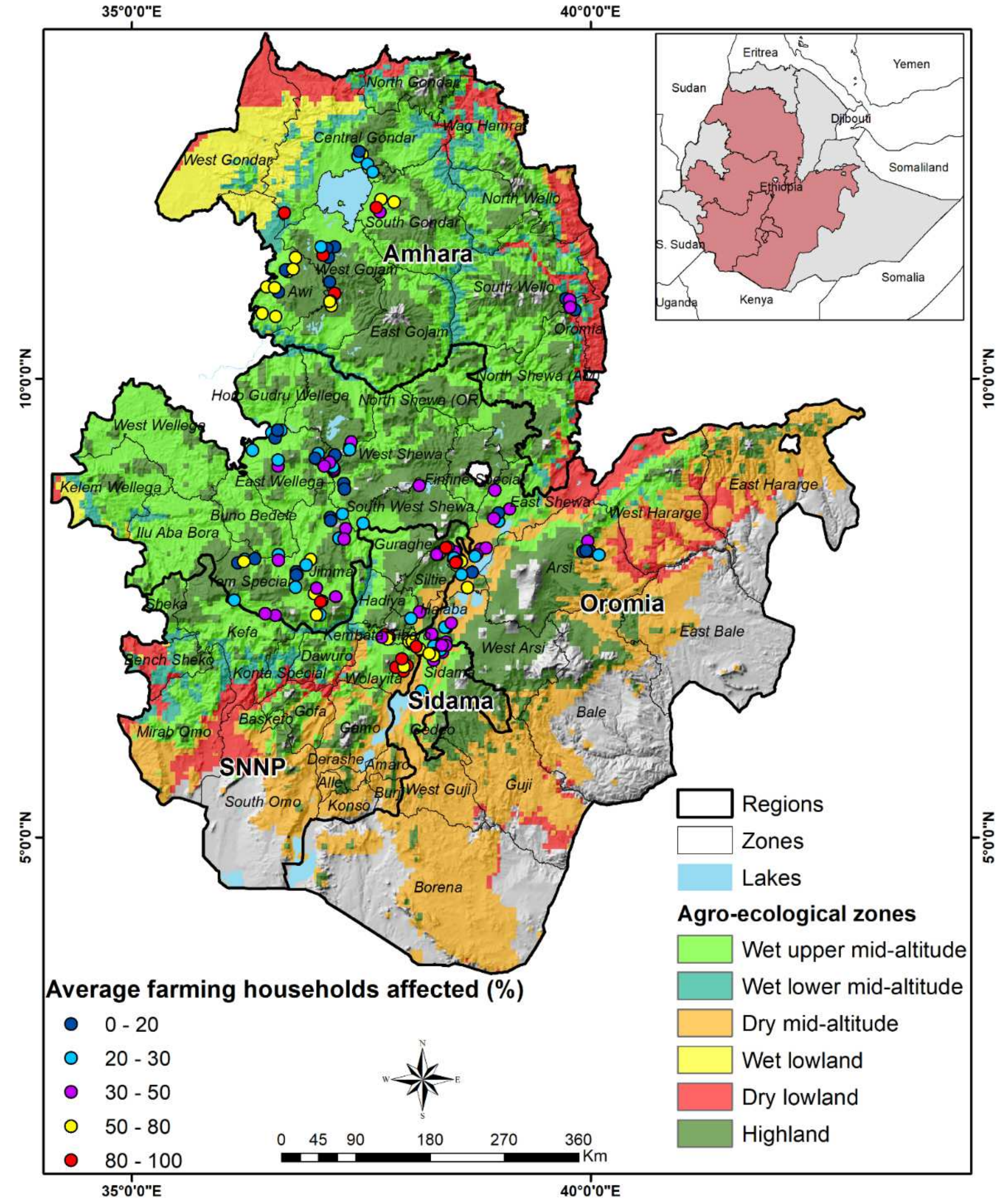


Figure 4. Geographic distribution of average farmers affected (%) by FAW, 2017-2019

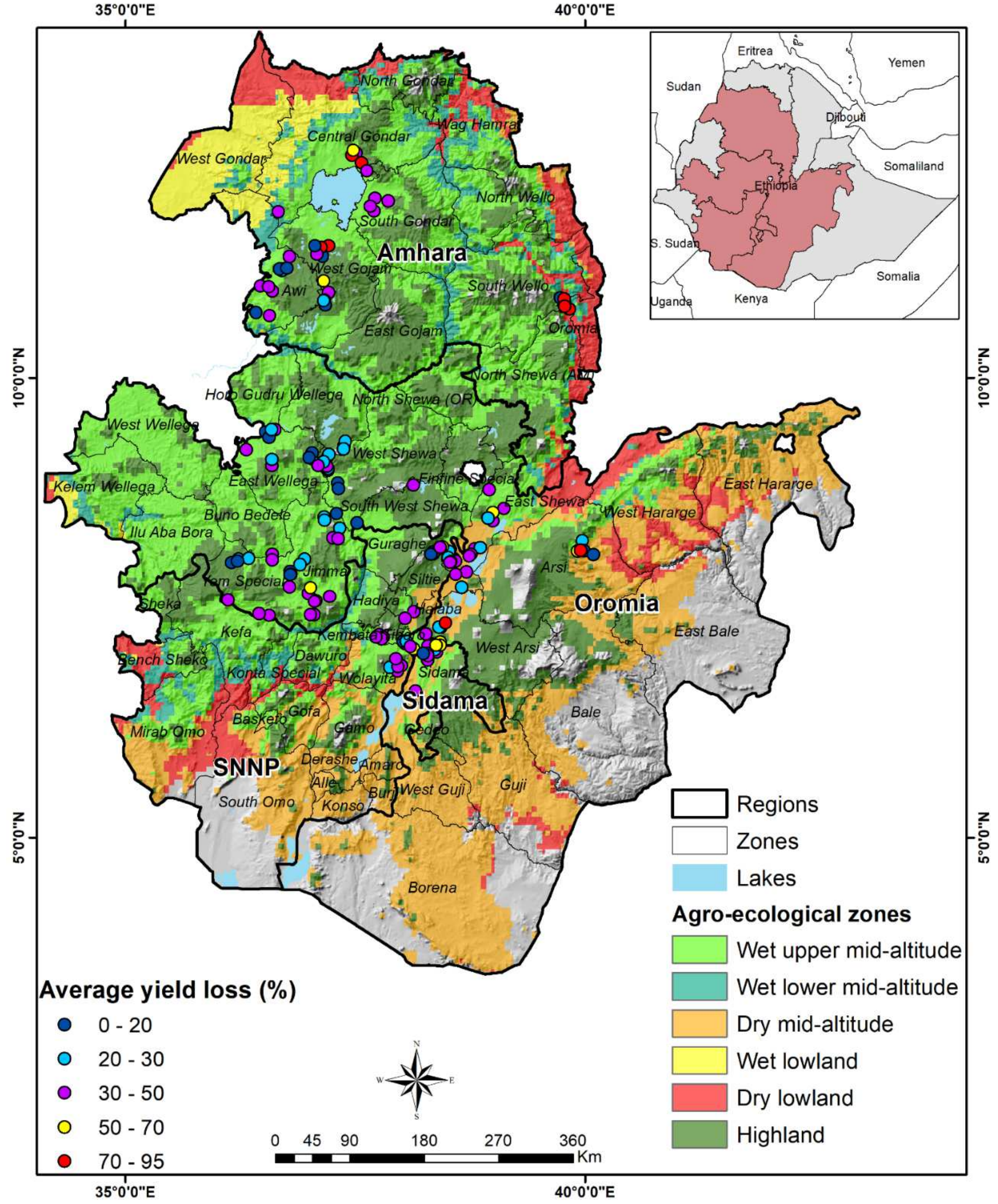


Figure 5. Geographic distribution of average yield loss (%) due to FAW, 2017-2019

Appendix

Table A1. Estimates of farmers affected and yield losses reported by agricultural experts (2017-2019)

Maize mega-environments	Farmers affected (%)	Yield loss (%)
Wet upper mid-altitudes	55	32
Wet lower mid-altitudes	79	40
Dry mid-altitudes	44	32
Dry lowlands	67	43
Highlands	47	30
Average	51	32

Source: experts' survey (2017-2019)

Table A2. Number of farmers producing maize

	Number of farmers (millions)		
Agro-ecological zones	2017	2018	2019
Wet upper mid-altitudes	3.28	3.33	3.62
Wet lower mid-altitudes	0.43	0.29	0.24
Dry mid-altitudes	1.24	1.11	1.51
Wet lowlands	0.10	0.16	0.13
Dry lowlands	0.41	0.30	0.29
Highlands	3.28	3.69	4.41
Total	8.75	8.87	10.20

Source: CSA's agricultural sample survey.

Table A3. Average land size per household

Agro-ecological zones	2017	2018	2019
Wet upper mid-altitudes	0.11	0.13	0.12
Wet lower mid-altitudes	0.06	0.08	0.09
Dry mid-altitudes	0.14	0.14	0.15
Wet lowlands	0.09	0.21	0.21
Dry lowlands	0.11	0.11	0.08
Highlands	0.10	0.11	0.12
Overall average	0.11	0.12	0.12

Source: CSA's agricultural sample survey.

Table A4. Zone and regional-level estimates of maize production losses

		Loss (tonnes)		
Region	Zone	2017	2018	2019
Amhara	Semen Gondar	7,036	808	775
Amhara	Debub Gondar	5,698	8,267	12,989
Amhara	Semen Wollo	1,566	1,003	1,387
Amhara	Debub Wollo	1,024	2,963	2,827
Amhara	Semen Shewa	1,650	1,545	936
Amhara	Misrak Gojjam	8,777	9,244	11,778
Amhara	Mirab Gojjam	7,456	14,868	18,693
Amhara	Waghimra	1,835	715	485
Amhara	Awi	4,667	8,412	5,068
Amhara	Oromia Liyu Zone	1,764	235	504
Amhara	Bahir Dar Liyu		1,675	339
Amhara	Argoba Liyu	774	95	
Amhara	Dessie Town Administration		481	60
Amhara	Gondar Ketema Liyu Zone		408	265
Amhara	Maekelawi Gondar		10,785	8,548
Amhara	Mirab Gondar		1,648	1,710
	Amhara	42,245	63,150	66,364
Oromia	Mirab Wollega	6,652	5,470	5,360
Oromia	Misrak Wollega	6,338	7,544	5,964
Oromia	Ilu Ababor	10,688	3,721	4,947
Oromia	Jimma	4,278	11,470	11,230
Oromia	Mirab Shewa	3,784	4,555	6,356
Oromia	Semen Shewa	576	718	758
Oromia	Misrak Shewa	7,545	11,804	21,663
Oromia	Arsi	3,728	6,087	7,629
Oromia	Mirab Hararghe	1,751	4,356	3,369
Oromia	Misrak Hararghe	1,074	3,275	2,817
Oromia	Bale	4,613	4,044	4,652
Oromia	Borena	2,696	54	418
Oromia	Debub Mirab Shewa	3,522	2,421	3,251
Oromia	Guji	5,320	2,651	5,643
Oromia	Mirab Guji		1,130	1,713
Oromia	Oromia Liyu Zone		413	209
Oromia	Mirab Arsi	6,373	10,323	14,363
Oromia	Kelem Wollega	4,986	4,187	3,752
Oromia	Horo Guduru Wollega	9,859	8,064	4,531
Oromia	Buno Bedele		3,473	5,249
	Oromia	83,783	95,759	113,874

		Loss (tonnes)		
Region	Zone	2017	2018	2019
SNNP	Gurage	3,072	4,281	5,074
SNNP	Hadiya	2,889	4,303	3,925
SNNP	Kembata Tembaro	1,356	1,350	954
SNNP	Sidama	1,248	2,211	5,844
SNNP	Gedeo	878	417	1,667
SNNP	Welayta	1,857	2,052	5,229
SNNP	Debub Omo	5,535	5,562	7,389
SNNP	Sheka	159	302	1,170
SNNP	Kefa	3,079	5,709	6,868
SNNP	Gamo Gofa	5,093	9,758	11,145
SNNP	Bench Maji	4,550	5,592	3,484
SNNP	Yem Liyu	2,027	1,279	622
SNNP	Segen Akababi Hizboch	9,058	6,883	5,572
SNNP	Alaba Special	5,235	3,999	3,184
SNNP	Dawro	1,203	954	1,864
SNNP	Basketo Special	2,728	623	302
SNNP	Konta Liyu	640	243	265
SNNP	Silite	5,565	7,987	8,857
	SNNP	56,171	63,505	73,414
	Ethiopia [¥]	182,199	222,414	253,652

[¥] Note that the grand total is slightly different from the total loss reported in Table 7. This is due to differences in the calculation of averages by maize mega-environments and zones.

Sources: authors' estimate based on community survey and CSA's agricultural sample survey.