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Estimating the impact of biological control of maize stemborers on productivity and poverty in Kenya: a continuous treatment approach

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Abstract

This study examines the farm-level effects of stemborers' biological control (BC) using biological and household survey data collected in rural Kenya. The authors use a continuous treatment impact-evaluation method to estimate BC's average and marginal treatment effects. Findings indicate that, on average, a one percent increase in the intensity of BC increases maize yield by 9.3 kg per hectare and reduces the poverty level of maize-growing farm households by 0.5%. Developing and promoting biological control can be seen as an additional tool in the fight against food insecurity and poverty in Africa through controlling important pests.

Keywords Impact assessment · Biological control · Productivity · Poverty · Continuous treatment

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1 Introduction

Sustainably increasing food production to meet the rising demands for food is a crucial research and development agenda in the developing world. One of the critical strategies for ensuring a sustainable food supply is to reduce production losses due to insect pests while improving and/ or maintaining natural resources and environmental quality through ecologically- and economically-sound integrated pest management (IPM) practices (Naranjo et al., 2015). In this respect, when successfully implemented, biological control (BC) of pests is a central strategy for plant protection. In addition to improving food security by reducing production losses due to pests, this strategy can reduce production costs and the threats to health and the environment associated with applying chemicals (Varela et al., 2003; Asfaw et al., 2011; Naranjo et al., 2015; Midingoyi et al., 2019). Since 1993, the International Centre of Insect Physiology and Ecology (icipe), in cooperation with national and international research organizations, has been conducting a biological control program in East and Southern Africa (ESA) to help tackle production losses due to stemborers. Biological control in crop protection is the use of natural enemies of pests (e.g., parasitoids or bio-agents) to reduce the level of pest populations to a desirable level to prevent damage to crops.

The cereal production environment in ESA is constrained by the persistent challenge of the stemborer pest (Songa et al., 2001; Kfir et al., 2002). Stemborers are recognized as a group of moths whose larvae cause essential economic damage to cereal plants, especially to maize and sorghum, the leading staple food and income-generating crops in the region (Kirimi et al., 2011). Many stemborer species are present in the region. The highest economic importance includes *Chilo partellus* Swinhoe, the most devastating pest in low-altitude areas, accidentally introduced into Africa from Asia (Tams, 1932); *Busseola fusca* Fuller, a significant pest in mid- and high-altitude areas, and *Sesamia calamistis* Hampson, the pink borer found in diverse altitudes (Ong'amo et al., 2006). During their life cycle, the larval stage appears to be the most damaging phase for plants, as the larvae feed on leaves and stems, thereby seriously hindering the normal growth of the plant and leading to a severe reduction in yield (Overholt et al., 2001). The reported yield loss due to stemborers varies in the literature and is estimated at 11 to 88% in Kenya (Overholt et al., 2001; Odendo et al., 2003; De Groote et al., 2011).

Pest control strategies available to farmers include physical pest control measures (such as the physical removal of infested plants, crop rotation, burning of crop residues, trap crops, planting density, etc.) and chemical pesticides (van den Berg et al., 1998). Physical pest control strategies are labor-intensive, while several factors, including the low purchasing power of farmers and negative impacts on the environment and human health, challenge the use of chemical pesticides. Additionally, chemical pesticides can negatively affect beneficial pests or pest natural predators. Furthermore, pests also develop resistance to chemicals, making their control difficult using conventional approaches. Biological control, or the use of the natural enemies of pests, which is disseminated naturally, is an alternative economically-, socially-, and eco-friendly strategy to the control of pests by pesticides (Varela et al., 2003; Kairo, 2005; Asfaw et al., 2011).

The icipe BC program has involved the mass rearing and releasing BC agents (or natural enemies) to regulate stemborer pest populations since 1993. These natural enemies include the following: the larval parasitoid *Cotesia flavipes* (Cameron), imported from Asia, the original home of the pest *C. partellus*; the egg parasitoid *Telenomus isis* (Polaszek), imported from West Africa; the pupal parasitoid *Xanthopimpla stemmator*

(Thunberg), imported from Asia to complement *C.flavipes;* and the larval *Cotesia sesamia* (Cameron), found in the western part of Kenya but redistributed in the region of Taita-Taveta, Kenya. Evidence on the effectiveness of these released natural enemies in the establishment and spread from release sites, as well as in reducing pest density, has been reported in various entomology studies (Zhou et al., 2001; Jiang et al., 2006; Omwega et al., 2006; Gitau et al., 2007).

More than two decades after the first set of BC releases, it is legitimate to ask whether biological control intervention contributes to the livelihood of maize-growing farm households in East and Southern Africa (ESA). The effectiveness of BC in controlling stemborers has mainly been demonstrated in terms of the reduction in pest density (Zhou et al., 2001; Jiang et al., 2006; Omwega et al., 2006), but the most crucial question is whether this can be translated into positive economic outcomes at the farm and household levels. Although there are previous biological control impact studies on different crops (rice, cabbage, cassava, banana, cowpea, barley) in other countries (Neuenschwander et al., 1989; Yaninek et al., 1992; IFAD, 1998; Bauer et al., 2003; Cardinale et al., 2003; Östman et al., 2003; Lv et al., 2010), there is limited empirical evidence on the link between BC and productivity and wellbeing at household level in Kenya and elsewhere (Asfaw et al., 2011; Muriithi et al., 2016). Muriithi et al., (2016) assessed the farm-level impacts of IPM of mango fruit fly (comprising BC) on pesticide expenditure, fruit losses, and farmer profits through a multi-valued treatments analysis and found positive impacts of IPM. Asfaw et al., (2011) studied the impact of BC on the diamondback moth (a cabbage pest) in Kenya and Tanzania. They found that BC farmers experienced higher cabbage yields compared to non-BC farmers. Both studies adopted a binary impact-evaluation treatment framework (= 1 if BC presents in the village and zero otherwise) without considering the level/distribution of BC, which might have provided more detailed results. That is, they assumed that different levels of BC have the same impact on outcome variables. The spread of natural enemies may vary from area to area due to environmental factors (e.g., wind, temperature, rainfall), which will likely lead to heterogeneous impacts. Studying the impact of diverse interventions allows us to go beyond the simple mean impact assessment that dominates the literature. Looking at features of the distribution of impacts other than the mean provides a more accurate picture of how interventions impact outcomes and provide evidence for or against economic models that imply heterogeneous responses (Djebbari & Smith, 2008).

This paper aims to evaluate the heterogeneous impacts of the biological control of stemborers on maize productivity and poverty in rural Kenya using a continuous treatment method framework. The BC agents considered in this study include *C. flavipes* and *T. isis*, released in 1993 in the lowland tropics and in 2005 in the highland tropics, respectively. This paper contributes to the existing stock of impact studies as follows: To begin with, to the authors' knowledge, this is the first paper to assess the impacts of BC on maize productivity and poverty at the household level. In addition, the authors employ a continuous treatment methodology (Cerulli, 2015) to investigate the impact heterogeneity of BC, unlike most previous similar studies that considered binary treatment and homogenous impact. This method allows the authors to assess the dose–response function and marginal treatment functions across the different levels of BC. In this study, the dose and response refer to the intensity of BC, and productivity and poverty indictors, respectively. In the impact literature, the dose–response function is synonymous with the average treatment effect (ATE). The rest of the paper is organized as follows: Sect. 2 develops the empirical approach and estimation procedure;

Sect. 3 describes the study area and data collection method; Sect. 4 presents the results and discussion; and the final section presents the conclusion.

2 Materials and methods

2.1 Empirical approach and estimation procedure

Most previous impact studies, including those on BC, have focused on the causal effect of a binary treatment on an outcome of interest. In certain contexts, what is relevant is not only the binary treatment status but also the level of exposure (or dose) to achieve the intended outcome. In this study, the BC level varies spatially from site to site (Le Corff et al., 2000; Frank, 2007). This has led the authors to go beyond binary treatment and extend this analysis to an impact evaluation based on continuous treatment. The authors adopt Cerulli's 2015 approach to examine the level (or dose) of BC agents on response function (dose in this study is the intensity of BC and response refers to outcome variables) and the derivative of the dose–response function (DRF). In the impact evaluation literature, the DRF and derivative of DRF are synonymous with ATE and marginal treatment effect (MTE), respectively. Hirano & Imbens (2004) introduced the generalized propensity score (GPS) estimator for continuous treatment impact assessment, which was applied by Bia & Mattei (2012). This method was the most commonly used in empirical studies (Kluve et al., 2012; Kassie et al., 2014; Magrini et al., 2014). The approach relies on normality distributional assumption and excludes zero-treated units in practice. Bia et al., (2014) proposed a semiparametric estimation of the dose–response function with various assumptions of distribution that accommodated zero-treated units, but it did not account for treatment endogeneity. Cerulli (2015) introduced a new approach that overcomes these limitations.

Let us consider $i (\text{where} i = 1, \dots, N)$ as the index of the randomly-sampled maize-farming households in the study area. For each household i, let's consider its potential outcomes (productivity, poverty status) as y_1 under biological control $(w = 1)$and y_0 in the absence of biological control $(w = 0)$. Let $x = (\mathrm{x}_1, \mathrm{x}_2, \mathrm{x}_3, \dots .\mathrm{x}_\mathrm{M})$ represent a vector of M exogenous observable characteristics (households, plots, environment); $\mathrm{g}_1(\mathrm{x})$ and $\mathrm{g}_0(\mathrm{x})$, the outcomes response associated with and without BC, respectively; b the biological control level indicator ($\mathrm{b} \epsilon [0, 100]$), and h(b) the intrinsic response of a given level of b. The possible outcomes for a given population can then be expressed as:

$$\begin{cases} w = 1 : y_1 = \mu_1 + \mathrm{g}_1(\mathrm{x}) + h(\mathrm{b}) + \mathrm{e}_1 \\ w = 0 : y_0 = \mu_0 + \mathrm{g}_0(\mathrm{x}) + \mathrm{e}_0 \end{cases} \tag{1}$$

At the individual level, the impact of biological control is measured by the treatment effect $(TE = y_1 - \mathrm{y}_0)$. Assuming a line-in-parameters form for $\mathrm{g}_0(\mathrm{x}) = \mathrm{x}\delta_0$ and for $\mathrm{g}_1(\mathrm{x}) = \mathrm{x}\delta_1$, ATE for the population conditional on x and b becomes:

$$ATE(x, b, w) = w * \left[\mu + x\delta_1 + h(b)\right] + (1 - w) * \left[\mu + x\delta_0\right] \tag{2}$$

Where $\mu = \mu_1 - \mu_0$ and $\delta = \delta_1 - \delta_0$.

The regression approach of estimating ATE is given as:

$$y_i = \mu_0 + w_i * \text{ATE} + x_i\delta_0 + w_i * \left(x_i - \bar{x}\right)\delta_1 + w_i\left[h\left(b_i\right) - \bar{h}\right] + \in_i \tag{3}$$

Where y_i denotes a vector of outcome variables (maize yield, poverty indicators) $\mu_0, \delta_0, \delta_1, ATE$ are parameters to be determined. Equation 3 will serve as an input to compute the dose–response and marginal treatment (derivative of DRF) functions at each level of the treatment. The dose–response function (DRF) curve is obtained as:

$$\begin{aligned}\widehat{\text{ATE}}\left(b_i\right) =& w\left(\widehat{\text{ATET}} + \lambda_1\left(b_i - \frac{1}{N}\sum_{i=1}^{n} b_i\right) + \lambda_2\left(b_i^2 - \frac{1}{N}\sum_{i=1}^{n} b_i^2\right) + \lambda_3\left(b_i^3 - \frac{1}{N}\sum_{i=1}^{n} b_i^3\right)\right)\\ &+ (1 - w)\widehat{\text{ATENT}}\end{aligned} \tag{4}$$

Where λ_1, $\lambda_2$and λ_3 are parameters obtained from the regression (3) assuming a polynomial parametric form of degree 3 for the h (b) function: ($h\left(b_i\right) = \lambda_1 b_i + \lambda_2 b_i^{\,2} + \lambda_3 b_i^{\,3}$). ATET indicates the average treatment effect on treated ($\text{ATET} = \mu + x_{b>0}\delta + h_{b>0}$) and ATENT indicates the average treatment effect on untreated units ($\text{ATET} = \mu + \bar{x}_{b=0}\delta$).

The DRF represents the conditional expectation of maize yield variations given confounding variables. The derivative of the DRF stands for the Marginal Treatment Effect (MTE), which illustrates how the effects of BC on the outcome of interest change as the intensity of BC increases.

The decision to use biological control is exogenous to farmer action since BC, once released, spreads naturally. The authors have also empirically tested the endogeneity of BC using the control function approach. Results confirmed the exogeneity of BC as the residuals from the first stage were not significant in the second stage regression. The authors thus assume that the treatment is not influenced by farmer behavior or socio-economic characteristics but by village-level variables such as climatic factors. In the regression models, agroecology indicator variables are included to capture some of the climatic factors that could influence the level of biological control in the study area.

2.2 Study area, data, and descriptive statistics

The study area was selected based on the preliminary results of the extensive survey conducted by the entomology team involved in the impact assessment program. The survey was carried out in five maize-producing regions of Kenya to assess the presence and extent (parasitism rate) of biological control agents, stemborers, and the degree of plant infestation. It was conducted along transects in the four compass directions away from the initial release locations of the natural enemies, extending up to 45 km. Villages located at distances of 15, 30, and 45 km from the release points were purposely chosen to represent agroecological diversity. In this study, a total of 10 transects made up of 40 villages were selected and distributed among five regions of Kenya: Coast (14), Eastern (12), Rift Valley (6), Nyanza (6), and Western (2) (Fig. 1). The authors randomly select 600 sample households from these villages (15 households per village) to collect household, plot, and village-level variables.

The household-level data used in this study were collected using a structured questionnaire, and trained enumerators who understood the local language administered the questionnaires under the supervision of the first author of this paper. The survey covered comprehensive household, plot, and village-level data (Table 1). These included 12 months recall household expenditure, total income, maize-farming systems, plot characteristics and investment, crop production including maize yield (kg/acre), prices, production costs,

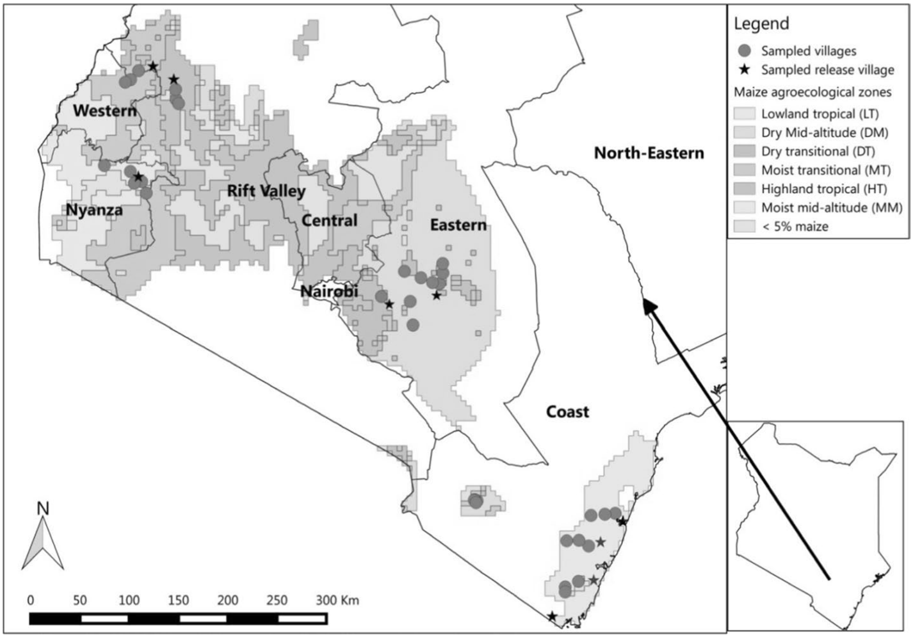

Fig. 1 Distribution of sampled villages in the maize agroecological zones

households' demographic composition, and socio-economic characteristics, access to infrastructure and services, households' assets, and agroecological variables. The variables included in the regression models were determined following economic theory and previous empirical literature (Alene et al., 2000; Geda et al., 2005; Kassie et al., 2009; Chianu et al., 2012; Yengoh, 2012; Awotide et al., 2013, 2016; Diagne et al., 2013; Mberu et al., 2014).

The treatment variable (the biological control level) was expressed by the parasitism rate or the proportion of parasitized pests of the total recorded pests at the field level. It expressed the ability or the susceptibility of the released natural enemies to control undesirable pests.

The dose–response and marginal treatment effects were estimated for maize productivity (kg per acre), per capita expenditure, and poverty indicators (headcount and poverty gap). The average maize yield in the sample was 1.5 tons per ha. Table 2 presents the average yield based on BC level by quartile. The unconditional means did not show a clear pattern between the BC level and outcome variables except for the fourth class, which showed a significant effect compared to the other three classes. However, maize yield depends on the level of BC and is influenced by a host of household, plot, and village variables. This calls for a conditional mean test using rigorous empirical methods. The average per capita expenditure for the sample households was about Kenya shilling (Ksh) 39 000 per annum (The exchange rate was that 1Ksh is worth USD 0.009). The Foster–Greer–Thorbecke (FGT) class of poverty measures (Foster et al., 1984) was used to compute poverty indices, which are defined below:

Table 1 Descriptive statistics of selected variables used in the analysis Source: Authors' household survey.

Variable	Variable description	Mean	Std. dev
Treatment variable			
Biological control level	Rate of parasitism (percent)	23.49	18.35
Outcome variables			
Maize productivity	Maize yield in kg/ha	1.482	1.607
Per capita expenditure	Per capita expenditure in thousands in Ksh	39.026	46.776
Head count	Household (Hhld) poverty status (1=poor, 0=non-poor)	0.274	
Poverty gap	Intensity of poverty	0.090	0.182
Household characteristics			
Age	Age of the Hhld head age (years)	48.40	14.11
Gender	Gender of the Hhld head (1=male; 0=female)	0.72	
Residence	Number of years of residence in the village	33.86	18.99
Education	Number of years of schooling	7.73	4.36
Experience in agriculture	Experience in agriculture (years)	21.54	13.36
Can read and write	Household can read and write (1=yes, 0=no)	0.82	0.38
Experience in maize	Experience in maize production (years)	20.79	13.30
Household size	Total Hhld size (number)	6.05	2.55
Livestock	Number of livestock (tropical livestock unit)	2.04	3.23
Salaried employment	Hhld member has salaried employment (1=yes, 0=no)	0.33	
Business	Hhld member has business (1=yes, 0=no)	0.39	
Handicraft	Hhld member has handicraft activity (1=yes, 0=no)	0.12	
Main activity crop	Crop production as main activity (1=yes, 0=no)	0.61	
Cropped area	Total crop area (acre)	3.53	3.83
Available land	Total available land (acre)	4.81	6.20
Input use and plot characteristics			
Fertilizer use	Hhld uses mineral fertilizers (1=yes, 0=no)	0.33	
Organic fertilizer use	Hhld uses manure (1=yes, 0=no)	0.15	
Low fertility	Low soil fertility level	0.18	

Table 1 (continued)

Variable	Variable description	Mean	Std. dev
Medium fertility	Medium soil fertility level (1=yes, 0=no)	0.71	
High fertility	High soil fertility level (1=yes, 0=no)	0.10	
Improved variety	Household uses improved maize varieties (1=yes, 0=no)	0.64	
Traditional variety	Household uses traditional maize varieties (1=yes, 0=no)	0.29	
Both varieties	Household uses mixed improved and traditional varieties (1=yes, 0=no)	0.06	
Access to development services			
Extension	Distance to the extension office (km)	5.62	4.68
Distance to the market	Distance to the nearest market (km)	3.44	3.37
Distance to the road	Distance to the nearest main road (km)	8.66	12.47
Training	Hhld participated in training on maize farming (1=yes, 0=no)	0.38	0.49
Research	Hhld had contact with research (1=yes, 0=no)	0.15	0.36
Location characteristics			
Agroecology1	Lowland Tropical (LT) agroecology (1=yes, 0=no)	0.30	
Agroecology2	Dry Midaltitude (DM) agroecology (1=yes, 0=no)	0.27	
Agroecology3	Moist Midaltitude (MM) agroecology (1=yes, 0=no)	0.13	
Agroecology4	Dry Transitional (DT) agroecology (1=yes, 0=no)	0.06	
Agroecology5	Moist Transitional (MT) agroecology (1=yes, 0=no)	0.15	
Agroecology6	Highland Tropical (HT) agroecology (1=yes, 0=no)	0.10	
Release point (RP)	Village where bio-agents were released (1=yes, 0=no)	0.25	
15 km from the RP	Village at 15 km from the release point (1=yes, 0=no)	0.25	
30 km from the RP	Village at 30km from the release point (1=yes, 0=no)	0.27	
45 km from the RP	Village at 45 km from the release point (1=yes, 0=no)	0.23	
Coast region	Coast region (1=yes, 0=no)	0.35	
Eastern region	Eastern region (1=yes, 0=no)	0.30	
Rift-valley region	Rift Valley region (1=yes, 0=no)	0.15	

Table 1 (continued)

Variable	Variable description	Mean	Std. dev
Western region	Western region (1=yes, 0=no)	0.05	
Nyanza region	Nyanza region (1=yes, 0=no)	0.15	

Table 2 Average productivity, expenditure, and poverty profile of households per BC class. Source: Authors' household survey.

Class of BC level	BC level interval (%)	Number of house-holds	Yield (ton/ha)	Per capita expenditure per year (000 Ksh)	Poverty (expenditure-base)	
					Headcount index (%)	Poverty gap index (%)
C1	[0 – 12]	188	1.55 a	41.88	0.38a	0.12ac
			(1.61)	(69.98)	(0.49)	(0.19)
C2	[12 – 21]	142	1.30 a	38.10	0.20a	0.05b
			(1.54)	(26.12)	(0.40)	(0.13)
C3	[21 – 36]	126	0.82 b	38.32	0.21a	0.07c
			(0.73)	(30.59)	(0.41)	(0.18)
C4	> 36	144	2.16 c	36.84	0.28b	0.10c
			(1.94)	(35.42)	(0.45)	(0.21)
Total		600	1.48	39.03	0.28	0.09
			(1.61)	(46.78)	(0.45)	(0.18)

Note: Standard deviation in parenthesis. Figures with different letters are statistically significantly different at 5% level.

$$P_\alpha(w,z) = \frac{1}{n}\sum\nolimits_{i=1}^{m}\left[max\left(\frac{z-w_i}{z},0\right)\right]^\alpha \tag{5}$$

Where w is the vector of per capita expenditure, z is the poverty line, $z - w_i$ is the expenditure shortfall for the ith household, m is the number of poor households, n is the total number of households, α is the poverty aversion parameter.

The two key parameters in this formula are the poverty line (z) and poverty aversion (α). The poverty line stands for a threshold that separates poor from non-poor households. The poverty line of Ksh1,562 per month was used in this study (Kenya National Bureau of Statistics, 2007). The value of α determines the poverty index type, and higher values express greater sensitivity to the poverty measures. When $\alpha = 0$, the index yields the poverty headcount, which in this case is equal to 1 if the household expenditure is less than the poverty line and 0 otherwise. When $\alpha = 1$, the index is the poverty gap index, a measure of the depth of poverty or the distance separating the poor from the poverty line. When $\alpha = 2$, the authors obtain the squared poverty gap, a measure of the poverty severity that considers the inequality among the poor.

The per capita expenditure and the poverty indices distributed by classes of biological control are presented in Table 2. About 27.5% of sampled households live below the poverty line, and the average poverty gap is 9%. Without any causal interpretation, the lower BC classes show the highest expenditure distribution (Ksh 42,000). However, there is no statistically significant difference between the four classes. These results may mean no relationship between BC level and household wellbeing, but this simple mean comparison has no causal effect interpretation. Indeed, many other factors or confounders may influence the association between BC and outcome variables. This calls for a conditional means test using a rigorous empirical method.

3 Results

In this section, the authors present estimation results based on two scenarios. In the first scenario, the authors estimate the pooled impacts of the two BC agents (*C.flavipes* and *T.isis).* Results for this scenario are presented and discussed in Sect. 3.1. In the second scenario, a separate impact assessment is carried out for each BC agent, and results are presented in Sect. 3.2. An understanding of the impact contribution of each agent can provide important information to those involved in the development and release of the agents.

3.1 Biological control impacts on maize productivity and poverty

The regression results from which the DRF and MTE were derived are presented in Tables 3 and 4. As the paper focuses on BC's average and marginal treatment effects, regression estimates are not discussed.

Figure 2 shows each outcome variable's DRF (average treatment effect). The results demonstrate that maize yields and per capita expenditure increased while poverty reduced with the level of BC. Maize yields increased from 390 kg/ha at a 0.5% level of BC to 1,415 kg/ha at a 73.32% level of BC, though the impact was constant at a lower level. On average, maize productivity increased by 453 kg/ha due to the release of BC agents. This is a 30.57% increment compared to the average sample yield: 1,482 kg/ha. Results for some specific levels of BC are presented in Table 5. In Chokwe and

Table 3 ATE-regression for assessing the impact of biological control: Dependent variable: maize yield (ton/ha)

	All		*C. flavipes*		*T.Isis*	
Biological Control	0.45	**	0.50	***	0.69	
	(0.22)		(0.18)		(0.70)	
Age	– 0.01		– 0.01		– 0.06	
	(0.01)		(0.01)		(0.06)	
Residence	0.01		0.01			
	(0.01)		(0.01)			
Experience in agriculture	– 0.01		0.01		0.23	
	(0.01)		(0.01)		(0.19)	
Experience in maize production	0.02		0.00		– 0.16	
	(0.01)		(0.01)		(0.17)	
Household size	– 0.05	**	– 0.02		– 0.27	**
	(0.02)		(0.02)		(0.31)	
Cropped Area	– 0.00		– 0.01		0.03	
	(0.01)		(0.02)		(0.06)	
Crop production as main activity	– 0.16		– 0.08		– 0.28	
	(0.11)		(0.10)		(0.34)	
Extension	– 0.02	*	– 0.03	**	– 0.02	
	(0.01)		(0.01)		(0.03)	
Use of organic fertilizer	0.70	***	0.39	***		
	(0.15		(0.14)			
Higher presence of pest	– 0.28		– 0.26	*	– 0.43	
	(0.16)		(0.15)		(0.64)	
Agroecology2	– 0.20		– 0.15		– 0.46	
	(0.13)		(0.11)		(0.40)	
Agroecology4	– 0.31	*	– 0.27	**	– 2.04	**
	(0.16)		(0.14)		(0.96)	
Agroecology5	0.28		0.36			
	(0.28)		(0.23)			
Agroecology6	0.96	***				
	(0.22)					
Higher slope	1.41	***			0.08	
	(0.28)				(0.66)	
15 km from the RP	– 0.15		– 0.10			
	(0.16)		(0.14)			
30 km from the RP	0.11		– 0.07		– 0.53	
	(0.12)		(0.11)		(0.91)	
45 km from the RP	0.52	***	0.56	***	– 1.08	
	(0.18)		(0.17)		(0.90)	
Maize as previous crop	0.04		0.21			
	(0.16)		(0.16)			
Lower soil fertility	– 0.17		0.19		– 0.22	
	(0.16)		(0.17)		(0.39)	
Parameter lambda1	– 0.04		– 0.45	***	0.67	
	(0.04)		(0.15)		(0.39)	

Table 3 (continued)

	All		*C. flavipes*		*T.Isis*	
Parameter lambda2	0.00		0.40	***	0.24	
	(0.00)		(0.13)		(0.18)	
Parameter lambda3	0.00		– 0.15	***	– 0.01	
	(0.00)		(0.04)		(0.01)	
Intercept	1.58	**	1.35	**	5.69	***
	(0.62)		(0.52)		(2.15)	
N	600		450		147	
F	13.86	***	11.06	***	1.84	***
Adjusted R2	0.40		0.407		0.27	
R2	0.36		0.37		0.12	

Standard errors in parentheses. * $p<0.1$, ** $p<0.05$, *** $p<0.01$. Interaction of treatment with variables terms not included in the table.

Machipanda districts of Mozambique, Cugala (2007) found that maize yields improved by 26.1% and 11.2% through exclusion experiment at field level, respectively. These results also corroborate findings from other BC impact assessment studies on the productivity of other crops in other countries. Among others, Lv et al., (2010) in Texas reported a 59% loss reduction in rice yields using *C.flavipes* to control *Diatraea saccharalis*. In Zambia, Neuenschwander et al. (2003) reported an increase in potato yields by 22% with the release of the natural enemies *Apanteles subandinus* and *Copidosoma koehleri* to control the potato tuber pest, *Phthorimaea operculella*. Similarly, in Savannah regions, the biological agent *Typhlodromalus aripo* for controlling cassava green mite (*Mononychellus tanajoa*) increased cassava yields by 30% (Yaninek et al., 1992; IFAD, 1998).

The DRF also showed that per capita expenditure increased from 2,165 Ksh at 0.5% of BC intensity to 23,573 Ksh at 73.32% BC level. The number of poor households (poverty gap) reduced by 2.3 (0.8) and 46 (16.3) percentage points at the 0.5% and 73.32% BC levels. On average, the release of BC agents increased per capita expenditure by 14,451 Ksh and reduced the poverty headcount (poverty gap) by 22.3% (7.5%); all these figures are statistically significant at a 5% level of significance.

The MTE results (Fig. 3) show an increasing trend even though the MTE values are small initially. The maximum MTE (32.6 kg) is achieved at 41.44% of the BC level. The per capita expenditure increased from Ksh 30 at 0.5% to Ksh 200 at 73.32% level of BC intensity. On the other hand, the poverty headcount (poverty gap) was reduced by 2.3 (1.1) percentage points to 1.9 (0.9) percentage points at 0.5% and 73.3% BC levels. The overall average marginal effects on maize yield, per capita expenditure, poverty headcount, and poverty gap were 9.3 kg/ha, Ksh 119, – 0.5%. and –0.09%, respectively. Table 5 presents additional results at various levels of BC.

These results show that implementing BC to control stemborers substantially reduced poverty in maize farming areas in Kenya. The findings show that the impact varies with the intensity of BC, confirming heterogeneity in impact. These poverty results are consistent with Bauer et al., (2003), who also provide evidence of poverty alleviation from the biological control of pests in bananas, the major subsistence

Table 4 ATE-regressions for assessing the impact of biological control on poverty

	Expenditure per year (000 Ksh)		Headcount index		Poverty gap index	
Biological control	14.45	**	− 0.22	***	− 0.08	**
	(5.86)		(0.08)		(0.03)	
Age	0.53		− 0.03		0.081	
	(21.94)		(0.31)		(0.13)	
Gender	− 4.03		0.02		0.01	
	(2.94)		(0.04)		(0.02)	
Education	0.96		− 0.14		− 0.07	
	(7.59)		(0.11)		(0.04)	
Experience in agriculture	2.32		0.03		− 0.00	
	(7.93)		(0.11)		(0.05)	
Residence	− 3.59		0.03		0.02	
	(4.49)		(0.06)		(0.03)	
Household size	− 12.30		0.31	***	0.14	***
	(8.39)		(0.12)		(0.05)	
Cropped area	8.33		− 0.11		− 0.04	
	(5.90)		(0.08)		(0.03)	
Cropping as main activity	3.74		− 0.14		− 0.02	
	(10.24)		(0.14)		(0.06)	
Extension	4.24		0.16		0.05	
	(8.26)		(0.12)		(0.05)	
Livestock	2.72		− 0.15	*	− 0.07	**
	(6.52)		(0.10)		(0.04)	
Salaried employment	− 0.32		− 0.02		0.00	
	(0.92)		(0.01)		(0.01)	
Business	0.87		− 0.01		− 0.01	**
	(0.90)		(0.01)		(0.01)	
Handicraft	0.26		− 0.02		0.01	
	(1.07)		(0.02)		(0.01)	
Credit access	0.26		− 0.10	***	− 0.03	***
	(2.05)		(0.03)		(0.01)	
Distance to the market	− 8.55		− 0.02		0.02	
	(11.32)		(0.16)		(0.07)	
Distance to the road	1.46		− 0.03		− 0.03	
	(7.68)		(0.11)		(0.04)	
associationyes	2.17		− 0.04		− 0.02	
	(2.72)		(0.04)		(0.02)	
15 km from the RP	0.48		0.06		0.04	
	(3.37)		(0.05)		(.019)	
30 km from the RP	− 5.90	*	0.14	***	0.05	***
	(3.34)		(0.05)		(0.02)	
Parameter lambda1	0.02		− 0.02	**	− 0.01	***
	(0.51)		(0.01)		(0.00)	
Parameter lambda2	0.00		0.00	**	0.00	***
	(0.01)		(0.00)		(0.00)	

Table 4 (continued)

	Expenditure per year (000 Ksh)		Headcount index		Poverty gap index	
Parameter lambda3	0.00		0.00	**	0.00	**
	(0.00)		(0.00)		(0.00)	
Intercept	35.88		0.50		– 0.22	
	(73.27)		(1.03)		(0.42)	
	600		600		600	
	5.61	***	4.66	***	4.41	***
	0.27		0.24		0.23	
	0.22		0.18		0.17	

Standard errors in parentheses. * $p<0.1$, ** $p<0.05$, *** $p<0.01$. Interaction of treatment with variables terms not included in the table.

food crop in Papua New Guinea, as is maize in Kenya. Overall, the results imply that

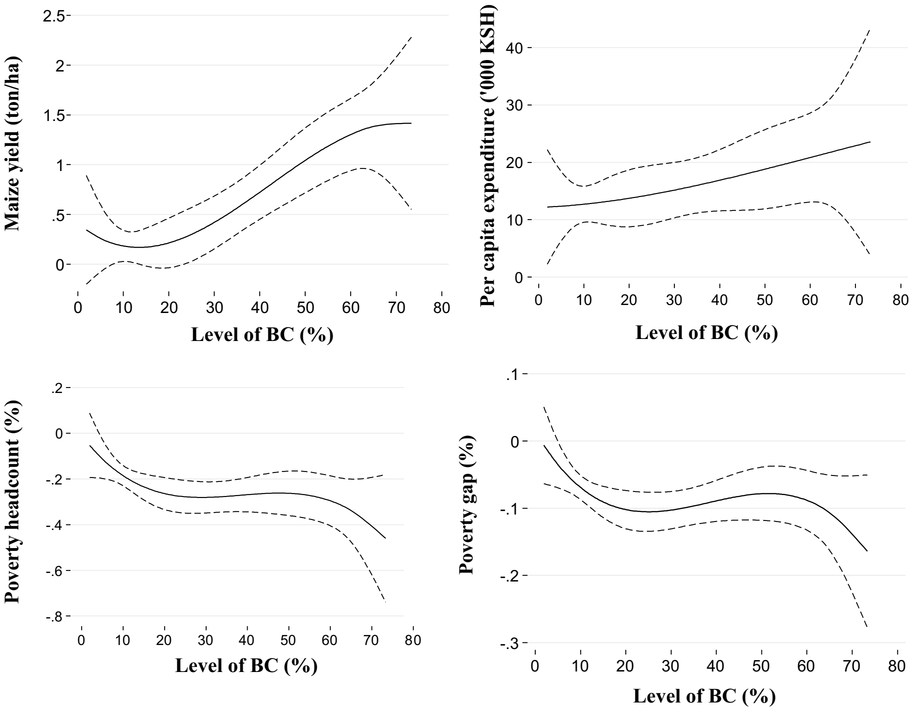

Fig. 2 Estimated dose–response function (Average BC impact) plot. *Note*: Solid line shows the estimated dose–response function; dashed lines are 90% confidence upper and lower bound intervals, KSH: Kenya shillings (Local currency).

Table 5 ATE and MTE values at some specific BC levels

BC level (%)	Productivity (ton/ha)		Per capita expenditure (000 Ksh)		Poverty headcount (%)		Poverty gap (%)	
	ATE	MTE	ATE	MTE	ATE	MTE	ATE	MTE
10	0.18	– 0.01	12.70	0.04	– 18.60	– 1.20	– 6.90	– 0.50
20	0.21	0.01	13.74	0.13	– 26.40	– 0.40	– 10.20	– 0.10
23.49	0.27	0.02	14.19	0.14	– 27.50	– 0.20	– 10.50	0.00
30	0.42	0.03	15.16	0.16	– 28.10	0.00	– 10.30	0.10
40	0.72	0.03	16.88	0.18	– 26.90	0.10	– 8.90	0.20
50	1.04	0.03	18.81	0.20	– 26.30	– 0.10	– 7.80	0.00
60	1.30	0.02	20.85	0.21	– 29.60	– 0.60	– 8.80	– 0.30
70	1.42	0.00	22.90	0.20	– 40.30	– 1.50	– 13.60	– 0.70
73.32	1.42	– 0.01	23.56	0.20	– 46.10	– 1.90	– 16.30	– 0.90

ATE – average treatment effect, MTE – marginal treatment effect.

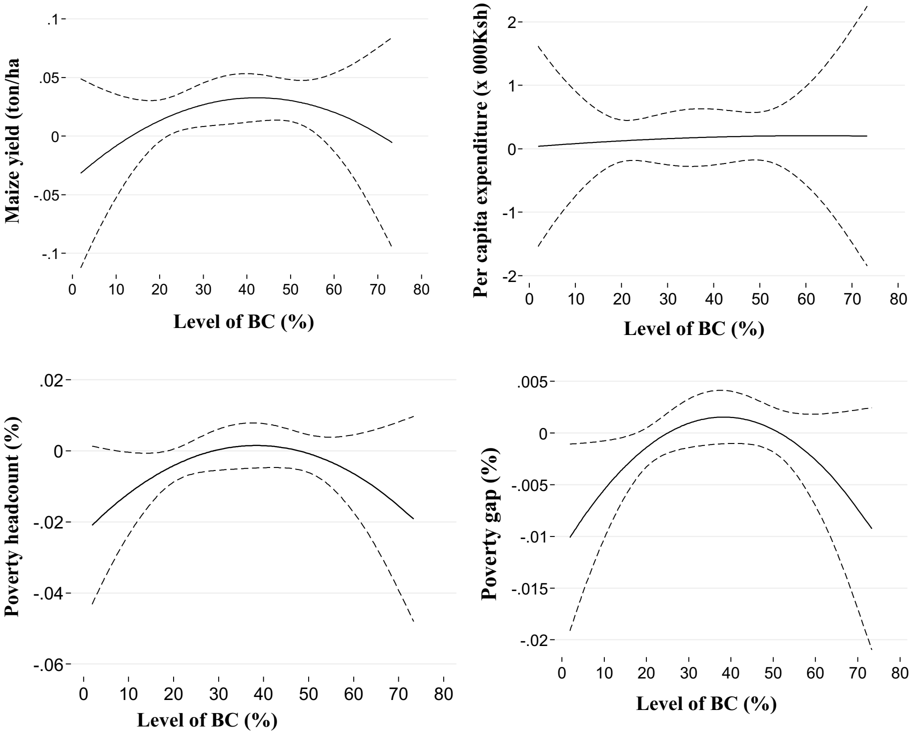

Fig. 3 Marginal Treatment Effect of productivity, household expenditure, poverty headcount and poverty *Note*: Solid line shows the marginal treatment effect; dashed lines are 90% confidence upper and lower bound intervals.

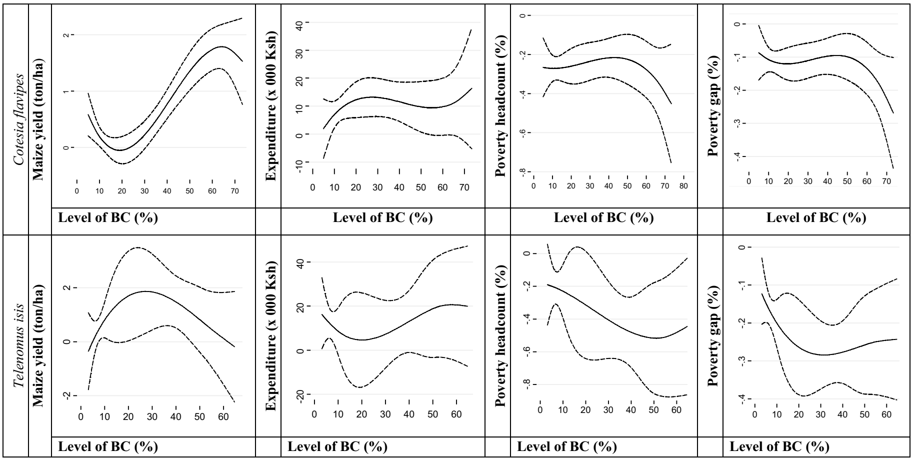

Fig. 4 Dose– Response Functions of productivity, household expenditure, poverty headcount, and poverty gap. Note: Solid line shows the marginal treatment effect; dashed lines are 90% confidence upper and lower bound intervals

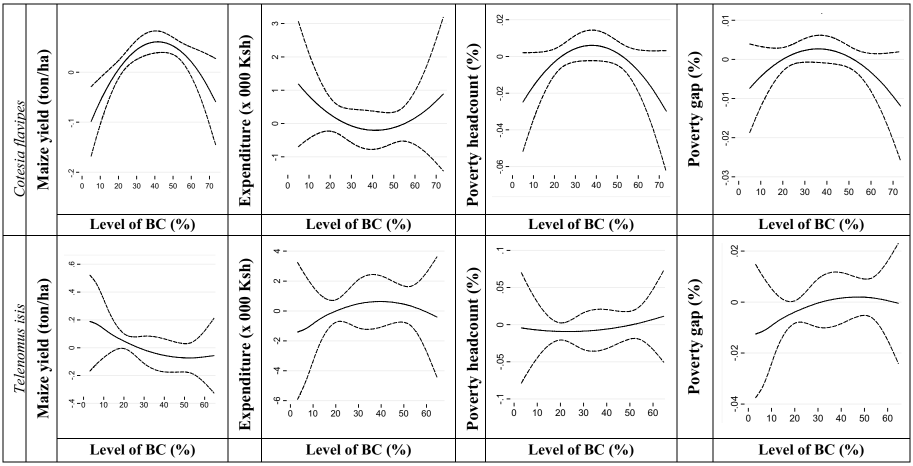

Fig. 5 Marginal Treatment Effect of productivity, household expenditure, poverty headcount and poverty gap *Note*: Solid line shows the marginal treatment effect; dashed lines are 90% confidence upper and lower bound intervals

developing and promoting biological control can contribute to the country's fight against food insecurity and poverty.

3.2 Disaggregated results by biological control agent type

Results on the average and marginal treatment effects of *C.flavipes* and *T.isis* are presented in Figs. 4 and 5. A significant association was found between *C.flavipes* and productivity, per capita expenditure, and poverty. Yield gain in regions where *C.flavipes* was released and spread varied from 0.58 t/ha at the 5% level to 1.53t/ha at the 73.52% BC level, with an average of 0.498 t/ha (which is statistically significant at a 1% level of significance as shown in Table A1). These results are slightly higher than the pooled estimation (where both agents were considered together in the analysis). The per capita expenditure increased from Ksh 1,980 at 5% to Ksh 16,350 at the 73.52% BC level, with a mean impact of Ksh 9,940. This is statistically significant at a 5% level of significance. The headcount ratio (poverty gap) reduced from −12.87% (− 5.34%) at 5% to −47.69% (− 15.57%) at the 73.52% level of BC.

Regarding the MTE results, the impact on yield varied from −0.098 t/ha to − 0.058 t/ha (passing through the maximum of 0.0607 at 41.44%) at the 5% and 73.32% BC level with a 1% increase in BC level. Regarding the expenditure outcome, the MTE varied from Ksh 1,188 to Ksh 882 at the 5% and 73.32% BC levels. A 1% increase in BC level led to a poverty headcount (poverty gap) in the range of − 2.48– −2.97% (− 0.73– −1.19%) at the 5% and 73.32% BC levels. On average, a 1% increase in BC intensity was associated with an increase in maize yield of 6 kg/ha, per capita expenditure by Ksh 227, and a drop in headcount ratio and poverty gap by 3.78% and 0.07%, respectively.

On the other hand, *T.isis* has no significant impact on average and marginal treatment effects for all outcome variables. This is probably associated with the release period. The *C.flavipes* was released earlier (1993), established itself well, and spread to many regions compared to *T.isis*, released in 2005.

4 Discussion

This study establishes the causal relationship between BC intervention and productivity and livelihood outcomes. The analysis provides evidence that partly fills the gap in studies on the socioeconomic contributions of the BC. A systematic review revealed the absence of interdisciplinary studies that addressed socioeconomic outcomes vital to support policy-making for biocontrol interventions (Midingoyi et al., 2021).

Findings from the study revealed that the use of BC, an environmentally safe crop protection measure, was associated with increased crop productivity in the study region. This could be explained by the fact that once released, the natural enemies are established, effectively saving plants from pest attack and preventing farmers from experiencing crop loss. This leads to an increased food supply and hence, ensures the pathway to food security. Among the scarce literature on the contribution of BC food security in SSA, Asfaw et al., (2011) provide insights into the role of BC in curbing cabbage yield losses due to diamondback moth. Outside the SSA region, Rodrigues et al. (2022) demonstrate that Brazilian farmers who use biological pest controls in farming are technically efficient compared to their counterparts who do not use them, showing farmers' ability to raise the productive performance of the country's agriculture. Other evidence of BC advantages in food security, with the BC embedded as a core component of an Integrated Pest Management (IPM) package, was provided by Midingoyi et al. (2019). They showed an increase in mango productivity with the effective control of mango fruit flies through IPM in Kenya. In Bangladesh, the bitter gourd growers who adopted IPM that include larval or egg parasitoids as BC component to combat several insect pests were found to be more technically efficient and hence, have a higher ability to increase production given the resources at their disposal (Rahman & Norton, 2019).

The BC effect analysis also demonstrated that using BC was associated with poverty reduction. The pathway to poverty reduction could be understood through increased crop productivity and quality due to yield loss and infestation reduction, which contribute to improved profitability and farmers' income. Bauer et al., (2003) illustrated the BC of banana skipper—a vital pest that defoliates banana plants, reduces yield and delays the maturity of bananas, a staple food for the Papua New Guinea population. The authors found that the BC intervention was associated with an increase in annual consumption shift that led to a proportion of growers above the country's poverty line. Fowler et al., (2016) conducted an ex-post economic evaluation of the BC of ragwort, a poisonous pasture weed for cattle. The BC resulted in a positive net present value and benefit-cost ratio. Other studies demonstrated the advantages of using BC (within IPM components) as a measure of pest control in reducing poverty through increasing income and profit from crops while controlling for invasive pests (Fernandez-Cornejo, 1998; Muriithi et al., 2016; Nyangau et al., 2017; Midingoyi et al., 2019).

Furthermore, the study explores the impact of BC by considering the level or intensity to account for the heterogeneity of biocontrol agents and revealed that higher intensity of BC is associated with higher impacts. The BC has the advantage of being a self-sustaining crop protection approach while safeguarding the environment by reducing the use of pesticides. Achieving this and reducing food insecurity and poverty requires continuous monitoring and reinforcing the area with fewer natural enemies through additional releases.

5 Conclusion

This paper analyzes the effects of the biological control of maize stemborer on productivity, per capita expenditure, and poverty. The authors took advantage of collaboration with entomologists to identify the areas covered by BC and the levels of biological control activity. A farm household survey based on available entomological data was used to estimate BC impact using a continuous impact assessment framework. Diverting from common impact studies that used binary treatment that ignored heterogeneity in the level of biological control activity, this study used a continuous treatment approach to assess the average and marginal distribution of the impact effects of biological control.

Results indicate that biological control significantly positively impacted maize yield, which varied with the level of biological control activity. On average, after controlling for all other factors, maize yield increased by 31% with the release and spread of the BC agents, compared to the sample average of 1,482 kg/ha. The disaggregated impact analysis by parasitoid species revealed an increase of maize yield by 47.29% for areas where *C.flavipes* were present. However, the authors do not find a significant increase in yield for areas where *T.isis* were present. The authors also find evidence that biological control reduces poverty in Kenya. A 1% increase in BC intensity was associated with a Ksh 119 increase in household expenditure and a 0.5% reduction in poor households. Overall, results suggest that promoting the biological control of stemborers can be a crucial strategy for improving food security and alleviating poverty in Kenya.

Finally, it is worth noting that this study is based on a cross-sectional household survey and might not reflect the dynamics of biological control, productivity, and poverty reduction features. Household and biological data from multi-seasons and multi-years will help to capture the fluctuations and uncertainty in biological control phenomena and the cyclical nature of infestation by stemborer pests. The establishment of a long-run monitoring system to measure the dynamic and sustained impact of the pests and control is helpful in this respect.

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Declarations

Conflict of Interest The authors declared that they have no conflict of interest.

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