JAE Journal of Agricultural Economics

Journal of Agricultural Economics, Vol. 70, No. 2, 2019, 452–470
doi: 10.1111/1477-9552.12306

Do Farmers and the Environment Benefit from Adopting Integrated Pest Management Practices? Evidence from Kenya

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(Original submitted February 2018, revision received July 2018, accepted August 2018.)

Abstract

We estimate the impacts of a bundle of integrated pest management (IPM) practices on mango yield, mango net income, insecticide use, human health and the environment, using recent household survey data of mango growers in Kenya. We employ a multinomial endogenous switching treatment regression model with an ordered probit selection rule to establish counterfactual outcomes. Our results indicate that IPM-adopting farmers have higher mango yields and mango net income, and also use lower quantities of insecticide and cause less damage to the environment and to human health. In addition, switching from one IPM to multiple IPM practices generates greater economic, environmental and human health benefits. These results suggest intensification of IPM-adoption efforts and encouragement of the use of multiple IPM practices. These positive outcomes could be achieved through greater provision of technical support and extension services to farmers.

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Keywords: *Economic impact*; *environmental impact*; *human health impact*; *integrated pest management*; *Kenya*; *mango*; *multinomial endogenous switching treatment*.

JEL classifications: *C34, H23, Q12, Q15*.

1. Introduction

Mango is an economically important fruit crop in Kenya, and is traded on domestic, regional and international markets. It provides many smallholders with employment opportunities and livelihood improvement, while generating foreign exchange earnings. However, Kenya's mango production is constrained by many problems, with fruit flies being a major threat to food security, poverty alleviation and agricultural livelihoods. Indeed, across Africa, fruit flies are estimated to cause annual losses of US$ 2 billion in fruit and vegetable production (Ekesi *et al*., 2016). On mango fruit, the larval stages of fruit flies that feed on the fruit pulp are responsible for direct damage to the produce, causing anything from 30% to 100% loss in the absence of any pest management (Ekesi *et al*., 2011, 2014). This not only reduces productivity, but also the quality, marketability and value of the produce (Ekesi *et al*., 2006; Rwomushana *et al*., 2008). Fruit-fly infestations also cause indirect damage to the economy by reducing foreign exchange earnings from fruit due to quarantine restrictions and the loss of opportunities to export to global markets (Lux *et al*., 2003; Ndiaye *et al*., 2008; Ekesi *et al*., 2016).

There is currently an over-reliance on synthetic insecticides by farmers to manage insect pests on mango, including fruit flies. Insects are increasingly developing resistance to varying classes of pesticides because of overuse (Vontas *et al*., 2011; Pretty and Bharucha, 2015; Gautam *et al*., 2017). Furthermore, excessive use of synthetic pesticides has adverse effects on financial returns and human health, as well as on the environment and biodiversity (Rejesus *et al*., 2009; Asfaw *et al*., 2010; Schreinemachers and Tipraqsa, 2012; Gautam *et al*., 2017). These negative consequences are more severe in developing countries, partly because insecticide regulations are less restrictive than in their developed counterparts, and partly because spraying is often conducted manually, without adequate measures to prevent negative effects on human health and the environment (Ghimire and Woodward, 2013). The increased use of insecticides on fruit also reduces competitiveness, especially on international markets, due to undesirable pesticide residues (Lux *et al*., 2003).

Thus, effective alternative pest management is essential to the economic vitality of the horticulture industry in sub-Saharan Africa. Researchers and development partners in the horticulture sector have devised an integrated pest management (IPM) approach to reduce fruit-fly numbers as a more sustainable option to the conventional application of pesticide (Norton *et al*., 1999; Ekesi *et al*., 2016). IPM combines pest control practices that minimise the use of synthetic insecticides, are economically and environmentally sustainable, and safeguard human health (Blake *et al*., 2007; Pretty and Bharucha, 2015). In Africa, IPM techniques for preventing and managing fruit-fly infestations have been developed and promoted by the International Centre of Insect Physiology and Ecology (ICIPE), in collaboration with its partners. In Kenya, for example, these techniques aim to improve mango production, enhance market access for mango producers, and increase their incomes (Ekesi *et al*., 2011; Muriithi *et al*., 2016).

The adoption and extent of IPM practices should have impacts on multiple outcomes, such as productivity, economic, environmental, social and human conditions. Measurement of these outcomes should help policy-makers and development partners to better design policies to encourage adoption of IPM practices. Empirical evidence on how IPM practices impact insecticide use, crop yields and household welfare is scarce in developing countries, especially in sub-Saharan Africa, and there is a lack of sound evaluation of such impacts (Pretty and Bharucha, 2015; Gautam *et al.*, 2017). For example, Pretty and Bharucha (2015) recently reviewed 85 IPM projects in Africa and Asia and found evidence that such an approach reduced pesticide use. Nonetheless, they concluded that IPM's impact on crop yields was more complex, depending on, among other factors, the incidence and severity of a pest infestation. The few existing farm-level impact studies (e.g. Fernandez-Cornejo, 1998; Isoto *et al.*, 2008; Kibira *et al.*, 2015; Sanglestsawai *et al.*, 2015; Sharma and Peshin, 2016) mainly focused on an impact evaluation approach using binary treatment variables, while ignoring the intensity of IPM adoption. However, intensity may contribute to heterogeneous treatment effects. Furthermore, to our knowledge, no study has so far examined whether IPM that has been developed specifically to reduce mango-infesting fruit-flies is able to help reduce the risk effects of insecticide use on human health and the environment within the African context. Furthermore, it is well understood that some insecticides pose great risk to human health (Okello and Swinton, 2010; Athukorala *et al.*, 2012), water quality (Arias-Estévez *et al.*, 2008), food safety (Liu *et al.*, 1995), aquatic species (Mullen *et al.*, 1997), and beneficial insects (Brethour and Weersink, 2001; Cuyno *et al.*, 2001; Skevas *et al.*, 2013). However, the results from these previous studies are not comparable, as the types of IPM practice considered in the analyses vary.

We contribute to the current literature on the impact of IPM and other agricultural technology adoption in the following ways. First, very few of the existing studies use the multinomial treatment effects evaluation approach. This paper develops a treatment-effects model that can be used to analyse the effects of an endogenous multinomial treatment – when one treatment is chosen from a set of more than two choices – on continuous outcome variables. Specifically, we examine to what extent Kenyan mango farmers have adopted a variety of IPM practices developed to suppress mango-infesting fruit-flies, and how such adoption impacts on their insecticide use, crop yields, mango net income, human health and the environment. Secondly, we contribute to the fragmentary empirical data on the impact of IPM adoption on human health and the environment. Thirdly, IPM is a sustainable production intensification approach which does not rely on the increased use of insecticide. As a result, its adoption could potentially allow farmers to increase their mango productivity and incomes, without increasing dependency on insecticide, and, consequently, without increasing impacts on the environment.

We outline our estimation strategy and model specification in section 2. Section 3 describes the study area and our data, and offers a definition of variables. The empirical results follow in section 4, while the conclusion of the study and its policy implications are presented in section 5.

2. Econometric Approach

2.1. Evaluation strategy

Estimating the impact of technology on development outcomes requires a reliable estimate of the counterfactual situation. Such estimates are a challenge in an observational study because adoption of the technology and selection of the adopters themselves may not be random. Adopters may differ from non-adopters in terms of unobserved endowments (e.g. managerial ability, ambition, physical strength and risk preference) and observable characteristics (e.g. resource endowments, proximity to input markets, access to extension, education and training), which simultaneously affect adoption and outcomes of interest. Farmers who adopt the technology might be more productive on average than non-adopters because of differences in their circumstances and characteristics.

We use two approaches to deal with the selection bias and treatment heterogeneity effects. In the first approach, we include a set of explanatory variables that affect both adoption decision and outcome variables. For the second, we develop a multinomial treatment endogenous switching regression (ESR) framework where the multinomial treatment variable is assumed to follow an ordered probit choice model structure. This is a variant of the instrumental variable approach to instrument the endogeneity of adoption using the inverse Mills ratio (Carter and Milon, 2005; Abdulai and Huffman, 2014; Teklewold and Mekonnen, 2017; Kassie *et al.*, 2018). In the ESR framework, separate regressions are estimated respectively for adopters and non-adopters of IPM to estimate true effects of adoption through controlling for the endogeneity of adoption decisions, and through capturing the differential returns to covariates of adopters and non-adopters, and the interaction of adoption variables with regressors in the outcome equations. The separate regressions help to capture the slope effect of IPM adoption in addition to its intercept effect, which was ignored in previous studies (Fernandez-Cornejo, 1998; Isoto *et al.*, 2008; Sharma and Peshin, 2016). The implementation of this framework involves a two-stage econometric model to control for selection bias. The first stage consists of an adoption decision model, to estimate the combination of IPM practices as well as generate a variable to account for selection bias to be included in the second-stage. The second stage consists of an impact model to estimate the effects of a bundle of IPM practices on outcomes, after controlling for selection bias and other covariates.

2.1.1. The first stage: Modelling the adoption decision

The multinomial treatment variable arises from the choice of bundles of IPM practices. Each farm household chooses one IPM practice (treatment) from J alternatives in a bundle of IPM practices (Table 1) that yields the highest benefit or utility. These alternatives are categorised as follows: (i) Category $j = 0$, for mango growers who use none of the IPM practices on their plots; (ii) Category $j = 1$, for mango growers who use only one such practice on their plots; (iii) Category $j = 21$, for mango growers who use a combination of two such practices on their plots; and (iv) Category $j = 31$, for mango growers who use a combination of three or more such practices on their plots. The use of more than three practices on a plot is seldom observed.

As the term integrated pest management implies, it involves a number of practices to manage insects and can be adopted to varying degrees (see Table 2). We use the number of IPM practices employed as our treatment variable to measure the extent of adoption, following Park and Lohr (2005), Wollni *et al.* (2010) and Teklewold *et al.* (2013).

Although the Poisson regression model is often applied where the treatment variable is count data, it is appropriate when the occurrence of an event (in our case adoption of an IPM method) does not alter the probability of another event (Plan, 2014).

Table 1
Definition and summary of variables (mean)

Variables	Description	Full sample	Non-integrated pest management (IPM) adopters	One IPM adopters	Two IPM adopters	Three or more IPM adopters
Family size	Number of family members in a household	4.76	5.17	4.74	4.64	3.99
Sex	1 if household head is male; 0 otherwise	0.92	0.90	0.91	0.94	0.95
Age	Household age in years	57.67	56.87	57.14	58.77	58.86
Education	Education, in years, of household head	9.66	9.45	9.85	9.59	9.66
Livestock	Livestock ownership in tropical livestock units	3.16	3.49	3.48	2.96	1.84
Occupation	1 if main household occupation is farming; 0 otherwise	0.73	0.65	0.75	0.74	0.78
Extension visits	1 if household was visited by an extension officer in the last 3 years; 0 otherwise	0.52	0.38	0.49	0.64	0.68
Training on insect pest management	1 if household received training on insect pest management; 0 otherwise	0.67	0.48	0.68	0.80	0.82
Membership	Number of rural institutions to which household belongs	2.41	2.21	2.42	2.43	2.80
Number of adopters	Number of IPM adopters known by respondents in a village	9.33	2.38	6.51	9.73	11.77
Fungicide use	1 if mango plot received fungicide; 0 otherwise	0.53	0.58	0.56	0.50	0.43
Insecticide use	1 if mango plot received insecticide; 0 otherwise	0.85	0.91	0.84	0.80	0.78
Insecticide unit price	Insecticide unit price (KSh/litre)	3,448	3,200	3,608	3,380	3,730
Unavailability of IPM (traps and Food bait) on time in the village	1 if unavailability of IPM technology is a constraint; 0 otherwise	0.73	0.51	0.81	0.81	0.74
Insufficient training a constraint	1 if insufficient training on IPM is a constraint; 0 otherwise	0.43	0.41	0.55	0.36	0.89
Insufficient labour a constraint	1 if insufficient labour for IPM application is a constraint; 0 otherwise	0.12	0.08	0.17	0.12	0.11

Table 1
(*Continued*)

Variables	Description	Full sample	Non-integrated pest management (IPM) adopters	One IPM adopters	Two IPM adopters	Three or more IPM adopters
Intercropping	1 if mango plot intercropped with other crops; 0 otherwise	0.81	0.80	0.79	0.81	0.89
Distance to plot	Plot distance from residence in walking minutes	6.07	6.91	5.56	6.06	5,57
Land quality	1 = Good, 2 = Medium, 3 = Low	1.64	1.76	1.68	1.50	1.46
Mango income	Proportion of mango income to annual household income	20.37	18.87	20.80	22.58	27.17
Mango loss	Proportion of mango production loss	30.00	28.84	31.95	27.89	24.72
High fruit-fly infestation (reference dummy)	1 if farmer reports fruit-fly infestation is high; 0 otherwise	0.56	0.63	0.62	0.49	0.39
Medium fruit-fly infestation	1 if farmer reports fruit-fly infestation is medium; 0 otherwise	0.24	0.16	0.23	0.24	0.43
Low fruit-fly infestation	1 if farmer reports fruit-fly infestation is low; 0 otherwise	0.19	0.19	0.15	0.27	0.19
Disease infestation	1 if farmer reports mango disease; 0 otherwise	0.96	0.96	0.96	0.95	0.97
Machakos (reference dummy)	1 if Machakos County; 0 otherwise	0.26	0.38	0.35	0.21	0.06
Embu	1 if Embu County; 0 otherwise	0.28	0.12	0.23	0.42	0.51
Meru	1 if Meru County; 0 otherwise	0.24	0.13	0.29	0.26	0.35
Makueni	1 if Makueni County; 0 otherwise	0.22	0.40	0.22	0.11	0
Observations		633	182	219	158	74

Table 2

Adoption of fruit fly integrated pest management (IPM) practices for suppression of fruit fly at plot level

	Number of plots treated with IPM	Percentage of plot treated with IPM (%)
Individual IPM practice		
Fruit-fly traps/male annihilation technique	394	52.39
Food bait spray	105	13.96
Biopesticides	18	2.39
Burning or burying fallen infested fruits	291	38.7
Orchard sanitation using an augmentorium	10	1.33
Fruit-wrapping bags	19	2.53
Smoking repellent herbs/spraying traditional concoction	56	7.45
Adoption of a bundle of IPM practices		
Non-adoption	182	28.75
Adoption of one IPM practice	219	34.60
Adoption of two IPM practices	158	24.96
Adoption of three or more IPM practices	74	11.69

Source: Households Survey of this study 2016.

This may not apply in our case as the probability of adopting the first IPM practice could change the probability of adopting a second or third practice, given that, in the latter case, the farmer has already gained some experience from adopting the first IPM and has been more exposed to information about IPM practices. In this paper, therefore, the number of IPM techniques adopted by farmers is treated as an ordinal variable and we use an ordered probit model in the estimation, following, for example, Wollni *et al*. (2010) and Teklewold *et al*. (2013).

The ordered probit model can be derived from a latent variable model (Wooldridge, 2010). Let I_j^* be the latent variable or utility that the individual farmer will generate with the choice of category $j = 0, \ldots, J$. This utility is determined by:

$$I_j^* = X_i\beta_j + e_j, \quad j = 0, \ldots, J \tag{1}$$

The vector X in equation (1) represents the set of household- and plot-level variables and location dummy variables with corresponding estimable parameters β; j is a categorical variable that describes choice of J alternative IPM practice bundle by farmers based on utilities I_j^*; and e is a disturbance term. The utility from adoption is not observed, but the decision of the ith household to adopt a bundle of IPM practices (I) is mapped as follows:

$$I_j = \begin{cases} 0, & \text{if } I_j^* \le c_1 \\ 1, & \text{if } c_1 < I_j^* \le c_2 \\ & \vdots \\ J, & \text{if } I_j^* > c_J \end{cases} \tag{2}$$

In equation (2), c represents unknown cut points or threshold parameters identifying the boundaries of moving through the different levels of IPM practice adoption.

The probabilities that the actual adoption variable Z takes the different possible values conditional on X and the standard normal assumption of e are expressed as follows:

$$\text{prob}(I_j = 0|X_i) = \Phi(c_1 - X_i\beta_j) \tag{3a}$$

$$\text{prob}(I_j = 1|X_i) = \Phi(c_2 - X_i\beta) - \Phi(c_1 - X_i\beta_j) \tag{3b}$$

$$\text{prob}(I_j = 2|X_i) = \Phi(c_3 - X_i\beta) - \Phi(c_2 - X_i\beta_j) \tag{3c}$$

$$\text{prob}(I_j = 3|X_i) = 1 - \Phi(c_3 - X_i\beta_j) \tag{3d}$$

The symbol $\Phi(.)$ is the standard normal distribution function. The parameters β and c are estimated using the command 'oprobit' available in STATA software.

2.1.2. The second stage: Modelling the impact of IPM on outcomes

The second stage of the econometric model to control for selection bias establishes the relationship between the outcome variables (*mango yield*, *mango net income* and *insecticide use*) and a set of explanatory variables that include household, plot and location characteristics. The outcome regression models are estimated separately for non-adopters and for the various categories of adopters for each bundle of IPM interventions. The four treatments categories mentioned in section 2.1.1 result in four outcome equations. These are defined as follows for each IPM bundle intervention j:

$$\begin{cases} \text{Regime } 0: \quad Y_{i0} = X_{i0}\beta_0 + \hat{\lambda}_{i0}\sigma_0 + \varepsilon_{i0} & \text{if } I_i = 0 \\ \text{Regime } j: \quad Y_{ij} = X_{ij}\beta_j + \hat{\lambda}_{ij}\sigma_{ij} + \varepsilon_{ij} & \text{if } I_i = j \text{ for } j = 1, 2, 3 \end{cases} \tag{4}$$

The symbol Y represents outcome variables of the ith mango grower for regime or category of jth IPM practice. $j = 0$ refers to the non-adoption of any IPM practice, while $j = 1, 2, 3$ represents the adoption of one, two or three or more IPM practices, respectively. The vector X represents a set of observable explanatory variables comprising household, plot and location characteristics. The variable $\hat{\lambda}$ denotes the inverse Mills ratio for the adoption of each j bundle of IPM practices obtained from the estimation of equation (3), and is included in second-stage equations to purge selection bias due to unobservable characteristics. β and σ are parameters to be estimated, while σ is the coefficient that represents the covariance between the error terms of equations (1) and (4).

Although the second-stage estimates are consistent, they have inefficient standard errors because of the two-stage nature of the estimation procedure. We use the bootstrap method to correct this problem. The other potential problem in the two-stage estimation is that the outcomes equations may not be identified if the same set of explanatory variables are used in both stages. The selection correction term ($\hat{\lambda}$) is nonlinear, but it may not be sufficient to identify outcome equations and may lead to multi-collinearity problems. We thus consider additional instrumental variables that influence adoption decisions but not outcome variables. These include number of adopters known by respondents, number of rural institutions to which a household belongs, training on pest management, and availability of IPM, training on IPM and labour for its application. We conduct a simple post-estimation test to check the validity of the instruments. The results confirm that these variables are jointly significant in

IPM adoption equation, but they are only weakly significant in 1 outcome equation of the 12 outcome equations (see Tables S2–S3 in the online Appendix).

2.2. Average adoption effect

The estimate of the average adoption effect requires deriving the expected actual and counterfactual outcomes using equation (4). The expected actual outcome that is observed from the data is computed for each bundle of IPM practices adopted, as follows:

$$E(Y_{ij}|I_j = j) = X_{ij}\beta_j + \sigma_j\hat{\lambda}_{ij}, \quad j = 1, 2, 3 \tag{5}$$

The expected value of the counterfactual outcome for each bundle of IPM practices adopted is given as follows:

$$E(Y_{i0}|I_j = j) = X_{ij}\beta_0 + \sigma_0\hat{\lambda}_{ij}, \quad j = 1, 2, 3 \tag{6}$$

In equation (6), β_0 and σ_0 are the regression coefficients obtained from the outcome equation for the regime $j = 0$ or non-adopters of IPM practices for mango farming (see equation (4)). The average adoption effect (ATT) for each bundle of IPM practices adopted is computed as:

$$\text{ATT}_j = E(Y_{ij}|I_j = j) - E(Y_{i0}|I_j = j) = X_{ij}(\beta_j - \beta_0) + \hat{\lambda}_{ij}(\sigma_j - \sigma_0), \quad j = 1, 2, 3 \tag{7}$$

In this equation, the terms $X_{ij}(\beta_j - \beta_0)$ and $\hat{\lambda}_{ij}(\sigma_j - \sigma_0)$ respectively denote the contribution of observed and unobserved heterogeneities to ATT.

2.3. Measuring the impacts of IPM adoption on the environment and human health

While the change in the volume of insecticide used due to the adoption of IPM is a useful indicator of environmental and human health impact, it is an imperfect measure because it does not capture the differences in specific insecticide products used by farmers in IPM and non-IPM farming systems (Table S4 in the online Appendix). Clearly, such products differ in terms of levels of toxicity, mobility and persistence. To capture this difference and approximately quantify the effects of IPM on human health and environmental risks caused by insecticides, we use the environmental impact quotient (EIQ) method developed by Kovach *et al.* (1992) (see also Eshenaur *et al.*, 2015). Although this measure uses arbitrary weights to combine the different effects on producers, consumers and the environment, and is therefore questionable, it has been used elsewhere (e.g. Fernandez-Cornejo, 1998; Schreinemachers *et al.*, 2011; Gerpacio and Aquino, 2014; Kniss and Coburn, 2015; Kouser and Qaim, 2015; Sharma and Peshin, 2016). In any event, it is important to consider the health and environmental effects, and there is no easily available alternative to the somewhat less satisfactory EIQ at present.

3. Data and Summary Statistics

Our data cover four of the major mango-growing counties in eastern Kenya, namely Embu, Machakos, Makueni and Meru (Figure S1 in the online Appendix). The data collection followed a multi-sampling framework. The four-major mango producing counties of the eastern region were purposively selected following *ICIPE's* previous dissemination and promotional activities of the mango fruit-fly IPM practices. Then, mango-growing wards and villages in each county were selected in collaboration with the local agricultural extension workers. Thereafter, we conducted a census of mango growers in the selected wards and villages who had 10 or more mango trees in each village. Then, well-trained enumerators – who understood the local language and were supervised by an *ICIPE* researcher – selected and interviewed a random sample of mango growers proportional to the listed number of such growers in each village. This led to a final sample of 660 mango-growing households being successfully interviewed. After data cleaning, we use a final sample of 633 mango growers for regression analysis. However, we use the 660 sample for computing the human health and environmental impacts of IPM as all the parameters to compute the EIQ are available. Data collection using a semi-structured questionnaire took place in November and December 2016 and referred to the preceding mango season (May 2015–April 2016).

Our control variables include household socio-economic characteristics, social capital and network, institutional capital, plot characteristics, investment and shocks, technology and location. Among the socio-economic indicators, livestock ownership, mango income and mango production loss were considered in addition to demographic characteristics such as the age, sex and education of the household head, and family size. The social capital and network variables included membership of rural institutions and associations, and the number of IPM adopters in the village known by respondents that could facilitate access to information and increase farmers' exposure to IPM practices. Institutional capital was captured using questions related to access to different development services (extension, training, credit and markets). Plot characteristics as well as investment and shock variables involved soil fertility indicators; insecticide, fungicide and fertiliser use; the incidence of insects and diseases; and the severity of insect infestations. The technology variables covered the number of IPM practices adopted, farmers' perception of the availability of IPM techniques, and whether labour and training were constraints on the use of IPM practices. Location dummies were included to capture unobserved agro-climatic and socio-economic heterogeneities among the sample counties.

Table 1 lists the definitions and summary statistics for all covariates used in the empirical analysis. The choice of these variables was based on existing agricultural technology adoption and impact studies (e.g. Isoto *et al.*, 2008; Kassie *et al.*, 2015, 2018; Korir *et al.*, 2015; Sanglestsawai *et al.*, 2015; Sharma *et al.*, 2015; Sharma and Peshin, 2016; Gautam *et al.*, 2017).

Mango growers reported using several IPM practices to suppress fruit-fly infestations and reduce the damage they caused (Table 2). The dominant practices included fruit-fly traps, food bait spray and burning or burying fallen fruit infested with fruit-fly larvae. About 29% of the sample plots received no IPM treatment, while 34%, 25% and 12% of plots were treated by either one, two, or three or more IPM interventions, respectively. Very few plots had more than three IPM interventions, and were merged with plots receiving three IPM interventions. The detailed descriptions and purpose of each IPM practice can be found in Ekesi and Billah (2007). Table 2 shows definitions of the adoption variables, together with their corresponding summary statistics.

Outcome indicators that represent the economic and environmental benefits and health of farmers include mango yield (pieces of fruit per tree), mango net income (Kenyan Shillings/KSh per tree), insecticide use (litres per tree) and EIQ (Table 3).

Table 3

Descriptive statistics: Outcome variables (mean)

Variables	Total sample	Non-adoption of integrated pest management (IPM) practices	Adoption of one IPM practice	Adoption of two IPM practices	Adoption of three or more IPM practices
Mango yield (pieces per tree)	148.92 (125.09)	133.11 (118.91)	145.72 (124.20)	157.26 (126.70)	179.51 (134.43)
Mango net income (KSh per tree)	1,126.09 (1,125.70)	1,009.07 (986.82)	1,105.08 (1,020.99)	1,148.51 (1,003.45)	1,428.235 (1,133.81)
Insecticide use (litres per tree)	0.033 (0.083)	0.040 (0.087)	0.023 (0.044)	0.045 (0.122)	0.024 (0.052)
Environmental Impact Quotient (EIQ)	14.32 (36.63)	22.65 (1.22)	14.74 (0.93)	15.77 (1.14)	13.53 (1.31)
Number of observations	633	182	219	158	74

Note: Standard deviation are given in parentheses.

Production costs deducted from gross mango revenue comprise fertiliser, pesticides and hired labour. Farmers count mango and make mango transactions in terms of pieces of fruit; thus, the unit for yield is pieces. Also, since farmers' chemical insecticide spray only targets trees, trees are used to measure insecticide use rather than mango production area. The survey data show that mango growers sprayed their mango trees four times during the 2016 season. These raw data suggest that IPM adoption generates higher yields and thus greater net revenues, but this suggestion needs testing.

4. Results and Discussion

4.1. Factors that influence the adoption of IPM

The results of the first stage ordered probit model are presented in Table 4. The findings suggest that the most crucial factors in determining the use of IPM practices are: (i) the number of adopters that respondents know in their vicinity, (ii) membership of rural institutions, and (iii) participation in insect pest management training. These factors point to the knowledge-intensive nature of IPM techniques. The major role of information in enhancing adoption of IPM practices has also been found in previous studies (Chaves and Riley, 2001; Timprasert *et al.*, 2014; Kabir and Rainis, 2015; Allahyari *et al.*, 2016).

Furthermore, as the explanatory variables in Table 4 show, the likelihood of adoption increases when farmers have a higher income share from mango production, and when the severity of fruit-fly infestation increases. We also find plot distance from the respondent's residence and a lack of training in IPM reduces the probability of using IPM practices, while there are also significant differences by district.

Table 4
Factors that influence the adoption of a bundle of IPM practices: Ordered probit results

Variable	Coefficient
Family size	−0.01
	(0.02)
Sex	−0.14
	(0.25)
Ln(Age)	0.13
	(0.23)
Education	0.01
	(0.01)
Livestock	−0.02
	(0.02)
Occupation	−0.04
	(0.11)
Extension visits	0.11
	(0.10)
Training on pest management	0.26**
	(0.11)
Ln(Membership)	0.06*
	(0.04)
Ln(Number of adopters)	0.21***
	(0.02)
Insecticide use	−0.04
	(0.12)
Unavailability of IPM	0.10
	(0.12)
Insufficient training a constraint	−0.32***
	(0.10)
Insufficient labour a constraint	0.16
	(0.13)
Intercropping	0.22*
	(0.12)
Plot distance	−0.01***
	(0.00)
Ln(Mango income)	0.10**
	(0.04)
Ln(Mango loss)	-0.10
	(0.09)
Medium fruit-fly infestation	−0.40***
	(0.14)
Low fruit-fly infestation	-0.05
	(0.14)
Embu	0.84***
	(0.14)
Meru	0.47***
	(0.13)
Makueni	−0.27*
	(0.15)
Joint significance of instruments, χ^2	128.30 (p = 000)***

Table 4
(*Continued*)

Variable	Coefficient
Wald $\chi^2(23)$	259.70***
Pseudo R^2	0.20
Observations	633

Note: Robust standard errors given in parentheses; *$P < 0.1$, **$P < 0.05$, ***$P < 0.01$.

Table 5
Mango yield and income effect of integrated pest management (IPM) adoption: Endogenous switching regression results

Adoption status	Outcome	Mango yield (pieces/tree)	Net mango income (KSh/tree)	Insecticides use (litre/tree)
One IPM practice	$E(Y_{i1} \mid j = 1)$	102.82	1,105.08	0.023
	$E(Y_{i0} \mid j = 1)$	97.03	1,015.01	0.072
	$\text{ATT}_j = E(Y_{i1} \mid j = 1)$	5.79	90.07**	0.049***
	$- E(Y_{i0} \mid j = 1)$	(5.10)	(42.55*	(0.005)
Two IPM practices	$E(Y_{i2} \mid j = 2)$	115.16	1,148.51	0.045
	$E(Y_{i0} \mid j = 2)$	90.89	865.88	0.127
	$\text{ATT}_j = E(Y_{i2} \mid j = 2)$	24.27***	282.63***	0.081***
	$- E(Y_{i0} \mid j = 2)$	(7.48)	(75.25)	(0.013)
Three or more IPM practices	$E(Y_{i3} \mid j = 3)$	143.797	1,428.24	0.024
	$E(Y_{i0} \mid j = 3)$	73.61	602.81	0.215
	$\text{ATT}_j = E(Y_{i3} \mid j = 3)$	70.18***	825.43***	0.191***
	$- E(Y_{i0} \mid j = 3)$	(13,37)	(141.18)	(0.022)

Notes: Standard errors in parentheses; *$P < 0.1$,**$P < 0.05$, ***$P < 0.01$; Y denotes mango yield, income and insecticide use; KSh = Kenyan Shilling.

4.2. Impacts of IPM technologies

4.2.1. Impacts on mango yield and mango net income

For brevity's sake, the second stage regressions results are not reported or discussed in detail here, but are provided in the online Appendix (Tables S1–S2). Table 5 summarises the estimated impacts of each bundle of IPM practices on mango yield and mango net income. IPM-adopting farms have significantly higher mango yields and incomes, which both increase with the intensity of adoption. Thus, the adoption of one, two, or three or more IPM practices provides yield gains of 6%, 27% and 95%, respectively, relative to the average counterfactual yield. Income impacts, correspondingly, show income increases of 9%, 33% and 137% using one, two and three or more IPM practices, respectively. These findings confirm the implications of the raw data (Table 3) as well as those of previous studies of the impacts of IPM adoption (Fernandez-Cornejo, 1998; Owusu and Kakraba, 2015; Muriithi *et al.*, 2016).

Table 6

Distribution of mango plots by level of adoption and class of insecticide toxicity

World Health Organization (WHO) class of insecticide toxicity	Non-adoption of integrated pest management (IPM)	Adoption of one IPM practice	Adoption of two IPM practices	Adoption of three or more IPM practices	Total
Extremely hazardous (Ia)	–	–	–	–	–
Highly hazardous (Ib)	1.31	4.48	1.87	0.56	8.21
Moderately hazardous (II)	25.93	26.68	19.59	8.96	81.16
Slightly hazardous (III)	–	0.37	0.19	0.19	0.75
Unlikely to present acute hazard in normal use (U)	0.93	0.37	0.19	0.56	2.05

Note: WHO (2010) classification adopted.

Table 7

Estimates of the impact of integrated pest management (IPM) adoption on human health and the environment using the environmental impact quotient (EIQ) method

Number of IPM practices adopted	Total FEIQ	Risk effect (%)	FEIQ value for EIQ components: Consumers	Risk effect (%)	Farm workers	Risk effect (%)	Environment	Risk effect (%)
0	22.65	–	4.53	–	7.31	–	56.09	–
1	14.73	−34.96	4.50	−0.66	4.78	−34.61	34.90	−37.78
2	15.77	−30.38	4.19	−7.51	4.95	−32.28	38.16	−31.97
3+	13.53	−40.26	3.57	−21.19	4.25	−41.86	32.76	−41.59

Notes: The EIQ values are computed by adding the EIQ value of each active ingredient multiplied by the proportion of mango area under the active ingredient (see online Table S5). The risk effect is calculated by dividing the difference between the EIQ values for adopters and non-adopters by the non-adopters EIQ value.

4.2.2. Impacts on insecticide use, human health and the environment

The results show that insecticide use is significantly reduced by 0.05 litre per tree for the adoption of one IPM practice, 0.08 litre per tree for the adoption of two and 0.19 litre per tree for the adoption of three or more IPM practices (Table 5), relative to the counterfactual. Owing to pesticide toxicity, fewer insecticide applications per tree are assumed to result in concomitantly lower negative impacts on human health, the environment and food safety. These results are consistent with those of Fernandez-Cornejo (1998), Rejesus *et al.* (2009) and Sanglestsawai *et al.* (2015), where IPM adoption was also shown to reduce pesticide use. The insecticide use regression results are reported in the online Appendix Table S3.

In terms of insecticide toxicity levels, the analysis reveals that about 8% of mango plots were treated with insecticides that were highly hazardous, while 81% received treatment with moderately hazardous ones (Table 6). Insecticides in these two categories pose greater human health and environmental problems than any of the other categories listed (Jeyaratnam, 1990; Krishna and Qaim, 2008). Of all the mango plots treated with insecticide from the two most hazardous categories, fewer occurred among those where IPM was adopted – except in the case of plots adopting only one IPM practice.

Lower insecticide quantities and lower levels of insecticide toxicity due to the adoption of IPM are reflected in a significantly lower EIQ value on IPM plots.[2] The EIQ value decreases by 35%, 30% and 40% for the respective adoption of one, two, or three or more IPM practices, respectively (Table 7). According to the EIQ values, the impact of insecticide use, notably associated with no IPM techniques being employed, is greatest for the environment, then for farm workers' health and lastly, consumers' health (Table 7), corroborating the findings of Fernandez-Cornejo (1998).

5. Conclusion and Policy Implications

Mango fruit-fly infestation is a major threat to the fruit production farming system in sub-Saharan Africa because it undermines food security and poverty reduction efforts. However, the synthetic insecticides being used by farmers to reduce such infestations are causing environmental and human health problems, and pests are developing resistance to these toxins. An alternative infestation control strategy being employed is the integrated pest management (IPM) approach, which reduces the use of synthetic pesticides. The IPM approach offers economic benefits to farmers, while improving food safety and minimising risks to human health and the environment. However, there is limited rigorous study on the economic impacts of IPM in Africa, and to our knowledge no study to date has analysed the environmental and human health impacts of IPM adoption targeting the mango fruit fly.

We examine the impacts of different combinations of IPM practices on mango yield, insecticide use, mango net income from mango farming, human health and the environment, using a sample of mango producers in four districts of Kenya. We use a multinomial treatment switching regression model to address selection bias arising from both observed and unobserved heterogeneities and use an environmental impact quotient to assess the impacts of IPM on human health and the environment.

Our findings confirm that IPM adoption significantly improves mango yields and incomes and reduces insecticide use. According to the (somewhat crude) environmental impact quotient, human health and environmental risks effect of insecticide use are also ameliorated. These positive outcomes increase substantially as farmers progress from using one to multiple IPM practices. Our findings reinforce the need for governments and their development partners to encourage and support smallholder farmers to adopt a bundle of IPM practices that not only enhance mango production but do so at less cost to the environment and human health.

Moreover, exposure to IPM practices – as measured by the number of IPM adopters that farmers know in their vicinity, membership of rural institutions, and training in pest management as well on IPM – has positive and significant effects on adoption. The clear implication is that strengthening existing and establishing further information delivery mechanisms are essential for facilitating and scaling up IPM adoption.

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[2]Tables S4 and S5 in the online Appendix show the different insecticide active ingredients along with their trade names and the EIQ values of the active insecticide ingredients by adoption status, respectively.

Nonetheless, despite the interesting positive impact stories of IPM adoption, the current study has some limitations that could be tackled in future research. Firstly, the study is based on cross-sectional data which do not capture the cyclical nature of pest invasion and the dynamics of IPM adoption and outcomes. Secondly, a tree's mango yield depends on its age; in our case, however, we used only two age categories: young trees that had not yet begun producing, and mature trees that had already begun. However, it is important to further disaggregate mature trees by age interval to capture mango yields more accurately.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1. Study areas and sample households' distribution.

Table S1. Estimates of determinants of mango yield, dependent variable – *ln(pieces per tree)*.

Table S2. Estimates of determinants of mango net income, dependent variable – *KSh per tree*

Table S3. Estimates of determinants of insecticide use, dependent variable – *litre/tree*.

Table S4. Active ingredient and trade names of the insecticide used by mango growers.

Table S5. Insecticide used and Environmental impact quotient results by adoption status.

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