# ECONOMICS OF BIOLOGICAL CONTROL OF CEREAL STEMBORERS IN EASTERN AFRICA: A CASE STUDY OF MAIZE AND SORGHUM PRODUCTION IN KENYA

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**A THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY (AGRICULTURAL ECONOMICS) IN THE SCHOOL OF AGRICULTURE AND ENTERPRISE DEVELOPMENT OF KENYATTA UNIVERSITY**

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# DECLARATION

I, Soul-kifouly Gnonna Midingoyi declare that this thesis is my original work and has not been presented for the award of a degree in any other university or for any other award

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# DEDICATION

To my parents: Mr. Soulé Midingoyi and Mrs. Nafissath Logbo for their unwavering support, encouragement and prayers.

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# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| $US | Dolar US |
| 2SLS | Two Stages Least Square |
| AD | Anno Domino (After Christ) |
| AfDB | African Development Bank |
| AgGDP | Agricultural Gross Domestic Product |
| APP | Average Physical Product |
| APRS | Allen Partial Rate of Substitution |
| AT | Action Threshold |
| ATE | Average Treatment Effect |
| ATENT | Average Treatment Effect on the Non-Treated |
| ATET | Average Treatment Effect on the Treated |
| BC | Biological Control |
| BCA | Benefit-Cost Analysis |
| BCR | Benefit-Cost Ratio |
| CBA | Cost-Benefit Analysis |
| CBBC | Commonwealth Bureau of Biological Control |
| CIBC | Commonwealth Institute for Biological Control |
| CILB | Commission Internationale de Lutte Biologique contre les Enemis des Cultures |
| CMI | Conditional Mean Independence |
| CPI | Consumer Price Index |
| DES | Direct Elasticity of Substitution |
| DM | Dry Mildaltitude |
| DRF | Dose Response Function |
| DT | Dry Transitional |
| EIL | Economic Injury level |
| ESA | East and Southern Africa |
| ESM | Economic Surplus Modeling |
| ET | Economic Threshold |
| FANTA | Food and Nutritional Technical Assistance |
| FAO | Food And Agriculture Organization |
| GIS | Geographic Information System |

| | |
|---|---|
| GLM | Generalized Linear Models |
| GPS | Generalized Propensity Score |
| HFIAS | Household Food Insecurity Access Scale |
| HHS | Household Hunger Scale |
| HT | Highland Tropics |
| IITA | International Institute of Tropical Agriculture |
| IOBC | International Organization for Biological Control |
| IPM | Integrated Pest Management |
| IPSW | Inverse Probability Weighting |
| IRD | Institut de Recherche pour le Development |
| IRR | Internal Rate of Returns |
| IV | Instrumental Variables |
| LT | Lowland Tropical |
| MES | Morishima Elasticity of substitution |
| MFC | Marginal Factor Cost |
| MM | Moist Mildaltitude |
| MPP | Marginal Physical Product |
| MT | Moist Transitional |
| MTE | Marginal Treatment Effect |
| NARO | National agricultural Research Organizations |
| NLS | Non-linear Least Square regression |
| NPV | Net Present Value |
| OE | Output Elasticity |
| OLS | Ordinary Least Square |
| POA | Potential Outcome Approach |
| SCS | Simple coping strategies |
| SDD | Simple dietary diversity |
| SY | Scientist Years |
| TLU | Tropical Livestock Units |
| WCS | Weighted coping strategies |
| WDD | Weighted Dietary Diversity |
| WDI | World Development Indicator |
| WW II | World War II |
| ZAR | South African Rand |

# ABSTRACT

The International Centre of Insect Physiology and Ecology (*icipe*), undertook a biological control (BC) programme for control of stemborers from 1993 to 2008, to reduce cereal yield losses due to stemborer attack in East and Southern Africa. The programme released four biological control agents—*Cotesia flavipes, Cotesia sesamiae*, *Telenomus isis* and *Xanthopimpla stemmator*—to control the economically important stemborer pests *Busseola fusca*, *Chilo partellus* and *Sesamia calamistis.* The purpose of this research was to assess the ex-post economic impact of the BC program among smallholder farmers in Kenya. Specifically, the study sought to: i) determine the productivity-effects of BC at farm level, ii) assess the impact of BC on food security and poverty and iii) estimate the global welfare-effect from the BC. Primary data was obtained from biological and household surveys. The household survey was conducted to collect socio-economic data on 600 households randomly sampled across maize agro-ecological zones of Kenya. Secondary data included time-series evolution of maize and sorghum production, yield, cropped area, market prices, price-elasticity of supply and demand and GIS information of the release locations. Methodologically, econometrics-based damage control function framework was adopted to address the first objective, the counterfactual framework using continuous treatment regression analysis for the second objective and economic surplus model analysis to address the third objective. Findings from productivity analysis show a reduction of insecticide use with the BC, thus demonstrating the potential environmental hazard-reducing effect of BC. Additionally, results show that BC has a positive impact on productivity and the derived marginal physical product show that 1% increase in BC level is associated with at least 12 kilograms per hectare increase in yield. The dose response functions (DRF) and the Marginal Treatment Effect (MTE) from the continuous treatment models provide evidence that BC has had a positive and increasing impact on poverty outcomes and food security components exept dietary diversity. For poverty, on average one percent increase in BC intensity is associated with a US$ 1.15 increase of household expenditures and a 0.5% reduction in poor households. With regards to food security, a one percent increase in BC level increased food expenditures by US$ 1.24 and calorie intake by 6.94 Kcal, and reduced the number of food-insecure households by 0.16%. Findings from the global welfare-effect show that BC intervention has contributed to an aggregate monetary surplus of US$ 0.74 billion to the Kenyan economy over 20 years period (1993 to 2013), with 76.71% ($US 568.06 million) from maize and the remaining 23.29% ($US 172.45 million) from sorghum. The net present value was estimated at US$ 142 million for both crops. The attractive internal rate of return (IRR) of 113% as well as the estimated benefit–cost ratio (BCR) of 276:1, illustrate the efficiency of investment in the BC research and intervention. The estimated number of people that could be lifted out of poverty was on average 57,400 persons (consumers and producers) per year, representing an annual average reduction of poor populations of 0.35%. These findings underscore the need for increased investment in BC research to sustain cereal production, and developing BC can be seen as an additional environmentally-friendly tool in the fight against food insecurity and poverty in Kenya. Policy implications are two-folds: boosting the effectiveness of the BC in regions with low level of control through augmentative and conservative BC, and up-scaling the BC strategy to regions with serious stemborers invasion.

# CHAPTER ONE: GENERAL INTRODUCTION

## 1.1 Introduction

Increasing food production in a sustainable manner to meet the rising demands for food is a key research and development agenda in developing world. One of the key strategies to ensure sustainable food supply is reducing 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; Nwanze, 2000). IPM strategies have largely been demonstrated to be critical for sustainable intensification of agriculture (Nwilene *et al.*, 2008; Pretty and Bharucha, 2015; Trumble, 1998).

Biological control (BC) is one the key components of the IPM that entails using the natural enemies of pests (e.g., parasitoids or BC agent) to control and reduce their population to a threshold where damage to crop become economically negligible. When successfully implemented, BC is a central strategy to plant protection. Over and above improving food security through reducing pre-harvest losses due to pests, this strategy can help reduce production costs and the threats on health and environment associated with chemicals application (Asfaw *et al.*, 2011; Naranjo *et al.*, 2015; Varela *et al.*, 2003). The use of natural enemies which disseminate naturally is an alternative economically, socially, and environmentally friendly strategy to pesticide control of pests (Asfaw *et al.*, 2011; Kairo, 2005; Varela *et al.*, 2003).

During the last three decades, BC of some key insect pests have been developed and implemented on major cereal crops throughout the East and Southern African (ESA) region with the greatest emphasis in Kenya. Its effectiveness and economic performance, however, is not yet determined.

## 1.2 Background to the problem

In Eastern and Southern Africa, cereals, especially maize [*Zea mays* L.] and sorghum [*Sorghum bicolor* (L.)], are among the most important and widely grown crops by commercial and small-scale farmers. These food grains are mainly used for subsistence and represent an important calorie intake source for resource-poor rural farmers. Maize and Sorghum grain represent an important source of revenue as they account for 30−50% of low-income households in the region (IITA, 2013). In Kenya, where agriculture is of tremendous importance, maize and sorghum stand for the major cereal crop as representing respectively 40% and 4% of the total cultivated area (Abate *et al.*, 2015). With an annual per capita consumption of 103 kilograms per person, maize represents the main staple commodity in the diet of over 85% of Kenyan population (Abate *et al.,* 2015; GOK, 2010; Onono *et al.,* 2013; Wambugu *et al.,* 2009). Approximately 75% of maize area in Kenya is under small scale farming which provide 65% of the produced and consumed commodity in the Country (Abate *et al.,* 2015). Recent years have seen some increase in annual maize production although this increase has been as a result of area expansion rather than improvement in productivity (Abate *et al.*, 2015).

Cereal production generally has been constrained by biotic and abiotic problems. Abiotic constraints included among others, climate change, low soil fertility and limited agricultural inputs use due to limited capital endowment. Among the biotic constraints, insect pests represent an important challenge and lepidopteran stemborers being the most injurious pests that occur when maize and sorghum are cultivated (Kfir, 2002; Ongamo *et al.*, 2006; Polaszek, 1998; Seshu Reddy, 1998; Songa *et al.*, 2001). Stemborers belong to a group of moths whose larval stages are the most destructive, as they initiate their feeding on the plant, thereby inflicting physically and economically important damage on crops. Infestation by stemborers caused important losses ranging from 11% in the highlands to 21% in the dry areasin Kenya (Odendo *et al*., 2003). Yield loss of 18% in maize due to *C.partellus* and *C. orichalchocilielus* was reported in Kenya. In Tanzania, 40 to 100% sorghum plants infestation was reported and in Ethiopia and Uganda, 15% and 80% of sorghum grain were lost respectivelly. Kfir (1998) in his review reported 100% infestation and considerable yield loss in Maputo and Gaza province in Mozambique. In Zimbabwe, borer infestations range from 30 to 70% in fields of small farms and less than 30% commercial farms.

To control stemborer infestation, different strategies have been used and can be grouped into three categories: Integrated Pest Management (IPM), Chemical control and cultural control (Polaszek, 1998). IPM and cultural strategies include among others the wild host plants, burning of crop residues, manipulating of planting dates, crop rotation, managing planting density and choice of varieties (Seshu Reddy, 1998, van den Berg *et al.*, 1998). Though very promising as strategies for reducing borer pests' damage (Seshu Reddy, 1998; van den Berg *et al.,* 1998), the IPM and cultural strategies have not been adopted due to constraints in their use, making them impracticable and unattractive to farmers (Van den berg *et al.*, 1998). On the other hand, inconvenience in chemical control (use of synthetic pesticides) includes the resistance to pesticides, adverse effects on non-target species, hazards of pesticides residues, direct hazard from pesticides, non-guaranteed success in application, tendency in pesticide overuse and application of pesticide cocktails (van den Berg and Nur 1998; Varela *et al.*, 2003). Moreover, use of pesticides requires a level of know-how for its efficiency but this is usually limited. In addition, the lower purchasing power due to the low-economic value of cereal crops was a limiting factor for resource-poor farmers.

Considering these constraints and the potentially negative impact of chemical control on human health and environment, BC has been fronted as a promising alternative. Because of its self-perpetuating characteristics when well established and the non-requirement for recurrent additional investment, BC remains undoubtedly an appropriate tool for pests control for resource-poor farmers (Hajek, 2004; Kipkoech *et al.,* 2009).

To control the economically important stemborers in the major maize and sorghum producing area in East and Southern Africa, the International Centre of Insect Physiology and Ecology (*icipe*) in partnership with National Agricultural Research Organizations (NARO) implemented stemborers biological control in two different forms: the classical and redistribution forms. The main one is the classical biological control approach, in which the exotic larval endo-parasitoid *Cotesia flavipes* imported from Asia in 1991 was firstly released in 1993 in the coastal region and in many other regions in the following years (Overholt *et al.*, 1997). In the same way, solitary pupal parasitoid *Xanthopimpla stemmator* was imported in 2000 and released for the first time in 2005 in the Eastern region and later in the eight ESA countries namely Kenya, Uganda, Tanzania mainland and Zanzibar, Ethiopia, Eritrea, Zambia, Mozambique and Malawi (Cugala, 2007). More recently, in 2006, the egg parasitoid *Telenomus isis* was released in Southeast Kenya against the two noctuid pests, *S. calamistis* and *B. fusca* (Bruce *et al.*, 2009). In addition to release of these exotic species, icipe and partners redistributed the indigenous *C. sesamiae* both in Kenya and Cameroon.

## 1.3 Statement of the problem

Implementation of BC program through the release of natural enemies in the various cited regions of Kenya is expected to offer small scale farmers the opportunity to significantly reduce their crop harvest losses, increase their income and meet their livelihood needs. Post-release survey and a number of studies reported establishment, acceptable level of parasitism, reduction of pest populations and increase in crop yield (Bonhof *et al.,* 1997; Emana *et al.*, 2002; Odendo *et al.*, 2003; Seshu Reddy, 1998; Songa *et al.*, 2001; Zhou *et al.*, 2001). These studies mainly focused on the success of the BC but according to Cock *et al.* (2016), one should make distinction between success of biological control and its socio-economic impact.

More than two decades after the first set of BC releases, it appears legitimate to ask whether or not the BC intervention has made an impact on the livelihoods of cereal growing farm households in East and Southern Africa (ESA). The effectiveness of BC in controlling stemborers has largely been demonstrated in terms of reduction in pest density (Jiang *et al.*, 2006; Omwega *et al.*, 2006; Zhou *et al.*, 2001) but the most important question is whether this can be translated to positive economic outcomes at farm and household level. Although there are previous evaluation studies (Asfaw *et al.*, 2011; Bauer *et al.,* 2003*;* Cardinale *et al.*, 2003; IFAD, 1998; Lv *et al.*, 2010; Macharia *et al.*, 2005; Myrick *et al.*, 2013; Östman *et al.*, 2003; Yanineck *et al.*, 1992; on different other crops: rice, cabbage, cassava, banana, cowpea, barely) in other countries, there is limited empirical evidences on the link between BC and cereal productivity and wellbeing at household level in Kenya.

Only a few studies have assessed the economic impact of this biological control program with analysis focussing on simple cost-benefit analysis that need to be up dated as the biological control is known to be a self-perpetuating and sustainable control. To our knowledge, the unique assessment of economic advantages of part of this BC-program is the one by Kipchoech *et al.* (2006). This ex-ante assessment was based on assumptions on yield loss reduction and extrapolations from past parasitism levels and pests' density. The study was based on predictions and hypothetical data and hence, actual and current measures of level of parasitism by the released natural enemies should help improving the impact estimations. Moreover, the limited scope of the study remains an issue as the assessment was limited to lower area coverage while taking into consideration the variability in term of agro-ecological characteristics existing in Eastern, Central, Rift valley and Western and Nyanza regions where the BC-agent has spread to should be of interest in knowing the real impact of the BC program. With respect to the impact methodology aspects, building an adequate counterfactual (meaning what would have happen, if BC were not released in the country) is crucial to establish the actual causal effect of the BC intervention. Moreover, there is a need to determine the relationship, if any, between BC and reduction in poverty and food security.

An important objective of this BC intervention, like most agricultural technology interventions, was the productivity enhancement (Irz *et al.*, 2001). Productivity-oriented intervention is decisive to decrease poverty and solving the problem of food insecurity (De Janvry, 2010). Increases in yields have the potential to lift a large number of individuals out of poverty (Irz *et al.*, 2001). Assessment of productivity enhancement requires utmost care using accurate framework to avoid overestimation that can occur when using the conventional production function (Lichtenberg and Zilberman, 1986).

## 1.4 Research questions

The following questions guided this research:

- Does the presence of BC agents result in reducing pesticide use and abating yield loss in cereal production?
- To what extent does the BC contribute to help improving food security and what is the causal relationship between damage abatement and poverty at household level?
- To what extent does public investment (research, release and expansion) in BC intervention exhibit efficiency and what are the benefits of the BC program for

producers and consumers as well as the equivalent number of persons lifted out of poverty?

## 1.5 Objectives

### 1.5.1 General objective

The study is part of an interdisciplinary research project titled "Impact of Biological Control of stemborers in East and Southern Africa" that is being implemented by International Centre for Insect Physiology and Ecology (*icipe*), the Institute of Research and Development **(**IRD**)** and the National Agricultural Research Organizations (NARO) of Kenya, Zambia and Mozambique.

The aim of this research was to provide insight into economics of biological control and to generate information towards improving policies of research and diffusion of this type of cereal pests' control. The overall goal of this research was to assess the ex-post impact of the BC program on productivity and welfare in Kenya.

### 1.5.2 Specific objectives

The specific objectives of the present study were:

i. To analyse the productivity-effects of BC at farm level
ii. To assess the impact of BC program on food security and poverty
iii. To evaluate the impact of the BC spread on social welfare (producers and consumers surplus, return to investment in research)

## 1.6 Significance of the study

Scientists from *icipe* in partnership with local researchers developed and implemented BC against the invasive stemborers, to reduce yield loss experienced by smallholders. Whereas a number of studies have reported on the effectiveness of BC in pest control and its entomological aspects (See Omwega *et al.*, 2006; Zhou *et al.*, 2001), little work has focused on quantifying the cost-effectiveness and socio-economic advantages of this intervention. This study intends to fill this gap and add to the literature on economics of biological control by shedding light on the ability of the implemented BC program to contribute to improving productivity and livelihoods among communities.

Up until recently, there had been no study that reported the productivity gain from the implemented BC in Kenya. Very few exclusion experiments were conducted in other countries especially in Mozambique (see Cugala, 2007), but the results on yield due to the presence of BC-agents are obtained at experimental field scale and cannot be representative at farms or household level because of variability in agro-ecological and farmers' skills and characteristics. This study integrates these dimensions by adopting production function framework in productivity analysis. In addition, when using this framework, many studies considering all factors as standards or yield-growth inputs lead to inconsistent and inefficient estimates resulting in overestimation or underestimation of the productivity-effect of the studied technology (Lichtenberg and Zilberman, 1986; Pemsl, 2005; Zhengfei *et al.*, 2005). This dissertation research fills this methodological gap by adopting the damage abatement modeling with the appropriate functional forms to take into account the characteristic of the biological control as a yield-preserving factor and not a yield-growing factor like fertilizers and seeds for instance.

For the causal-effect relationship between BC and poverty and food security, most studies considered the binary treatment (categorizing sampled units into treated and non-treated) ignoring the existence of different levels within the group of treated that might result in heterogeneity in impact estimates (Bia *et al.*, 2014; Bia and Mattei, 2008; Cerulli 2015). The thesis fills this methodological gap by considering the biological control level instead of the traditional "with" and "without BC" settings as encountered in the impact assessment literature.

The significance of undertaking this economic impact assessment of the biological control of stemborer pests relies on the need of knowledge on accountability of invested funds in biological control program, the need of informing on magnitude and distribution of payoff from the biological control and the need of information to redesign or improve future or other BC research programs to increase their chances of success.

Filling these knowledge and method gaps will enhance the understanding of the implications of the BC intervention in terms of farming performance, food security and welfare effects. Given that in many zones of the region, stemborers still remain detrimental to smallholders, this economic impact analysis of BC program is important because the knowledge on its precise social benefits will guide in decision-making about its best adaptation and scaling up. The findings will also provide policy-relevant and necessary information to redesign future programs in the biological control strategies (Baker, 2000).

## 1.7 General analytical framework

### 1.7.1 Sustainable Livelihood Framework

The role of research and development is to provide agricultural practitioners with effective and efficient technologies to improve their performance and life conditions. The biological control program initiated and implemented by *icipe* in collaboration with researchers from NARO fits perfectly within this framework for its goal of achieving a costless reduction of pests and sustaining cereal crops farming to improve the livelihood of small households. The general relationship between the biological control (BC) and livelihood improvement can be conceptualized following the framework of Sustainable Livelihood (Adato and Meinzen-Dick, 2003; Scoones, 1998) as depicted in Figure 1-1, allowing conducting ex-post assessment of the impact of the BC on smallholder's livelihood.

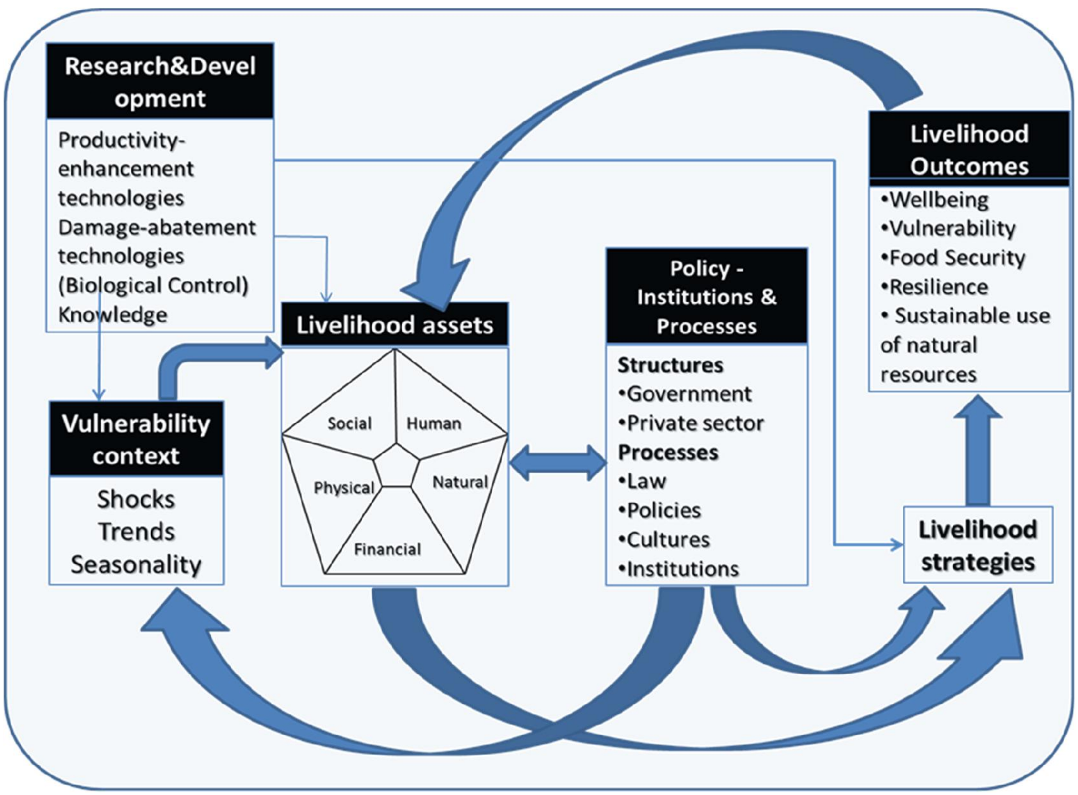


**Figure 1-1**: Analytical framework for linking Biological Control to Household livelihoods

Source: Adapted from Adato and Meinzen-Dick (2002)

The framework puts people (here small-scale households characterized by their social, human, physical, natural and financial) in the centre of analysis and show how they operate in a given environment (institutional, vulnerability context) and develop strategies to achieve better and sustain livelihoods.

For practical purposes, the exhaustive analysis based on the above-described holistic framework may not be appropriate (Scoones, 1998). The principle of 'optimal ignorance' was applied in adapting the framework to this research context and purpose. This allows considering the key connections and linkages between presented elements on the field and the biological control intervention. The way the Sustainable Livelihood Framework was adapted and applied to the Biological Control intervention is depicted in the Table 1-1.

Analysis started with the understanding of broader context in which maize and sorghum farming systems are practiced and the information to be investigated is related to abiotic and biotic stresses including the stemborer pests. The context was extended to the agro-ecology, market, commodity trends and seasonality and their relation to the sustainable livelihood. The livelihood resource encompasses the household socio-demography and economic characteristics, as well as available infrastructures and natural assets. Attention was next given to the institutional environment, organizational context and their influences in sustainable livelihood achievievement. Regarding research and development role, the analysis focused on implemented technologies mainly in maize and sorghum farming including biological control. The livelihood strategies covered the range of options to achieve sustainable livelihood objectives including on-farm and off-farm choices.

**Table 1-1**: Application of the sustainable livelihood framework to the BC program impact

| Framework elements | Vulnerability context | Livelihood resources | Policy-Institutions-Processes | Research and development | Livelihood Strategies | Livelihood Outcome |
|---|---|---|---|---|---|---|
| **Adaptation** | **Shocks**: Biotic constraints (Stemborer pests - *C. partellus, S. calamistis, B. fusca* - diseases; invasive weeds, animals). Abiotic constraints (Fertility level, drought, heat stress, temperature variations) Agroecology, climate, demography, distribution of stem-borers and intensity of presence and damage<br><br>**Trends**: Commodity market and prices, Maize and sorghum market characteristics<br><br>**Seasonality:** Seasonal prices, seasonal wages, availability of labor in the village | **Human**: Socio-demography, household labor availability, Access to training and education, health concerns<br><br>**Financial**: Household's savings, income, investments, financial services and conditions<br><br>**Social**: Class or social differentiation, gender analysis,<br><br>**Natural**: Types of soil, water (rainy seasons),<br><br>**Physical**: Access to infrastructure, transportation, quality of dwelling, equipment and machinery, other material possession | **Policy**: Land policies Credits program Food aid program, Market policies<br><br>**Organisations**: NGOs, Farmers association, Extension, national research, international research center and other development institutions, private sectors<br><br>**Cultural** (beliefs, traditions, identity and values) | **Productivity-enhancement technology or knowledge**: Seed varieties, water management techniques, New fertilization formulas, innovations on farming practices<br><br>**Damage reduction technologies**: biological control, chemical control, integrated pest control | **Agricultural intensification/extensification**: Land use, crop choice, endogenous practices of pests control, technological options, tradeoffs between technology and vulnerability, reduction of pesticide use<br><br>**Livelihood diversification**: In addition to maize and/or sorghum, cash crops, livestock's, Non-farm activities, forestry, Other sources of income,<br><br>**Migration**: Migration patterns and contribution to livelihood sustainability | **Livelihood:** Poverty Food security, Welfare at household or national level<br><br>**Sustainability:** Vulnerability and resilience to food insecurity, Environmental-risk reduction associate to the reduction of pesticide use |

Source: Adapted from Adato and Meinzen-Dick (2002)

### 1.7.2 Impact pathway

The goal of this assessment was to build a sound and comprehensive causal relationship between the biological control intervention and advantages to households and communities. In other words, this study intended to explain the transmission channels through which the bio-control program likely delivered benefits to maize and sorghum smallholders as the expected finality of the BC intervention. As indicated in Figure 1-2, the starting point of the BC pathway to welfare is the research and release of bio-control agents in infested regions. Following the release, it was expected that the BC would self-sustain through multiplication and spread of the released bio-agents to new area. From the resulting reduction in pest density, it was assumed a reduction in yield loss that could be translated to a gain in yield. In turn, the resulting increment in production was expected to increase food availability at household level and it also assumed to lead to reduction in poverty as well as welfare gain at community or country level.

## 1.8 Organization of the thesis

The overall content of this thesis is organized into five chapters. The first chapter stands for the introductory part of the study. It provides the background for the study, describing the general context of cereal farming and the challenges of stemborer pest as well as the *icipe* BC program implementation. The chapter introduces the problem under investigation, objectives of the study, and establishes the sustainable livelihood framework (SLF) as starting point and general analytical guidance for evaluating the impact of *icipe* BC program.

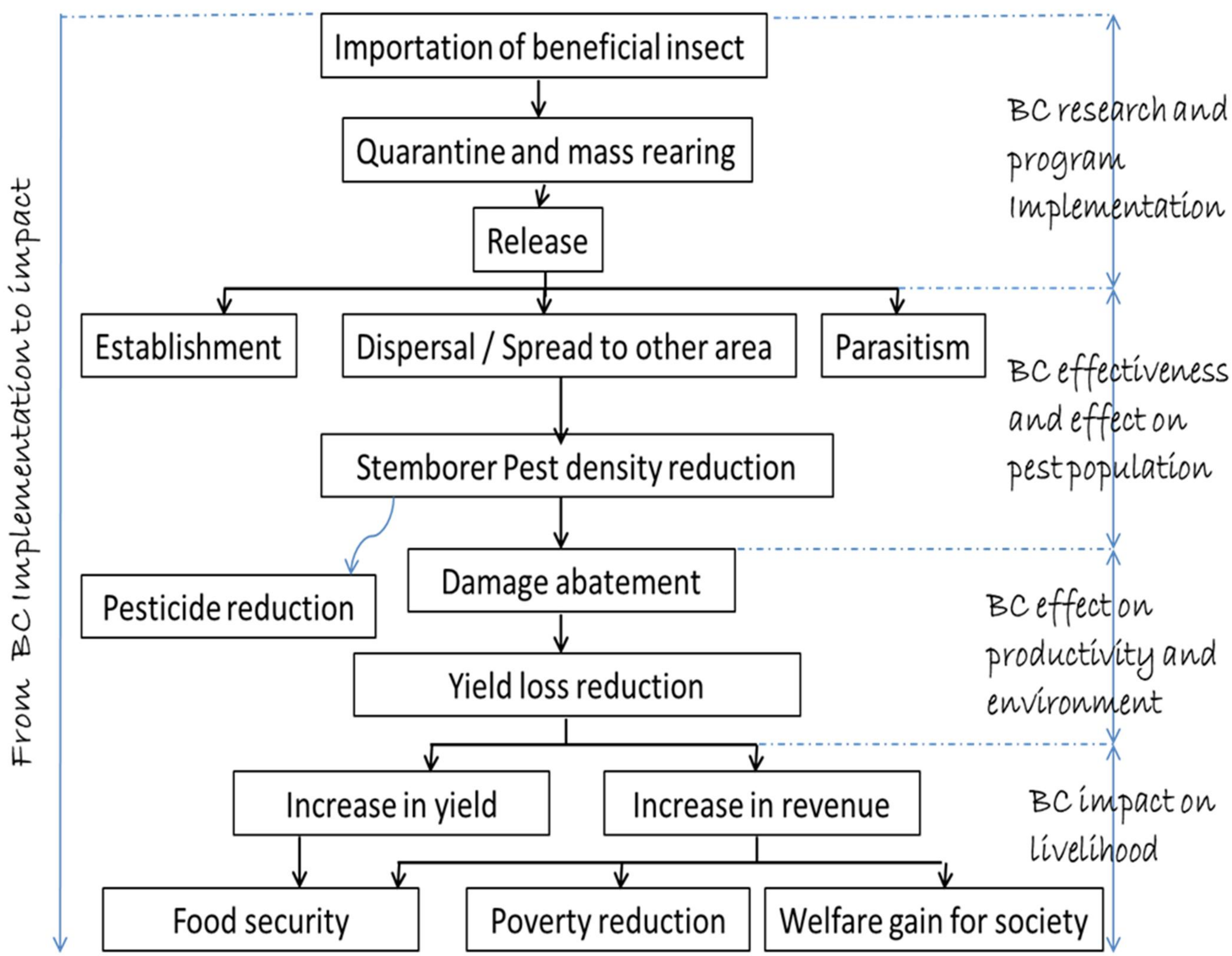


**Figure 1-2**: Causal pathway of the biological control

Source: Author's design

Chapter two reviews the literature on biological control of pests and presents a review of the approaches used to analyze their socio-economic impact. The strengths and weaknesses of the various approaches are provided in order to orient in the choice of the analytical models.

Chapter three addresses the research methodology. It describes the study area and discusses the sources of data and data collection methods. This chapter establishes the theoretical foundations and empirical frameworks to estimate the productivity-effect, the poverty and food security impacts and the changes to social welfare associated with the implementation of icipe Biological control program. The production function with damage abatement framework was used to estimate the productivity-effect; the potential outcome framework with continuous treatment approach was used to quantify the poverty and food security impact, whereas welfare economics based on the economic surplus models were used to estimate social gains resulting from the BC program.

Chapter four presents the empirical findings from the analytical models organized in three subsections corresponding to each of the three specific objectives of the study. The findings are used to draw conclusions and outline recommendation for further research, which are presented in chapter five. The chapter also discusses the implications of the findings to policy and suggests the areas that need further research.

# CHAPTER TWO: LITERATURE REVIEW

## 2.1 Biological control: Definition, history, approaches and applications

### 2.1.1 Definition

In their attempt to define biological control, Lazarovits *et al.* (2007) provide a simple idea of the concept that they defined as managing a pest which is a living organism by deliberate use of living organisms. Simmonds (1967) provides a more elaborate definition that: "biological control denotes the use of living organisms in the control of a pest or, using biota to control biota according to the International Biological Programme". The used living organisms for control are also called beneficial organisms, natural enemies or bio-agents. A more operational definition in pest management stated that biological control refers to action of biological agents, usually arthropods or pathogens as opposed to chemicals, for the regulation of host population densities or reducing its numbers below a level causing economic injury (Alston 2011; Ferrar *et al.*, 2004).

This type of control stems from natural ecosystem function principle by which populations of an organism are regulated by other organisms. This natural principle has then been applied to agriculture with the goal of effectively manage populations of beneficial organisms and their ability to reduce the pests' activities within environmental, legal and economic constraints (Lazarovits *et al.,* 2007).

The definition of biological control varies among scientists. For pathologists, the concern is mostly the plant desease and biological control is defined as the control of the plant disease through a biological process (Wisniewski *et al.*, 2007). Ecosystem scientists also put emphasis on plant, host and enemy relationships and expand the definition of biological control to include management of plant disease through the manipulation of host ecology and its resistance to pathogen (Cook, 2007).

For entomologists, biological control is defined as the use of living organisms or natural enemies to manage a pest population.

In this study, we consider the biological control as the use of parasitoids (or natural enemies or BC agents) to parasitize stemborers and control them with the expectation of significantly reducing their population densities and abating damage to crops. The BC agents involved in this study include the exotic larval parasitoid *Cotesia flavipes* the exotic solitary pupal parasitoid *Xanthopimpla stemmator,* the egg parasitoid *Telenomous isis* and the indigenous *Cotesia sesamiae*.

### 2.1.2 Historical overview of Biological control

The history and evolution of the biological control as strategy in crop protection is summarized in three periods comprising the early history from 200 AD to 1887 AD, the intermediate period from 1888 AD to 1955 and the modern period from 1956 to present (Hagen and Franz, 1973). The earlier period corresponds to the first ever known attempts of using predators to control undesirable pests. The most commonly cited example is the one related to the Chinese history which stands for the first use of biological control in agriculture. According to this thought, the history of biological control stems from reported primitive ideas with the ancient history when Chinese noticed that ants were effective predators for citrus pests, and started collecting net of ant colonies from their natural habitat and placing them in the surroundings their orchards (Van Lenteren, J.C., 2008). Other primitive use of BC was reported in this same region of Asia but based on archaic knowledge as biological control were practiced haphazardly without any scientific support. Later in this same period, new knowledge on predator-pest relationship was being developed and BC crossed to Europe where its implementation was still basic, and later to the US. The intermediate period of

Biological control was characterized by the first ever noted success of BC of the invasive cottony cushion with the vedalia beetle and *Cryptochaetum iceryae,* both natural enemies being brought from Australia. This breakthrough would give rise to the implementation of many other BC projects in the early 1900s worldwide till reaching the peak of BC activity in 1940 with 57 different natural enemies established around the world. This expansion declined later with the world war II (WW II) after which entomological research will shift to pesticide research. Preserving and strengthening the achievements before the WW II put in place many international organizations such as the Commonwealth Bureau of Biological Control (CBBC) in 1947, Commonwealth Institute for Biological Control (CIBC) in 1951, the Commission Internationale de Lutte Biologique contre les Enemis des Cultures (CILB) in 1957 and the International Organization for Biological Control (IOBC) in 1962. The third phase or the modern period is characterized by more advanced scientific knowledge on the BC and pest management. Among others, the concepts of the economic injury level and economic threshold emerge and allow rationalizing the use of pesticide. IPM programs in which BC was core component were developed. Scientists In their review on the introduction of insect BC-agents for pest control worldwide, Cock *et al.* (2016) reported that by the end of the year 2010, 2384 different natural enemies were involved in a total of 6158 introductions to control 588 different pest species. Of the total introductions, 2007 representing 32.6%, got established and 620 satisfactorily contributing to the control of 172 different pest species accounting for 29.3% of the total targeted pests. The supply-demand features of BC show that so far, high-income economies (USA, Canada, France, UK, etc) represent the most important users of biological control with 63.7% of the total world releases whereas low-income economies account for just 2.4% of the total world release (Cock *et al.*, 2010). On the other hand, the providers of bio-agents who mostly represent the countries of origin of the targeted pests were discovered to reach at least 119 countries. In sub-Saharan Africa, Kenya ranks second after South Africa regarding the total number of bio-agent releases, with a total of 58 releases in which 6 were successful against 18 targeted pests (Greathead and Neuenschwander 2003**).**

### 2.1.3 Approaches of biological control

The literature of the biological control distinguished between three broad categories of biological control: the Classical, the Inundative (augmentative) and Conservation Biological controls (Hint et Lazarovitz *et al.*, 2007; Flint and Dreidstats, 1998).

i. Classical biological control: in classical biological control also known as importation, a living organism is introduced to an area where it had not previously existed. The aim is to establish this organism, a natural enemy or competitor, in its new location in order to provide long-term control of a pest. The target pests are, in many cases, non-indigenous to the ecosystem in the first place.
ii. Inundative biological control: in inundative or augmentative biological control, the aim is to introduce sufficient numbers of the control organism(s) to reduce the pest population, at least temporarily. Such introductions would normally need to be repeated, in much the same manner as a traditional pesticide.
iii. Conservation Biological Control: Conservation Biological Control encompasses efforts to conserve or enrich the biological control agents that are already present, through either manipulation of the environment or crop and pest management practices.

In addition to these three categories, Simmonds (1967) added other aspects of biological control which achieved considerable interest by the past in some countries. These methods include the use of the sterile male technique by irradiation or chemically, introduction of lethal gene in a pest population and the use of sex attractants. These are other forms of biological control in that they involve the use of living organisms.

### 2.1.4 Applications of biological control

Biological control measures have been implemented wordwide in diverse environments and for different purposes. The biological control of the cassava mealybug (*Phenacoccus manihoti* Matile-Ferrero) with the natural enemy *Anagyrus lopezi* (DeSantis) is one of the most cited examples of successful biological control implementation in Sub-saharan Africa. The cassava mealybug was a devastating exotic pest originated from South America and probably brought in Africa through overseas transportation. This pest first discovered in 1970s in Congo invaded many countries and was causing severe damage on plants leading to important yield loss, cassava is one the major sources of carbohydrate for hundreds of millions of populations in the region. Exploration of the pest's natural enemy in South-America lead to the finding of the wasp parasitoid *A. lopezi*, which after quarantine, mass rearing and administrative authorizations, was released, established and helped reducing the pest density to the extent that the pest is no longer a threat to cassava production throughout Sub-saharan Africa regions.

Another application includes the release of two natural enemies (*Cotesia plutellae*, Kurdjumov and *Diadromus collaris* Gravenhorst) to control the Diamondback moth (*Plutella xylostella* L.) pest. This pest was the most injurious insect of brassica crops in South Africa and the release resulted in the establishment of the two parasitoids followed by high rate of parasitism and pest density reduction (Kfir, 2005).

Combined efforts of many key public and private stakeholders involved in citrus production in Brazil were made to implement the biological control of the citrus leaf miner moth (*Phyllocnistis citrella* Stainton) which was a serious pest damaging citrus by directly feeding on the leaves and engendering the spread of the canker bacterium in orchards. Its natural enemy (*Ageniaspis citricola* Logvinovskaya) was imported from Florida in USA, reared and repeatedly released from 1998 to 2004 and got established (Villanueva-Jiménez *et al.,* 2000) These releases resulted in high parasitism levels ranging from 18% to 100% and significant reduction in the pest density, damage on citrus and incidence of citrus canker all over the main production regions of the country.

As part of their biological control program against the invasive cassava mealybug (*Phenacoccus herreni* Cox & Williams) originated from Guyana and South America, Brazilian institutes and government agencies released a group of three natural enemies of the pest comprising *Acerophagus coccois* (Smith) and *Aenasius vexans* (Kerrich) from Venezuela, and *Apoanagyrus diversicornis* (Howard) from Colombia. Pest density and infestation level of the cassava mealybug was reduced after establishment of these natural enemies, allowing the re-integration of the cassava agroecosystem in the region (Bento *et al.,* 2002).

Failure of obtaining a sustainable pest management with chemical control in eradicating the new agromyzid leaf miner species (*Liriomyza trifolii* Burgess) from the USA, led The Netherlands authority to fall back on biological control program (Minkenberg and van Lenteren*,* 1986). For this purpose, research was conducted on many natural enemies and three species (*Diglyphus isaea* Walker, *Dacnusa sibirica* Telenga and *Opius pallipes* Wesmael) showed promise for effective control of the leaf miner. These bio-agents allow to effectively control another new accidentally introduced leaf miner pest (*L. huidobrensis* (Blanchard)). The resulting success story favored the extention of the use of the bio-agents to Europe, Africa and Latin America.

The larvae of the alfalfa weevil (*Hypera postica* Gyllenhal) infest and heavily damage Chinese milk vetch which is used as an important green manure in rice production and its flower is also a great source of honey production. As part of biological control, four species of natural enemies (*Bathyplectes anurus*, *B. curculionis* (Thomson), *Microctonus aethiopoides* Loan and *M. colesi* Drea) were released and followed by the establishment of a single bio-agent (*B.anurus*) which led to a substantial reduction in damage to Chinese milk vetch, contributing to restoration of paddy and honey production (Takagi *et al.,* 2005).

The predatory South American coccinellid beetle (*Hyperaspis pantherina)* was used as bio-agent to control the invasive scale insect (*Orthezia insignis*) infesting and devastating forest of the gumwoods in St Helene. The release saved the endemic gumwood species from extinction (Fowler, 2005).

The decision to end chemical control of the codling moth (*Cydia pomonella* (L.)) which is a notorious fruit boring pest for walnuts and some stone fruits in California led to biological control strategy. Three BC-agents (*Bassus rufipes, Liotryphon caudatus* and *Mastrus ridibundus*) were released and resulted in the establishment of the third one which helped reducing damage onfruit and nut in orchards (Mills, 2005).

Many other BC programs have been implemented and well-known examples include control of water hyacinth with the release of *Neochetina* species (*Neochetina eichhorniae* (Warner) and *N. bruchi* (Hustache)) in Benin and East Africa (De Groote *et al.*, 2003), control of the cabbage pest

*Plutella xylostella* Linnaeus using *Diadegma semiclausum* (Hellén) in Kenya (Asfaw *et al.*, 2011; Macharia *et al.*, 2005), and control of the invasive fruit fly *Bactrocera dorsalis* (Hendel) using the bio-agents *Fopius arisanus* (Sonan) and *Diachasmimorpha longicaudata* (Ashmead) in citrus (Ekesi, 2015).

## 2.2 Biological control of cereal stemborers in Kenya

### 2.2.1 Stemborers: damage and yield losses

Stemborers are insect pests that cause, during their larval stage, important physical and economical damages on cereal crops. These insects belong to the Order of Lepidoptera and develop through a complete metamorphosis with four stages including egg, caterpillar, chrysalids or pupa and adult stage. The prejudicial and harmful phase for plants and agricultural crops is the caterpillar phase as these larvae are essentially herbivorous and possess feeding organs with potentially destructive effects on plants. Their mouthparts are adapted for biting and chewing (Maes, 1998). Stemborers cause damage on plants by feeding on the leaves, the stems and the cobs. They feed on young succulent leaf tissue and leave small holes and thin layer of transparent leaf epidermis. Some others feed in the leaf sheath and tunnel into the stem. Others bore and feed on the stem and cause the deadheart, killing then the growing point of the plant (Overholt *et al.*, 2001). Deadheart and whiteheads are two visible symptoms caused by stem borer larva infestation (Kfir *et al.*, 2002).

Many studies have revealed the presence and the high diversity of stemborer species in East and Southern Africa (Kfir, 1998; Le Ru *et al.,* 2006 a b; Matama-Kauma *et al.*, 2008; Moolman *et al.*, 2014; Ong'amo *et al.*, 2006; Seshu, 1998; Sohati *et al.*, 2001) but the most economically important species are the crambid *Chilo partellus* (Swinhoe), and the noctuids *Busseola fusca* (Fuller) and

*Sesamia calamistis* Hampson (Bonhof, 1997; Kfir *et al*., 2002; Ong'amo *et al*., 2006). The summary of their main characteristics is presented in Table 2-1.

*Chilo partellus* also known under the common name "spotted borer" infests maize, sorghum, rice sugarcane and a high number of weed species (Overholt *et al.,* 2001). It is an Asian native species that was first recorded in Africa in 1935 in Malawi and is currently encountered in almost all ESA countries. It is considered as the most important stemborer in areas of low or medium altitude. Its biology showed a life cycle adapted to the maize growing season. Damage on maize plant begins when its eggs produced young larvae that ascend the plant, enter leaf whorls and start feeding on it. Older larvae tunnel into stem tissue, feed on it, pupate in it and can also enter in diapauses for 6 months. It is a pest of high economic importance as its damage can cause yield losses up to 88% in maize or sorghum (Overholt *et al*., 2001).

For *Busseola fusca* or the African maize borer, the larva infests maize, sorghum, millet, sugarcane and a large number of grass species (Overholt *et al*., 2001). This pest is distributed throughout sub-Saharan Africa and mainly found in East and southern region where it is restricted to mid and high elevation areas. The female lays up to 50 eggs between the sheath and the stem and the issued larva feed on the young blades of the leaf whorl. They penetrate the stem by boring through the whorl base, destroy the growing point and tunnel downward. In economic point of view, *Busseola fusca* is often the most serious maize stem borer. The yield loss reported varies with countries and can reach 50%.

*Sesamia calamistis*, commonly named "Pink stemborer", infests maize, sorghum, finger millet, rice and sugarcane. It is encountered on numerous species in natural habitats. This pest is widespread in tropical region of Africa. The female lays up to 350 eggs inserted between the lower leaf sheats and stems. The issued larva penetrates then the stem directly after feeding on the leaf sheath.The larvae may attack a number of young stem or tillers and pupate generally inside the stem. It is a major stemborer for sorghum on which some important economic losses have been recorded in some African and Asian countries.

Based on survey data, De Groote *et al.*, (2002) estimated crop loss due to stemborer to 12.9%, found to be equivalent to a yearly lost quantity of 0.39 million tons of grain and a lost value of USD 76 millions. Odendo *et al*. (2003) examined the economic loss due to stemborer and found the average loss in maize to be at 14 %, ranging from 11% in the highlands to 21% in the dry areas. An extrapolation to the Kenyan national production in maize revealed that about 0.44 million tons valued at US$ 25-60 million and which is enough to feed 3.5 million[1] people per annum are lost.

[1] The per capita annual maize consumption is 125 kg

**Table 2-1.** Targeted stemborers and their characteristics

| Stem borers | Origin | Common name | Crop infested | Damage on crops | Distribution | Reported yield loss |
|---|---|---|---|---|---|---|
| *Chilo partellus* (Swinhoe) (Lepidoptera: Crambidae) | Exotic (Accidentally introduced in Africa through Malawi in 1935) | Spotted borer | Maize, sorghum, rice sugarcane | Leaf damage, dead-heart, direct damage to grain, increase susceptibility to stalk rot and lodging | East and Southern Africa in warm and low altitude | 14-40% on maize (De Groote *et al.*, 2002)<br>12-30% (Polaszek, 1998) |
| *Busseola fusca* (Fuller) (Lepidoptera: Noctuidae) | Indigenous to Africa | African maize borer | Maize, sorghum, millet, | Feed on stem and leaves | Sub-Saharan Africa, in cool high-altitude area in Eastern | 20-80% (Kfir *et al.*, 2002)<br>26 – 28% (Harris, 1962) |
| *Sesamia calamistis* Hampson. (Lepidoptera : Noctuidae) | Indigenous to Africa | Pink borer | Maize, sorghum, finger millet, rice sugarcane | Attack a number of young stems, feed on stem | Sub-Saharan Africa, prevalent in medium and low altitude areas | 20-40% (Nsami *et al.*, 2001) |

Source : Author's compilation

### 2.2.2 Stemborer management strategies

Several strategies have been developed to control stemborers in order to reduce damage on plants. Polaszek (1998) grouped them in four categories including the integrated pest management (IPM), the cultural control, the chemical control and biological control. The cultural control groups a high number of controls including, the wild host plant, management of crop residues, tillage, tillage practice in commercial agriculture, grazing, burning of crop residues, manipulating of plant dates, crop rotation, intercropping, planting density, physical control and removal of infested plants, volunteer plants, fertilizer use, choice of variety, trap crops and water management. Although these options appear promising not many of the recommendations have been adopted by African farmers. Field sanitation, crop rotation, specific intercropping patterns and manipulations of sowing dates each have their own constraints, making them impractical or unattractive to farmers. Cultural control is therefore severely constrained by the limited management capabilities of farmers, especially in area where farmers' communities lack the support of adequate advisory services.

The chemical control calls for the use of insecticides with direct elimination effect on stemborers. Even if the chemical control is efficient, its benefits appear to be for short term because of some constraints and consequences. The resistance to pesticides, adverse effects on non-target species, hazards of pesticides residues, direct hazard from pesticides, non-guaranteed success in application, tendency in pesticide over-use and application of pesticide cocktails are among the main inconveniences of the chemical control (Van den berg and Nur 1998, Varela *et al.*, 2003). Moreover, the use of pesticide requires a level of know-how for its efficiency, but which usually lacks. Furthermore, even if pesticides are perceived to be an important tool against stemborers in commercial agriculture, the lower purchasing power due to the low-economic value of cereal crops seem to be limiting factor in affording them by the resource-poor farmers. These insufficiencies of the IPM, cultural and chemical control engendered an increasing interest to the biological control.

### 2.2.3 Biological control or natural enemies release as sound strategy

The necessity of using biological control as measure against stemborers in maize production arose with the advent of the invasive and devastating pest *C. partellus* which was originated from Asian countries. It had become urgent to find its natural enemies from the pest country of origin. The first attempts of releases involved the introduction of nine (09) species of natural enemies by the Commonwealth Institute of Biological Control (CIBC) in the period of 1968 – 1972 (CIBC, 1972) but this resulted in failure as none of the released bio-agents got established (Overholt *et al*., 1994). The exotic larval parasitoid *Cotesia flavipes* Cameron (Hymenoptera, Braconidae) was then imported from Asia in 1991 and released from 1993 in East and Southern Africa starting at the coastal region of Kenya (Overholt *et al*., 1994; Overholt *et al.*1997, Omwega *et al.,* 2006) as part of the icipe project called "Biological control of insect pests in subsistence crops grown by small-scale farmers". The objective of complementing the control by this first released BC-agents and tackling another stage of the pest life cycle, the solitary pupal parasitoid *Xanthopimpla stemmator* Thunberg (Hymenoptera, Ichneumonidae) was imported and released in the early 2000s in many East and Southern African countries including Kenya (Cugala, 2007).

The egg parasitoid *Telenomus isis* (Polaszek) (Hymenoptera, Scelionidae) is one of the most important stemborers' natural enemies found in West Africa (Schultess *et al.*, 2001; Bruce *et al.*, 2009) and introduced by *icipe* in East Africa in 2005. In addition to this last species, the virulent strain of the indigenous larval parasitoid *Cotesia sesamiae* Cameron from Western Kenya was introduced in Taita Hills in the same year.

Altogether, these four (04) species of natural enemies were released to date to control stemborer pests through the Icipe biological control program composed of four different projects. Among these projects, the first entitled "Biological Control of Crop Pests and Tsetse", began officially in 1990 for a period of three years, the second "Biological control of insect pests in subsistence crops grown by small-scale farmers" implemented in the period of 1993 to 1996, the third one "Biological Control of Cereal in Subsistence Agriculture in Africa" covered the period of 1997 to 2001 and the fourth one entitled "Biological control: a sustainable solution for smallholder maize and sorghum farmers in East and Southern Africa" covered the period of 2002 to 2005.

### 2.2.4 Establishment and impact on pest density reduction

The establishment and parasitism efficiency assessment are a pre-condition for any economic assessment. The effective dispersal and acceptable level of controlof the natural enemies a are key elements. Evidences on the presence and spread following the release of bio-agents have been confirmed through many studies and surveys (Assefa *et al.*, 2008; Cugala, 2007; Omwega *et al.,* 1995; Getu *et al.*, 2003; Mailafiya *et al.,* 2011; Moonga, 2007; Omwega *et al.*, 2006; Omwega *et al.,* 1997; Sallam *et al.*, 2001). In addition, the parasitism and suppression-effect[2] of the released bio-agents has been demonstrated and confirmed the effectiveness in pest densities reduction (Zhou *et al.,* 2001; Jiang *et al.* 2006; Cugala 2007). Furthermore, during a recent insect sampling survey, the *T.isis* has been found just in the regions where it has been released and the *C.sesamiae* has not been recorded (Ongamo *et al.* 2014, unpublished data).

[2] *C. partellus* density has been proved to be reduced by 50% with the release of C. *flavipes* (Zhou et al., 2001; Jiang et al., 2006).

## 2.3 Economics of Biological control

### 2.3.1 Economic approaches of Biological control impact evaluation

#### 2.3.1.1 Partial budget economic analysis

Partial budget (PB) is a basic assessment method used in farming business to measure the economic effect of minor changes or adjustments in production process (Soliman *et al.*, 2010). This tool is also used as a planning and decision-making framework to compare the costs and returns of alternative plans faced by a business management (Roth and Hyde, 2002). The principle of this method is that any modification in input, output, techniques or any component of the production process will result in reduction in cost or revenues while adding others at the same time. The finality is to compare changes in revenues and costs through the calculation of the Net Benefit (NB) representing the net economic effect of change.

Trumble and Morse (1993) used the partial budget analysis to compare biological control, three pesticide-based controls as well as the combination of the controls (bio-control and pesticide-base control) in the protection of strawberry production against the twospotted spider mite. Harvest value was calculated for the control (production untreated or without any control measure) ($Y_{CT}$), for the bio-control ($Y_{BC}$) and for each of the pesticide-base controls and combinations ($Y_{PC}$ and $Y_{PC+BC}$), representing harvest quantity multiplied by strawberry price (Free On Board value). The costs of the various control measures were also calculated. The biological control option cost ($C_{BC}$) was the cost of releasing the bio-agent estimated per hectare whereas the cost of the chemical control options costs ($C_{PC}$) were composed of the ground application cost and the commercial costs of the pesticides. The Net Benefit for each control option was calculated by subtracting the harvest value of the strawberry from the untreated control from the harvest value from each option minus its cost of application, yielding $NB_{BC}= (Y_{BC} - C_{BC}) - Y_{CT}$ for the biological control measure; $NB_{PC}= (Y_{PC} - C_{PC}) - Y_{CT}$ for the pesticide-base control measure and $NB_{PC+BC} = (Y_{PC+BC} - C_{PC+BC}) - Y_{CT}$ for the combination of the chemical and bio-control options.

Partial budget was also indicated as a tool of economic assessment in pest risk analysis (Soliman et al. 2010). The reference situation without pest is compared to the alternate situation with the assumption of pest invasion. When assuming the additional cost (A) as the costs under the alternate situation that are not required under the reference situation and the reduced revenues (B) as revenues under reference situation that will not be received under the alternate situation, the total costs is then A+B and represent the negative effects. When assuming the additional revenues (C) as the revenues under the alternate situation that are not received under the reference situation and the reduced costs (D) as the costs under the reference situation that will be avoided under the alternate situation, the total benefits (C+D) represents the positive economic effects. The net variation in profit ((C+D)-(A+B)) representing the net economic effect of the invasion.

Pemsl (2005) introduced stochasticity in partial budget modeling in assessing the economic performance of crop protection strategies at farm level to account for the stochastic nature of various parameters and compare alternative strategies and possible various scenarios. The author highlighted and integrated the existence of uncertainty concerning the fluctuation in yield, pest pressure which can vary with the climate conditions, input cost and output price and the effectiveness of applied control strategy. The established partial model which accounts for the future value of costs discounted to the equivalent costs at the time of harvest is given in the equation 2-1 below.

$$NB_j = \left(\sum_t AYL_{jt}\right) * p_Y - C_{jt} * (1 + r)^{(T+1)-t} \quad ( 2\text{-}1)$$

Where $NB_j$ is the net revenue for the strategy $j$, $AYL_j$ total avoided yield loss for different point in time t ($AYL_j = \sum_i Y_i * \left(1 - L_i * \left(1 - E_{ji}\right)\right) - Y_i * (1 - L_i)$), $Y_i$ the potential yield under a given control strategy, $L_i$ the pest pressure, $E_{ji}$ the effectiveness of pest control of the strategy $j$, $p_Y$ output price, $C_{jt}$ the control cost, $T$ time span for crop season and $r$ discount rate reflecting the farmers' opportunity of capital. Accounting for uncertainty in variables, implies generating stochastic parameters using the Monte Carlo simulations and computing the probability density function (PDF) and the cumulative distribution functions (CDF or F(NR)) of the net revenue (NR). These functions allow comparing different strategies based on the criteria of first-degree stochastic dominance (FSD) and the second-degree stochastic dominance (SSD) depending on the relation of the decision-maker to risk-aversion. The FSD stipulates that all NR of control strategy1 are lower than or equal to those of the different strategy2 ( $F_1(NR) \leq F_2(NR)$) and decision makers would prefer the strategy that is first-degree stochastic dominant. Based on SSD criterion, control strategy 1 will be preferred to control strategy 2 if the area under $F_1$is less than that under $F_2$ or :

$$F_1 = \int_{-\infty}^{NR} F_1(NR)dNR \ \leq F_2 = \int_{-\infty}^{NR} F_2(NR)dNR \quad (2\text{-}2)$$

#### 2.3.1.2 Bio-economic models in risk and impact assessment

Bioeconomic modeling implies combining economic and biological or epidemiological information to assess the effects of a change on a particular system (Dovorshak and Neeley, 2012). In an operational point of view, a bio-economic model can be defined as a comprehensive set of functional relationships between biological and economic variables, designed to represent a system in mathematical terms (Accadia, 2006). Compared to many other economic methods, it is a more interdisciplinary approach to tackle research problem as it seeks to closely integrate important biophysical information and ecological process with economic decision behavior with the expectation of providing more sound and useful policy recommendation on how interventions can result in response (Dovorshak and Neeley, 2004, Pemsl 2005). The importance of integrating bio-economical models which have enough detail in both biological and economical for sound impact assessment is demonstrated in Garcia *et al.* (2012). Holden *et al.* (2005) argued that bioeconomic models are useful tools for interdisciplinary analysis, since they allow integration of biophysical and socio-economic dimensions of the problem in a consistent manner. The subsequent integration of the "with" and "without" policy appears useful to predict impact of technology, policy or project and to perform sensitivity analyses to assess the robustness of uncertain assumptions.

Garcia *et al.* (2012) categorized bioeconomic models into two groups: simulations (what if?) and optimizations (what's best?). The purposes of the optimization models are to identify the optimal solution to objective function (for example maximizing utility or profit or minimizing risk, etc) under some defined constraints. Bio-economical simulation models seek to mimic a system by projecting a set of biological and economic variables.

When coming to pest management, Pemsl (2005) argued that bioeconomic models are key to depict the high degree of interaction between the ecosystem and control intervention. Pest management systems and production environment in general are subjected to number of elements such as resistance build up, the long term negative externalities and uncertainty concerning yield, pest pressure and market aspects. Integrating all these aspects through the combination of biological and economic models helps in capturing dynamics that cannot be provided with only purely economic modeling.

In recent applications of bioeconomic modeling in biological control, Martin and More (2010) proposed a general stochastic control framework to design the optimal policy of management strategies that integrate bio-agents and pesticide use to control the hemlock woolly adelgid pest in eastern region of the US. The biological component of the model was represented by the predator-prey population dynamics and expressed as:

$$dX_t = \left[\alpha\left(1 - {}^{X_t}/_{K}\right) X_t - \beta P_t X_t\right] dt + \sigma_X X_t dW_t^X \quad (2\text{-}3)$$

and

$$dP_t = \mu\left(1 - {}^{\in P_t}/_{K}\right) P_t dt \ + \sigma_P P_t dW_t^P \quad (2\text{-}4)$$

where $X_t$ the prey population at time t, $P_t$is the predator (bio-agent) population, K is a constant. In addition, the damage functions ( $(X_t) = F{X_t}^2$ and the economic components including the cost of applying pesticide ($\gamma(X_t) = \gamma/X_t$) and the marginal cost function for biological control ($\pi(P_t) = \pi$). The results from the combination of this different equations allow demonstrating the long-term positive impact from combining chemical and bio-control and that the implementation of bio-control was sufficient to manage the infestation.

Zhang and Swinton (2012) measured the profitability impact using a bioeconomic optimization model with and without accounting for the presence of natural enemies in soybean aphid management. The authors derived the optimal management strategy from an improved version of the Economic Threshold (ET) integrating natural enemies called the natural enemy-adjusted economic threshold – (NEET) that they compared to the one from the static economic threshold model without the presence of bio-agents. The value of the bio-control which represents a natural ecosystem service was further evaluated and estimated at $84 million in 2005 in four states of the USA.

Skevas *et al.* (2014) examined how biomass supply changes when accounting for the use of the bio-control service. A base model of biomass production was first considered and was extended by adding insecticide use cost which was adjusted with agricultural bio-control use component, giving the mathematical expression of overall bio-economic model as follows:

$$Max_{x_{ij}} \sum_{i=1}^{n} \sum_{j=1}^{m} \Big[-c_j x_{ij} - \sum_{l=1}^{3} r_l o_{lj}\, x_{ij} - (\overline{w}_j / \left(1 - BCI_{T_{ij}}\right)) * x_{ij} + \sum_{s=1}^{15} p_s (1 - \varphi_s)(\rho_s x_{ij} - \delta_s {x_{ij}}^2)\Big] - \sum_{h=1}^{9} TC_h^t \qquad (2\text{-}5)$$

Where the terms $c_j x_{ij}$, $r_l o_{lj} x_{ij}$ , $p_s(1 - \varphi_s)\left(\rho_s x_{ij} - \delta_s {x_{ij}}^2\right)$ , $TC_h^t$ and $\overline{w}_j / \left(1 - BCI_{T_{ij}}\right) * x_{ij}$ were the variables cost of production, mineral fertilizer cost, crop product quantity, transportation cost and adjusted insecticide use cost with biological control respectively. This objective function was maximized under various constraints including land resource constraints, permitted environmental output levels and transport constraints. The results of the analysis showed that integrating biological control in production system leads to higher supply of biomass from crop residues at a lower relative price.

#### 2.3.1.3 Benefit-Cost Analysis

Benefit-cost or cost-benefit (BCA or CBA) analysis is an evaluation technique that weighs the monetary value of economic benefits of an investment in a program against its costs to determine if it was (or, in the case of ex-ante analysis, is expected to be) economically worthwhile (Ruerg and Jordan, 2011). With reference to biological control, Morin *et al.* (2009) define the BCA as a measure of the expected or actual return on investment from a biological control program, which is expressed as a benefit–cost ratio or as a net present value. The return on investment is computed through three quantitative performance indicators which comprise the net present value, the benefit-cost ratio and the internal rate of return. The net present value is defined as a net value indicating how much cash value the program adds to the value of the existing system. The benefit–cost ratio of the biological control is derived by dividing the value of the losses avoided through the implementation of the biological control (benefits) by the research and development costs of the program. Both benefit and cost values are discounted at a specified rate to account for differences in the time when they were incurred (Morin *et al.*, 2009).

However, a comprehensive assessment can only be made on the basis of complete information and this requires a sound measurement of the costs and benefits (Eijgenraam *et al.*, 2000). For Florio *et al.* (2016), the fundamentals of the cost-benefit can be summarized in four points: i) shadow prices to capture costs and benefits beyond the market or other observable values; ii) a counterfactual scenario to ensure that all costs and benefits are estimated in incremental terms relative to a 'without program' world; iii) discounting to convert any past and future value in their present equivalent; and iv) a consistent framework to identify benefits by looking at the different categories of agents who directly or indirectly benefit or lose from the program.

Estimating the cost component when conducting a biological control BCA is the easiest to be done as the cost is simply the sums of the costs of different activities including base line research, foreign exploration, shipping, quarantine processing, mass rearing, field releases and post release evaluation (Gutierrez, 1999). Cost can also be measured in term of scientist years (SY) representing the administrative and technical support costs for one scientist for one year (Harris, 1979). The product of the total number of SY used in the program implementation by the unit cost of SY will yield the costs of the program. Debach (1974) argued that the biological program costs can be either inexpensive or costly, depending on the complexity encountered during the program implementation. Success might be consecutive to multiple failures and total program should include cost of failures as failures have generated useful knowledge for final success of the program. Some externalities' costs such as environmental costs derived from suppression or eradication of a non-target native species should be accounted for provided that it can be given a monetary value (Turner, 1985).

Biological control benefits computation is the most difficult as it requires transforming complex multidimensional factors and ecological effects into readily comprehensive economic effects or in monetary value. Various methodologies are used in literature of the biological control impact evaluations. Tisdell (1990) summarized the conventional ones in his review on economic impact of biological control. These include :

- *Crude indicators*: this involves crude measures of impact of the bio-control qualified to be better than no measures at all. This includes simple measures such as reduction in target pest population density, increases in yield or production of the affected crop and increase in total crop revenue or receipts.
- *Cost saving as measure of economic benefit*: this is an economic benefits measure that is equal to the sum of the value of the saved proportion of losses in production due to pest and the value of any savings over alternative pest controls which may include pesticide use, mechanical control or cultural control.
- *Profit increase or variations*: the measure method is considered for short term and stipulates that the benefits of biological control is reflected in the variations of profits received by the farmers when the price of the product does not vary with the volume of production. The entire economic benefit from the bio-control implementation is therefore captured by farmers.
- *Variations in land values*: the successful implementation of the biological control in protecting crop can translate into more production and in higher returns from agricultural land and so can the rent paid for land use. The total increase in value can be an accurate indicator of economic benefits and this can be assimilated to the capitalized value of the extra profits from the land as result of the bio-control program. However, variations in land value might not capture all the benefits due to the biological control. To be integral, in addition to the land value, benefit estimates should integrate the

savings from alternative control or any additional profits available and take into account variations in value due to land speculation and other influencing factors of the land value.

- *Variations in producers'surplus and consumers'surplus:* considering the increase in producers' profits or land value variations alone may lead to underestimating the benefit from biological control or any new production technology. The decline in crop price as consequence of a greater supply (as result of the pest control and higher production) impacts consumers who get non- negligible benefit from the technology. The total economic benefit of the biological control equals then the sum of the values of the changes in producer and consumer surplus (Tisdell, 1990; Culliney, 2005).

Assessing the impact of the biological control program through BCA often imply deriving a stream of all annuals costs and benefits associated with the effects of investment on a determined period horizon. Avoiding price-effect or confounding effects of inflation leads to consider costs and benefits values at their constant monetary unit (Culliney, 2005). The consumer price index (CPI) plays a key role as adjustment factor for this concern (Masters et al., 1996). In addition, discounting factor is used to convert the stream of the net benefits over a period of time to a present value. Discounting reflects the tendency of immediate benefits to be more highly valued than differed benefits (Culliney, 2005).

#### 2.3.1.4 Economic Injury level and Economic threshold level

When defining biological control, many authors refer to some thresholds under which pest population densities have to stabilize to (Gutierez *et al.*, 2013; Huffaker, 2012). The objective of biological control like most other types of control is not to eradicate the pest but reducing their population to an acceptable density with insignificant, minor or non-economically important damage (Pedigo *et al.*, 1986). These limits are the Economic Injury level (EIL) and the Economic Threshold (ET). The EIL stands for the pest population density from which damage engendered by pest starts being economically important. At this point, the cost of pest management strategy exactly offsets the benefits from the management (Riley, 2008). Below this pest density represented by the EIL, the control costs exceed the benefits and taking pest control actions become economically irrelevant. Conversely, economic damage can occur when control actions are not taken until the pest population surpasses the EIL (Mahr et al., 2001). The ET also called Action Threshold (AT) is more of action concern and represents typically the pest population density at which a pest control action should be taken in order to prevent an increasing pest population from reaching economically damaging levels, which is the EIL (Mahr *et al*., 2001).

Stern *et al.* (1959) and Pedigo *et al.* (1986) provided the basic model to determine the EIL as $EIL = C/VIDK$ where $C$ is the cost of the pest management per production, $V$ is the market value of crop, $I$ injury per pest density, $D$ lost per unit of injury and $K$ the efficacy of the control or the proportional reduction in injury with management. Further improvements of this model are provided in Riley (2008) taking into account the temporal and dynamic nature of the pests. For example, seasonal difference should lead to calculate separately for earlier season and late season. The EIL formula was also adjusted to the environmental cost ($EC$) to take into account for the cost to the agro-ecosystem where the exploitation is located ($EIL_E = (C + EC)/VIDK$).

Riley (2008) distinguished between stochastic and deterministic thresholds. The latter assumes a fixed and unique outcome while the former incorporates probabilities based on population dynamics. The author argued that the stochastic model of ET best suits for the biological control or other long-term pest management strategies as estimating the bio-control response necessitates the life table for pest and prey species related to temperature, time and spatial dynamics.

In order to account for multi-pest, multi-stress and dynamically changing production, Mi et al (1998) brought some improvements to the conventional insect-specific EIL by introducing a plant-based economic injury level. In addition to the traditionally considered parameters in EIL, the developed EIL incorporated the plant tolerance for easy insect damage, and the growth characteristics of the plant (shed and nodal development). The combination of the insect characteristic, plant phenology and economic parameters allow to define a threshold called the break-even shade rate at first flower which represent the point when plant injury becomes economic damage.

Brown (1997) provided a framework that models the biological control into the ET. This author developed the biological gain threshold (BGT) that entails the difference in economic thresholds with and without biological control which is expressed as:

$$BGT = ET_{BC} - ET_0 = (\sum_{i=1}^{n} a_i B_{i,t})/(1 + r) \qquad (2\text{-}6)$$

For uncouple case and

$$BGT = ET_0(\sum_{i=1}^{k} \alpha_i B_{i,t})/((1 + r) - \sum_{i=1}^{k} \alpha_i B_{i,t}) \qquad (2\text{-}7)$$

For coupled case. $B_{i,t}$ is the biological control agent population, $r$ is the fixed growth rate of the controlled pests $a$ is the rate at which the biological control agent reduces the pest population and $\alpha$ is the pest consumed. These threshold models can be used to determine whether or not bio-agents impact economic thresholds sufficiently to warrant the additional expense of sampling the natural enemies in pest management program. These models discount the pest population growth rate and this results in higher ET and restricted difference between ET and EIL (Naranjo *et al.*, 2015). This also presents the advantages of avoiding cost through delay pesticide sprays, reducing uncertainty and reducing risks of wrong decision-making (Naranjo *et al.*, 2015). EIL and ET can then be seen as important references in judging the usefulness and success of biological control.

#### 2.3.1.5 Production functions efficiency measures in biological control

In economics, production function is defined as a production process that relates physical output to physical inputs, productive resources or factors of production. In practice, production function is established through a mathematical function ($q = f(x)$) that gives the maximum amount of output $q$ that can be obtained from a given set and amount of inputs $x$ (Rasmussen, 2012). Coelli *et al.* (2005) emphasized on some key properties of the mathematical relationship for getting an economically interpretable production function in concordance with economic theory. First is the property of non-negativity which stipulates that $f(x)$is a finite, real and non-negative number. The weak essentiality property states that the production of positive output is possible only with at least one input. The monotonicity property or non-decreasing in input stipulates that there is no possibility of decrease in output with increase in input. This means when considering two quantities of input $x$ in such a way that $x^0 \leq x^1$ , this results in the following relationship in outcomes$f(x^0) \leq f(x^1)$. The property of concavity in x describes that the outcome of a linear combination of inputs will be no less than the same linear combination of the outcomes of the individual input ( $(x^0)$ and $f(x^1)$ or $(f(\emptyset x^0 + (1-\emptyset)x^1) \geq \emptyset f(x^0) + (1-\emptyset)f(x^1))$.

Many useful quantities of interest are derived from the production function and include the Marginal Physical Product (MPP), the Average Physical Productivity (APP), the Marginal Rate of Technical Substitution (MRTS), the Output Elasticity OE, the Direct Elasticity of Substitution (DES), the Allen Partial Rate of Substitution (APRS) and the Morishima Elasticity of substitution (MES) (Chambers, 1988). One of the most frequently used in productivity analysis is the marginal physical product which measures the output response when one input is varied and all other inputs held fixed (Coelli *et al.*, 2005). This quantity is obtained by partially differentiating the production function with respect to the target input ($MPP_x = \partial f(x)/\partial x$). It helps to determine how each input affects the overall outcome and how important each input is in the production process. According to OECD (2001), the purposes of productivity measurement are multiple and include tracing technical change, identifying change in efficiency, identifying real cost saving in production, benchmarking production processes and assessing standards of living.

The marginal physical product is also useful in efficiency analysis of input or resource use based on the comparison of the value of the $MPP_x$ (or $VMP_x$) with the Marginal Factor Cost ($MFC_x$) (McIntosh *et al.*, 2013). The $MFC_x$ approximates market input price when assuming that farmers are prices takers in input market. When $VMP_x > MFC_x$, the input $x$ is underused and farmer earnings from farm can be raised by increasing the use of the input or there is still scope of increasing the efficiency level of the farm. $VMP_x < MFC_x$ implies that the input is overused and increasing farm revenue or efficiency level will require a reduction in this input. In consequence, efficiency in productive resource allocation (maximum profit or minimum cost) is achieved when $VMP_x = MFC_x$ .

### 2.3.2 Empirical studies on economic impact of Biological Control

Using cost-benefit analysis in evaluating the economic value of releasing *C. flavipes* to control *C. partellus* in maize production in East and Southern Africa, Kipkoech *et al.* (2009) found a positive impact for this pest control program. The yield loss abatement varies from 5.1% to 25.7%, the total annual benefits of the biological control program ranged from 43 to 76 million

USD showing the existence of the potential of using biological agents to improve yields among the poor households who can seldom afford purchased inputs.

Van Wilgen and De Lange (2011) examined the impact of the biological control of invasive alien plants in South Africa in a holistic economic evaluation perspective. After considering the major invasive alien plants and their impact on water resources, grazing and biodiversity, they determined the controlled area by diverse existing control strategies and deducted the potential value of ecosystem services protected by weed biological control as a proportion of the value from all types of control. They found an estimated additional ZAR 41.7 billion (USD 3.51 billion) had no control been carried out, and 5 - 75% of this protection was due to biological control and the resulting benefit: cost ratios ranged from 50:1 to 3726:1 suggesting that biological control has brought about a considerable level of protection of ecosystem services.

Macharia *et al.* (2005) used economic surplus model approach to assess the potential economic impact of controlling the diamondback moth, a cabbage pest (*Plutella xylostella)* with the exotic parasitoid *Diadegma semiclausum* on cabbage production in Kenya. The authors estimated the yield loss due to the pest prior to the economic benefits calculation. Yield loss assessed through measurements from farmer-managed fields gave 31% whereas that from farmers' direct interviews was 36%. Based on the field-measured loss of 31 %, yield loss was estimated at 6.8 tons per hectare or USD 452.9 per hectare, and at USD 7.9 million per year for the whole country, showing the extent of the seriousness of the loss experienced with the occurrence of the pest. With assumptions on the crop loss abatement (30%) and reduction on use of pesticide (50%), the economic surplus generated by the release of the parasitoid accrued to USD 28.3 million for 25-year period. Consumers were estimated to get the largest share (58%) of this benefit compared to producers (42%). Impact results showed a net present value of USS 1.2 million. The benefit-cost ratio was estimated at 24:1 with an internal rate of return of 86%, indicating a high future return to the investment in the bio-control project.

Norgaard (1988) evaluated the economic impact of the biological control of the cassava mealybug, *Phenacoccus manihoti*, which was inadvertently introduced from South America in the early 1970s, and spread in sub-Saharan Africa representing a critical challenge for production. Loss as high as 80% in yield and rising in price of cassava-made product were reported in many countries. The aim of keeping in check the pest and reduce its effect on cassava productivity led IITA researchers to introduce its natural enemy (*Anagyrus lopezi*) in many countries. The author used a benefit-cost approach with conservative assumptions on parameters such as diminishing impacts of the bio-agent considering the maximum loss at 20% without the bio-control intervention and a yearly 1% reduction till the last year of evaluation. For the percentage yield loss saved, the maximum was assumed to be 60% as the parasite becomes established and to decline to zero towards the end of the analysis period. Results from the study demonstrated a high profitability of the bio-control project with a benefit-cost ratio of 149:1. These economic advantages were however judged as of low bound estimates by the author because of the conservative assumptions on parameters based on the "reasonable, least-favorable" scenario. The potential benefits from the ecological and health preservation and the benefits to other cassava producing countries would have increased the economic returns on the program implementation.

Zeddies *et al.* (2001) later conducted economic evaluation of the same project over 40 years (1974–2013) for 27 African countries. Country-level data collected included annual area and cassava production and their distribution across ecological zones, proportion of cassava area under bio-control and intrinsic damage coefficients of the pest. The analysis was done through four scenarios involving the additional quantity of cassava to be produced or to be imported to compensate for losses loss by the pest and the additional quantity of substitute to cassava (i.e maize) to be locally produced or imported to compensated for losses including transport and market conditions. Findings indicate benefit-cost ratios ranging from 94:1 (under very pessimistic assumptions) to 800:1 (under optimistic assumptions), showing the substantial net gain attributable to the bio-control project against cassava mealybug.

Bokonon-Ganta *et al.* (2002) assessed the socio-economic impact of the biological control of mango mealybug (*Rastrococcus invadens*) which was first observed in Benin in 1986. This pest was accidentally introduced to West Africa from Southeast Asia and was causing serious damage to various fruit trees, especially mango, in Bénin, Ghana, and Togo. Natural enemies of the pest (*Gyranusoidea tebygi* and *Anagyrus mangicola*) were imported from India and released at different times from 1988 to 1993. As approach of evaluation the author adopted the comparison of data on mango yields and prices, before and after the establishment of natural enemies' use. Average economic gains by mango farmers by province were derived and extrapolated to the whole of country. Findings from the study showed that releasing bio-agents for controlling mango mealybug has resulted in significant impact as each mango farmer gained US$328 per year and extrapolation to all the country gave an annual gain of US$50 million. The present value of these benefits over a period of 20 years accrued to a high value of US$531 million compared to a present value of program cost of US$3.66 million. The benefit-cost ratio was then estimated at 145:1, which demonstrated the success of the project.

De Groote *et al.* (2003) carried out an economic impact assessment of the biological control of water hyacinth in Benin. This plant appreciated for its ornamental characteristics (Attractive purple colored flowers) elsewhere in the world, has become an invasive weed because of its extremely fast-growing capacity, hindering fishing, fluvial transport and water exploitation. Following the inefficacy of the existing control measures including mechanical and chemical controls, the biological control was implemented through the release of a combination of three host-specific natural enemies comprising two weevils (*Neochetina eichhorniae* and *Neochetina bruchi*) and one moth (*Sameodes albiguttalis*) during the period of 1991 to 1993. Data were collected on views, attitudes and income of the people living in the affected areas through household survey on the periods before the arrival of water hyacinth, during peak infestation, and after peak infestation. The impact of the biological control of water hyacinth was derived as the difference in household income during and after peak infestation. Results indicated that water hyacinth had affected agriculture, fishing, trading and had lessened household income as and the corresponding estimated economic loss averages US$2151 per household. On the other hand, the biological control impact was estimated to amount to US$783 per household. The benefit-cost analysis assuming the same benefit of the bio-control for all the years indicated a total higher present value at a 10% discount rate of US$260 million compared to a present cost of the program of US$2.09 million, giving a benefit-cost ratio 124:1.

Asfaw *et al.* (2011) carried out an ex-post impact of the biological control of the diamond back moth (*Pluttela xylostella*) with the BC agent (*Diadegma semiclausum*) on cabbage production in Kenya and Tanzania. Specific attention was given to the role of yield loss reduction of the BC agent and the study used the production function with damage control function to correct the traditionally used production function without differentiating inputs. The study found that the presence of the BC agent leads to the decrease in pesticides expenditure and indicated that either using pesticide or the presence of the BC agent has a positive impact on cabbage output.

Chavez *et al.* (2012) carried out the yield impact of the pest biocontrol in apple production using the microbial inoculants bio-agents as alternative to insecticide use in USA. This case study considered the biological control strategy using a multiple bio-agents including Granulovirus, *Bacillus thuringensis, Bacillus subtilis, Bacillus pumilus* and *Thricoderma sp* to control apple against varieties of pests and diseases such as Codling moth *(Cydia pomonella),* Apple pandemis, Leafrollers, Western tussock moth, Velvetbean caterpillar, Green fruitworm, Fire Blight, Botrytis, Sour Rot, Rust, Sclerotinia, Powdery Mildew, Bacterial Spot and White Mold. Data was collected from 547 farms, where197 farms had one or more BC-agents for the BC strategy. The study noted that the use of pesticides was not totally discarded because of the existence of some pests that the bio-agents could not control and then the bio-control plays a complement role rather than a substitute one. The study confirmed this by performing the analysis of the technology's effect over the pesticide use. The OLS estimation of a Cobb-Douglas type functional form of pesticide use model was estimated and yielded positive but not significant relationship between biological control and pesticide use, meaning that biological control strategy is not acting as substitute of insecticide usage in his case study. To assess the impact of the BC, three types of production functions was used: the standard Cobb-Douglas production function considering the MI as standard factor, production function including logistic damage abatement function considering the MI bio-agent as damage-abating factor and the Cobb-Douglas stochastic production frontier. Findings displayed that MI or bio-control adopters benefit significantly from higher yields compared to those not using it.

McConnarchie *et al.* (2003) conducted the economic evaluation of biological control of the red waterfern (*Azolla filiculoides*), a South-America native invasive aquatic plant that was causing important economic losses in farming and recreational activities in South Africa. The natural enemy of the pest, the frond-feeding weevil (*Stenopelmus rufinasus*) was then released since 1997 as part of biological control program against the pest. To use the benefit-cost approach, data was first collected from water users on the direct costs from the invasion including stock losses, costs of replacing irrigation pumps, of setting alternative water supplies, recreational activities losses. These costs accounted for the benefits or the avoidable costs through the implementation of biological control program which amounted to US$450 per hectare. The cost of the program (US$276 per hectare) was far lower than that the mechanical and chemical control, highlighting the more cost-effectiveness of the biological control compared to the two types of control method. Comparing benefit and cost, these authors found a highly significant savings from the program as the Net Present Value (NPV) was US$1093 per hectare and an absolute amount of US$206 million for all South Africa from 1995 onwards. The time-increasing Benefit-Cost Ratio demonstrated that the value of economic losses that could have been avoided would have risen substantially over time without the biological control intervention.

Using benefit-cost analysis, Basse *et al.* (2015) provided an impact assessment of biological control of the clover root weevil (*Sitona obsoletus*), an important pasture pest which feed on plant root and reduces its cover and soil nitrogen fixation in New Zeeland. The pest was first discovered in the country in 1996 and was causing serious damage to pasture leading to more expenses in inputs such as supplying synthetic nitrogen, growing additional forage and increasing supplementary feed for livestock. The natural enemy of the pest (the parasitoid wasp *Microctonus aethiopoides*) was released in 2007, got established and reduced the pest population by more than 70%. The economic impact was estimated predominantly on dairy sheep and beef farms by comparing costs and benefits of releasing the bio-agents, based on data from experts'opinions and available studies. The net benefits were made of the savings due to biological control on dairy farms, sheep farms and beef farms. These include the costs of application of synthetic nitrogen (as urea) at level required to maintain normal production, the costs of increased use of supplementary feed and the cost of cultivating additional non-susceptible forage. After accounting for the cost of implementing the biological control, results for Southland show that biological control returned $14.78 per hectare per year or $2.3 million over 158,017 ha for dairy farms and $6.86 per hectare per year or $4.7 million over 719,854 hectares for sheep and beef farms. Sensitivity analysis using Monte Carlo simulations showed that returns were positive in at least 97.5% of simulations.

Nordblom *et al.* (2001) carried out the economic benefit of the biological control of some dominant species of pasture weeds (Echium, spp) of Mediterranean origin in Australia. The weeds represent a threat to meat and wool industries as susceptible of causing livestock to reduce weight gain and wool clip and in severe cases mortality. Of the several natural enemies' species found after exploration, only the crown and roots weevil (*Mongulones larvatus*) was successfully released and spread and showed ability to limit the weeds growth. Assuming a logistic function of the bio-agent attack rates and the geographic spread of the insect, the authors estimated and the stream of benefits derived from the program. As results, annual benefits in terms of increased productivity of grazing lands are projected to rise from near-zero in 2000 to some $73 million by 2015. The comparison to the cost incurred in the program demonstrated the positive impact of the biological control as the discounted (5%) net present value (NPV) of the benefit-cost stream from 1972 to 2015 is projected at $259 million, for a B/C ratio of 14:1 and an internal rate of return exceeding 17%. The discounted NPV for the 1972-2050 period is estimated to be $916 million, with a B/C ratio of 47:1 and an internal rate of return exceeding 19%.

Myrick *et al.* (2014) quantified the economic benefit associated to the classical biological control of the invasive papaya mealybug pest *Paracocus marginatus* in India with three imported parasitoids from Puerto Rico including *Acerophagus papaya*, *Pseudleptomastix Mexicana* and *Anagyrus loecki*. The authors conducted the study on papaya, mulberry, cassava tomato and eggs plant representing the five most important crops attacked by the papaya mealybug. Using data on these crops prices, productions, yield loss reductions, cost production and assumptions on their adoption rate, the change in total surplus analysis was applied. Findings showed that annual benefits for the biologically-based protection of these five crops range from $121 million to $ 309 millions. The authors concluded on the economic significance of biocontrol as program that help Indian farmers and consumers in saving huge amount and put emphasis on the high value of international research cooperation in dealing with exotic papaya pest.

Waterhouse and Vincent (1998) assessed the economic benefits from biological control of banana skipper (*Erionota thrax*) in Papua New Guinea and Australia. Banana skipper was an exotic invasive pest first observed in north-western Papua New Guinea in 1983 and which covered the mainland next 6 years at the rate of up to 500 km/year, causing economically important damage to banana known as an important staple food in the country. Motivated by the successful implementation of the biological control against the pest in neighboring countries, the natural enemy of the pest, the larval parastoid *Cotesia erionotae* was released in subsequent years, established and spread, leading to plant damage reduction from 60% to 5%. Benefit cost analysis was adopted comparing the cost incurred in the project during its implementation from 1988 to 1990 with the stream of financial benefits till 2020 horizon. Costs were made of project outlays, research and release expenses while benefits the steam of the annual value of banana production saved by the control agent. Benefits and costs were discounted at the rate of 5% per annum over the period of the assessment. The results of the study displayed that the successful implementation of the biological control project led to a significant economic impact on banana production sector as the present value of accrued benefits equals $424.7 million ($201.6 million to Papua New Guinea and $223.1 million to Australia) over a period of 20 years. Present cost was estimated at $0.70 million, which result in an internal rate of return of 190% and a benefit–cost ratio of 607:1.

Bauer *et al.* (2003) conducted further analysis on the impact on poverty reduction of the same biological control intervention in PNG where poverty problem was critical as 30% of the population have their income below the poverty line. The poverty line was defined as the income that enables to meet the minimal need of 2200 calories per day of food consumption and cover the cost of essential non-food items. The impact evaluation was conducted by researching improvement in banana growers' income, provision of benefits through reduced prices for rural and urban consumers and reduction in the impact of unforeseen events. The major assumptions considered by the author were from the previous benefit-cost study by Whaterhouse and Vincent (1998). Findings indicated that the biological control of *E. thrax* has significantly impacted both growers and consumers by improving the supply of bananas and lowering the price of bananas. Specifically, for subsistence growers identified as major beneficiaries, the bio-control allows generating a 0.9% and a 2.2% increase in households' annual consumption depending on the assumptions. These increases were associated to the shifting of 6000 and 15000 people above the poverty line respectively, confirming the reduction of poverty among banana growers in PNG. Urban consumers also benefited from lower urban banana prices obtained with the rise in banana supply. The assumed reduction of around 15% of market price as the consequence of introducing a bio-agent to control skipper pest was found to allow around 28000 consumers to get out of the group of poor people.

Cooke *et al.* (2013) adopted the loss–expenditure frontier models with and without biocontrol scenarios, to assess the economic benefits of the biological control of the wild European rabbits (*Oryctolagus cuniculus)* designated as serious agricultural and environmental pest in Australia. As control strategy, two diseases virus were released over 60 years including the myxoma virus and the rabbit hemorrhagic disease virus. Economic tradeoff between production losses (economic costs of rabbits'damage associated to reduction in wool and livestock production) and invested amount in the rabbit control was established through exponential curves (with and without biological control). Findings from the superposition of the curves show that biological control of rabbits with the release of the deadly viruses produced a benefit of A$70 billion (2011 A$ terms) for agricultural industries over 60 years.

Doleaman (1989) examined the costs and benefits from biological control of an aquatic weed (*Salvinia molesta*) in Sri Lanka. This fern was causing important havoc because of its extremely rapid growth, interfering with drainage and irrigation in rice production, reducing fishing activities and engendering health risk as providing sound environment for mosquitoes' reproduction. As bio-control strategy, the natural enemy of the weed pest, the weevil *Cyrtobagous solvinioe*, was released from 1986 to 1989 in many area and resulted progressively in successful control. The authors determined the benefits from the bio-control program by examining the various categories of costs associated with the weed pest prior to biological control which included the paddy production losses, the fishing losses, other commercial losses (power generation, transport, washing and bathing), human health and environmental costs and the abatement costs. Findings revealed a positive impact of the biological program as the present value of weed pest control was A$16 million corresponding to a benefit-cost ratio of 53:1, this ratio becoming 1673:1 when taking into account the value of Sri Lankan labour.

### 2.3.3 Research gap

This literature review chapter gave an overview on the biological control concept and provided examples of its practical application worldwide before an in-depth description of the biological control of stemborers in Kenya which is the core concern of this socio-economic research. The chapter latter reviewed the various approaches to evaluating the economic impact of biological control interventions. These approaches include partial budgeting, production functions, bio-economic modeling in risks analysis, threshold level methods and benefit-cost analysis that dominates the existing studies.

The chapter reviewed empirical studies relating to economics of biological control conducted in and outside sub-Saharan Africa (SSA). This review revealed that majority of the studies focused on Benefit-Cost Analysis whereby estimated monetary benefit is compared to the cost of implementing projects. The total value of the increase in production is often subjected to assumptions that might lead to inconsistent estimates. The knowledge of accurate yield gain or productivity gain or yield loss reduction from biological control is a precondition for the best estimation of the benefit (Tisdell, 1990) and this have scarcely been approached. Moreover, ignoring productivity-effect analysis is to fail to consider that productivity or yield enhancing is the ultimate objective of the BC implementation. The study by Asfaw *et al.* (2011) was the unique at our knowledge that determines productivity from biological control using production function approach in cabbage production. This study however used the "with and without BC" approach ignoring that the BC level may varies across fields.

Poverty alleviation and food insecurity reduction are usually the aim of development interventions and it is easy to notice that the contribution of BC to these two important development goals was still undocumented. Some attempts are shown in Bauer *et al* .(2003) but this poverty estimates were based on determination of increase in income and this does not take into account the complexity among variables of production environment, households characteristics and self-sustaining nature of the biological control. Other potential factors that can also contribute to poverty and food security were not considered. Quantitative methods base on econometrics analysis that can help overcoming this gap and producing more accurate and robust estimates are needed.

This present study sought to add to the literature on economic impact of biological control by investigating on productivity-effect of the BC, establishing the causal effect relationship between the BC poverty and food security and determine the gain in welfare and its distribution among producers and consumers. The next chapter is the research method that will also present the theoretical frameworks and empirical models used in estimating the impact of the implemented biological control.

# CHAPTER THREE: RESEARCH METHODOLOGY

## 3.1 Introduction

This chapter presents the procedure of data collection and analysis methods that were used in the study. The chapter first provides a description of the study area and the BC agents release locations. This is followed by the sampling techniques and the methodology of data collection which consisted of mixed methods including literature review, use of geographic information system (GIS), secondary data, focus group discussions and households' survey. The theoretical framework and empirical procedures of the employed methods in analyzing the primary and secondary data were also presented.

## 3.2 Description of the study area

The study was conducted in Kenya where agriculture is the mainstay of the economy as this sector employs approximately 80% of the population and represents 70% of the earnings from the country's exports. Labor force is predominantly in rural areas (representing 82%) with the small-scale agriculture absorbing the largest share. The country has climate and ecological extremes, with altitude varying from sea level to over 5000 metres above sea level (m.a.s.l) in the highlands. The average annual rainfall ranges from less than 250 mm in the arid and semi-arid areas to 2000 mm in high potential areas. Based on the climatic conditions (mean annual rainfall and its distribution) and soils, Kenya has seven agro-ecological zones (Kabubo-Mariara and Karanja 2007). Regarding farming system, in Kenya, maize stands for the major food crop consumed by the largest share of the population as staple food. Maize occupies approximately 1.4 million hectares of cultivated area with limited possibilities for further expansion. Sorghum is another cereal crop which helps provide better food security in areas with limited rainfall;

there is a growing recognition that sorghum has great advantage in providing for food security. Sorghum is indigenous to Kenya and is becoming a suitable alternative in many places where maize fails (Mwadalu and Mwangi, 2013).

These two crops were facing the constraints of attacks from stemborers especially in the region of Eastern and Southern Africa (ESA) which was known as the major infested area in sub-Saharan Africa with the stemborers including *Chilo partelus, Busseola fusca, Sesamia calamistis and Chilo orichalcocileilus*. Biological control interventions, particularly the release of *C. flavipes* and *X. stemmator*, were initiated in the eight ESA countries (Kenya, Uganda, Tanzania mainland and Zanzibar, Ethiopia, Eritrea, Zambia, Mozambique and Malawi). The selected area for this survey was limited to Kenya. This country is representative of the region for its geographical locations and reflects the diversity of the region's agro-ecological zones.

## 3.3 Points of release

The parasitoid release zones are of high importance in this study as villages/communities were the entry point for the villages' sampling. The distribution of the release points in Kenya is highlighted in Figure 3-1. It shows that biological control agents have been released in 6 Regions and 11 Counties. The released species include *C. flavipes*, the first parasitoid released to control maize and sorghum stemborers from 1993 to 2000. *X. stemmator* was released in 2004 and 2005 whereas *T. isis* and *Cotesia sesamiae* were the most recent released parasitoids in 2007.

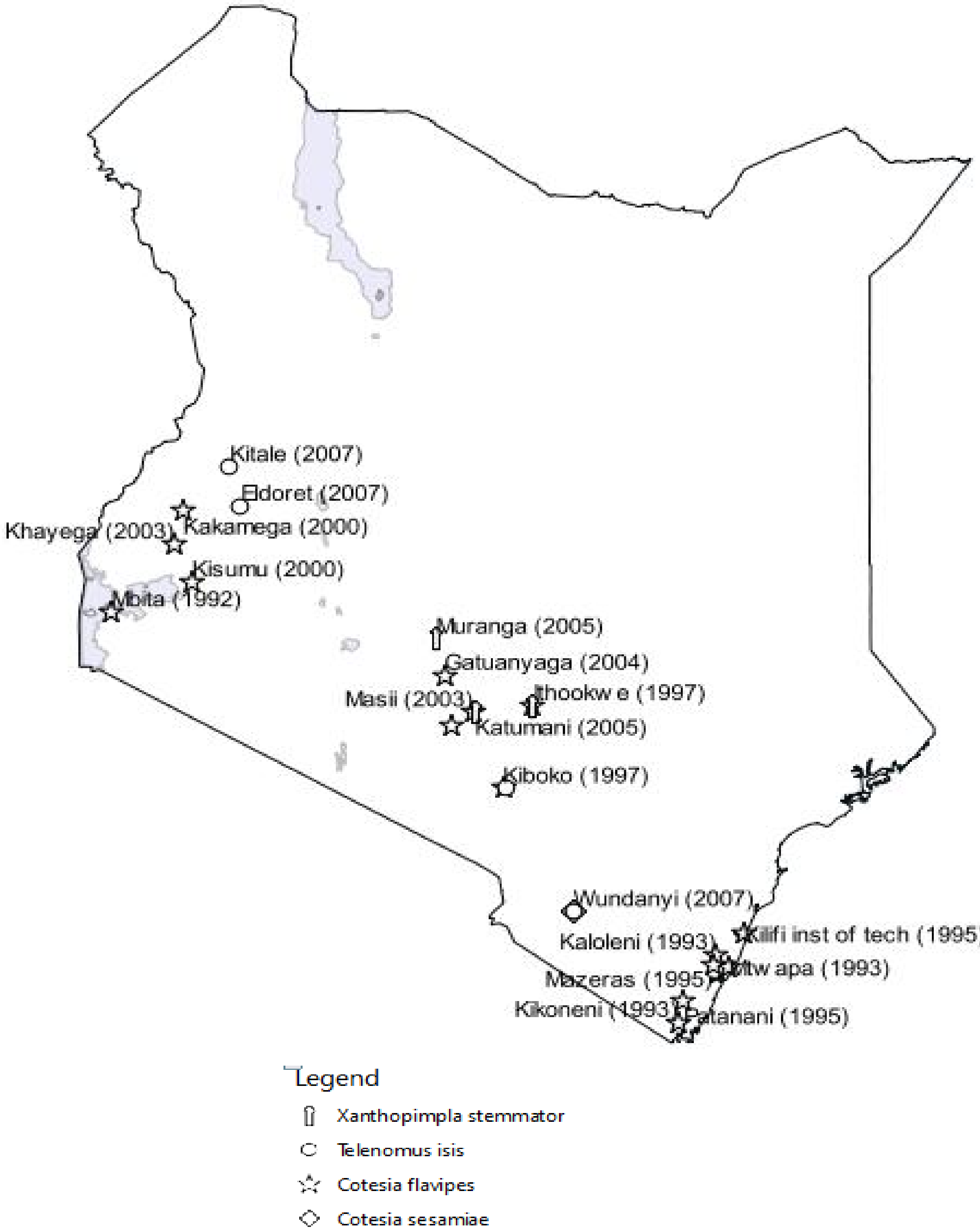


Figure 3-1: Release sites and released natural enemies in Kenya

Source: Author's design based on collected information

## 3.4 Entomology surveys: the prerequisite for economic method design

The Biological Control impact assessment is an interdisciplinary evaluation conducted by entomologists and economists' teams. Its development covers two interdependent thematic areas, entomology and socio-economic themes. The sampling methodology of this study was essentially based on that of the entomology team. The entomology team was assessing the establishment of biological control agents as well as the measurement of their spread/ dispersal from the release sites. To achieve these objectives, extensive and exclusion surveys were conducted.

The extensive survey revealed the status of the biological control agents with respect to their presence, extent of spread and success of their action. Survey fields were randomly selected at intervals of 15 km in the four cardinal compass points. Movement along transect from release point in the four cardinal points extended to 45 km. Field infestations were estimated and infested maize and sorghum stems were sampled and dissected. Collected eggs were monitored for eventual emergence of the released natural enemies released. Collected larvae were reared on artificial diet to adulthood for identification. The number and identity of resultant moths per plant were recorded and were used to estimate the percentage infestation per field and per area once the data was completed. The parasitism rate was also calculated and comparisons done for different areas. This survey by entomologists made available data on the presence of natural enemies and pests and important parameters for economic analyses comprising the parasitism rate (level of biological control activity), the pests 'density and the rate of plant infestation. This preliminary work then provided biological primary data which were the basis for undertaking the sampling and socioeconomic analyses.

## 3.5 Sampling description

The determination of sample followed the proportionate sampling approach as proposed in Groebner and Shannon (2005) and specified here as: $n_0 = z^2 * P(1-P)/e^2$, where $n_0$ is the sample size, z is the abscissa of the normal curve that cuts off an area (z is chosen here to be equal to 2.56), e is the acceptable sampling error chosen to be equal to 0.05 (Determined so as to keep the sampling error below 5% for most of the key variables). P is the estimated proportion of small scale households growing maize. Indeed, the target population of this study involved rural smallholders who grow maize and/or sorghum as part of the objective of the BC program implementation. The calculation considered two P values[3] found in the literature. 90% of rural households grow maize and the production is dominated by small scale who represent for 75% of the overall maize sector (Kanghete, 2011); therefore, small scale households account for approximately 67.5%. Under this value the computed sample size is 584. Another percentage of small scale farmers engaged in maize production of 65% (Munyua *et al.*2010), yielded a computed sample size of 605. The sample size was then harmonized at 600 households.

A geo-referenced map was used to project and group the surveyed villages from the sampling conducted by entomologists. In order to follow the gradient of parasitism, 10 transects which consisted of 4 villages (release point, 15 km, 30 km and 45 km) (summing up to 40 villages) were purposely selected to cover the regions and the different maize growing agro-ecological zones. The distribution of the sampled villages in the different regions and agro-ecological zones is presented on the Figure 3-2. At village level, 15 households were randomly selected from a list of maize households obtained during a focus group discussion. A total of 600 farm households in five regions, and nine counties were thus considered for the study.

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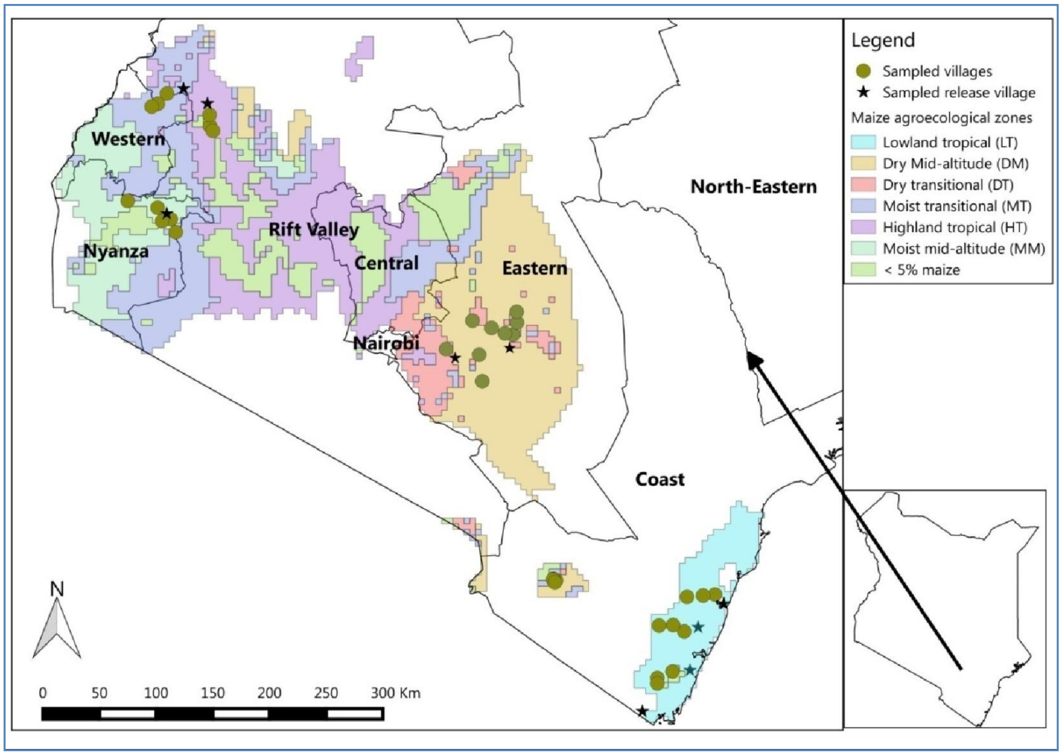



**Figure 3-2**: Distribution of sampled villages in the agro-ecological zones

Source: Author's design based on collected information

## 3.6 Data

In this study, data were sourced in four main ways: literature review, secondary data, case studies and the survey methods.

### 3.6.1 Literature review

Literature review was undertaken to provide comprehensive background information, up-date knowledge on BC and methods used in previous BC impact studies. This phase entails gathering and meticulously exploiting documents such as:

- BC project documents including monitoring and evaluation reports, the benchmark studies, BC agents release reports, scientific publications issued from the project.
- Available scientific writings on the biological control in other projects or countries
- Available scientific write-up on economic assessment of BC projects
- Monographs of the studied country and on maize and sorghum production, their supply, demand and price characteristics

The means used included the internet, journals websites, and visits to local institute of agricultural research (KALRO), Universities libraries and some key researchers involved in the BC project.

### 3.6.2 Secondary data and case studies

Secondary data was obtained from national bureau of statistics, agriculture ministry, national meteorological departments and some international institutes' websites (such as FAO, UNDP and World Bank). Time-series data on maize and sorghum production, area and yields as well as market-related data such as price evolution, were collected. Case studies on maize and sorghum demand and supply was also gathered and exploited. These gathered time-series data and market information were useful in the economic surplus analysis

### 3.6.3 Survey methods

#### 3.6.3.1 Focus group

Focus group discussions were undertaken to have a first overview on the constraints in maize and sorghum production, the place and importance of stemborers, the problematic of stemborers pressure and damages as well as the history of introduction and perceptions on biological control in the village. It consisted of gathering key informants and maize or sorghum producers and to conduct a group discussion through a predesigned interview guide). The focus group discussion will also help collecting data on general characteristics of the villages (maize and sorghum production, development infrastructures, existence of credit institution, other development projects/intervention and market access) and having a list of households on which the random selection of the households will be performed.

#### 3.6.3.2 Households' survey

Survey was conducted consecutively to the entomological survey, soon after the harvesting period of the long and short raining seasons of the cropping year 2014-2015 in Coastal Eastern and Nyanza region and during the only one raining season of the same cropping year for Western and Rift-valley.

A structured interview schedule[4] was developed and pre-tested to reduce the occurrence of errors in the data before being used to collect the household and plot level data. The interview schedule was administered by a group of trained enumerators made of post-graduate students from agricultural economics faculty and experienced officers from the Ministry of Agriculture. The enumerators' selection was conditional on their understanding of the local language and their knowledge of the farming system of the selected regions.

The interview schedule contained questions regarding perception and knowledge of the stemborers and natural enemies, the socio-demographic, economic and farming backgrounds of the sampled households and plot-level characteristics, inputs and outputs use during the considered cropping season. Questions on output concerned the harvested quantity of maize and selling prices whereas questions on input included quantities, purchasing prices and types of seed, insecticides and herbicides used, as well as quantity of family and hired labor and cost,

[4] Interview schedule and questionnaire are erroneously used interchangeably. In this study, we use the interview schedule (with more complexe questions and filled by enumerators) and not a questionnaire (as it was not directly filled by respondents)

production equipment and depreciation patterns and household's income, expenditures and consumption characteristics. Village level questions were also collected and include administrative locations and agro-ecological zone, existence of market, extension office, research and other development infrastructures.

## 3.7 Theoretical frameworks for economic analysis of Biological Control

The range and diversity of issues covered required the use of a variety of analysis methods. The results from the framework were organized in three key themes: Damage abatement framework, continuous treatment approach and economic surplus modelling.

### 3.7.1 Damage abatement function framework for productivity-effect analysis

#### 3.7.1.1 Classical approach in production economics

To determine the productivity-effect of a technology, the establishment of production function constitutes the starting-point in economic analysis (Parish and Dillon, 1955). Elements of the theory on production economics are then used to provide accurate description of the production technology that well-illustrates the economic behavior of a unit or entity of production (Rasmussen, 2012).

The input-output relationship is computed by means of mathematical function. Production economics entails finding out and establishing the best fitted functionnal form that is capable to simultaneously illustrate the empirically observed interlink between all used inputs and the obtained output. Rasmussed (2012) argued that, in addition to establishing the production curve with the appropriate mathematical functionnal form, a complete and precise representation of the production technology should include all the actual possibilities at the producer disposal. Accounting for this precondition of free disposability of input, a sound production technology comprises both observations on and outside (and bellow) the production function explaining all possible combinations of inputs and output.

Let assume a firm or farmer using a set of $n$ inputs: $x = (x_1;\ x_2; \dots \dots . x_n)$ (such as labor, fertilizer, seed, machinery, pesticides, etc) to produce a single output $q$ (maize) through a given technology $T$. The global production technology is illustrated as follows:

$$T(x, q) = \{(x, q) | x \text{ can produce } q\} \qquad (3\text{-}1)$$

This above-explained illustration of production technology gives a formal and precise definition of the production function which is the maximum output obtainable with a given level of inputs. The mathematical expression of the production function $f$ is generally given as follows:

$$q = f(x) = f(x_1, x_2, \dots \dots, x_n) \qquad (3\text{-}2)$$

Practical applications or technological representation of this relationship $f$ requires a functional form. The Cobb-Douglas production function ($q = \prod_{i=0}^{n} x_i^{\beta_i}$) is the best known despite the existence of many other functional forms in literature. Griffin *et al.* (1987) identified in their review thirty functional forms including among others the trans-logarithmic (or translog), the constant elasticity of substitution (CES), the quadratic, the cubic, the generalized Leontieff, the generalized Box-Cox, the transcendantal and the square root functional forms. Griffin *et al.* (1987) underlined that determining the true functional form of the input-output relationship is impossible but provide four categories of criteria useful to choose the best form while conducting analysis. The maintained hypothesis, the statistical estimation process, the goodness of fit and general conformity to data and the application-specific characteristics guide in the choice of the best functional form.

The next important step after the production function specification is the productivity which is often represented by the marginal productivity ($MPP_x$.) This estimate is derived from the production elasticity$\varepsilon_x$ wich is expressed as the relative change in production through a relative change in additional input.

$$\varepsilon_x = \frac{\partial f(x)}{f(x)} \Big/ \frac{\partial x}{x} = \frac{\partial f(x)}{\partial x} \Big/ \frac{f(x)}{x} = MPP_x / APP_x \qquad (3\text{-}3)$$

Therefore,

$$MPP_x = \frac{\partial f(x)}{\partial x} = \varepsilon_x * APP_x \qquad (3\text{-}4)$$

The above-specified production function framework can be seen as conventional as new developments make distinctions between inputs and modify the function structure accordingly. Indeed, the manner in which certain inputs such as damage control ones, contextual variables and production risk-weather factors enter the production function gave rise to questions on the conventional specification. As the production technology is concerned with the determination of the input-output relationship as stipulated by the classical production theory, the actual knowledge on the types of input uses become a prerequisite for sound establishment of production function and the derivation of the input productivity.

#### 3.7.1.2 Growing and damage-reducing factors in productivity assessment

Van Ittersum *et al.* (1997) and van Ittersum *et al.* (2013) on the causal factors of yield gap, provide a quiet useful distinction between many factors on which it seem useful to rely to deduct the types of input in production function specification. These authors with respect to the type of considered output (Figure 3-3) distinguished in general, three levels of production comprising the potential output, the attainable output and the actual output. On input side, they considered three groups including growth-defining, growth-limiting and growth-reducing factors. The potential output represents the highest production level achievable within the given physical environment[5] and the genetic characteristics of plant and assuming no growth-limiting or growth-reducing factors. Growth-limiting factors include shortage of water and nutrients. When these factors occur, the resulting output is defined as attainable output. The farmer can control through a sound management the level of water and nutrients by irrigating, fertilizing to attain a certain output level. The attainable output level assumes no growth-reducing factors, defined as weeds, pests, diseases and pollutants. Growth-reducing factors lower the production level further to the actual output level. However, when no action is taken to control the growth-reducing factors when they actually occur, the output is reduced to the actual output.

[5] According to van Ittersum et al (2013), the potential output may vary with some factors totally uncontrollable by farmers including among others the atmosphere carbon dioxide, the solar radiation, the temperature and the genetic features of the seed.

This categorization and the diverse concepts used entail that measures against these factors should therefore be treated differently and then, inputs influence differently output and must be modeled differently. Taking this into account in economic modeling led to divide the correponding inputs into two groups: yield enhancing inputs and the damage reducing inputs. Yield enhancing inputs are different from the damage reducing inputs in that the firsts intervene directly in the biological process of the plant growing whereas the laters increase the share of the attainable output that producers realize by reducing damage from damaging agents (Babcock *et al.*, 1992; Fox and Weersink, 1995). This asymmetry in inputs influence on output should be cared for in the production process (Zhengfei *et al.*, 2005).

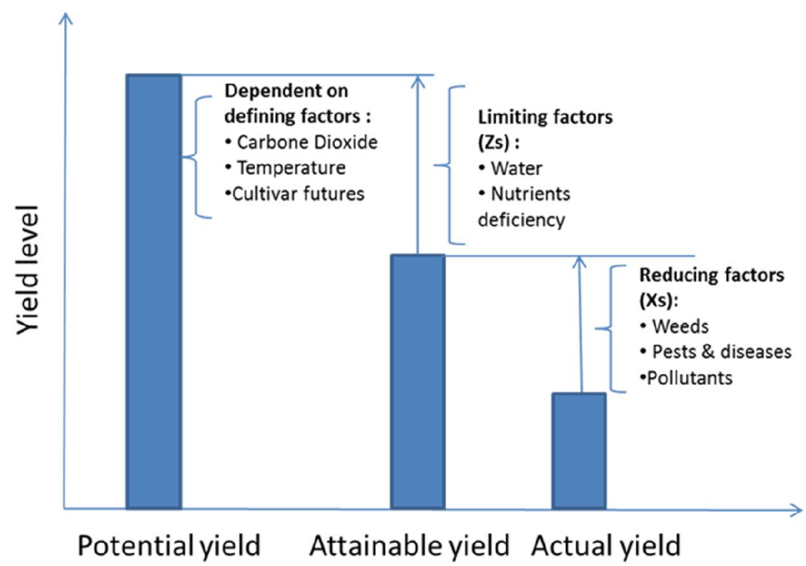



**Figure 3-3**: Yield influencing factors

Source: Adapted from van Ittersum *et al.* (2013)

### 3.7.1.3 Biological control as damage-reducing factor

In general, disease and pests management measures and especially chemical control using pesticide have been considered as damage-abating variable in different studies (Fox and Weersink, 1995; Babcock *et al.*, 1992). By reducing pests' densities and attacks on plant, biological control is also used against plant-damaging agents and can be a perfect substitute for insecticide. BC is therefore considered as damage-reducing agent in the production function modeling.

#### 3.7.1.4 Neoclassical production function integrating damage-reducing factors

When investigating productivity of factors, the above-described difference in inputs consideration is seldom accounted for. It is common to find many authors who use the standard Cobb Douglas specification in modeling the production function without making any distinction between the types of production factors. The common case in the literature is the pesticide input that past studies considered as yield-increasing production factor. Many studies such as Headley, (1968) and Campbell (1976) failed to consider pesticides as damage control input and found that the derived marginal product in value from their production function was higher than the marginal cost, results that would have been different if this input were considered in its right nature. Establishing such model in productivity assessment may be misleading because of the risks of overestimation of some types of factors and the underestimation of types of others (Asfaw *et al.*, 2011; Blackwell and Pagoulatos, 1992; Lichtenberg and Zilberman, 1986; Pemsl, 2005). The alternative method proposed in the literature to correct this potential bias is the damage abatement framework also called damage control function framework.

Lichtenberg and Zilberman (1986) introduced this framework to address the problem raised by taking into consideration the distinction between inputs in production process. They distinguished standard factors of production including for instance land labor and capital on one hand, and the damage control agents such as insecticides, natural enemies of pests and herbicides on other hand. As it can easily be noticed, there is no direct causal relationship between control agents and productivity as it evidently known for the standard factors. Rather, the control agents influence indirectly productivity or total output by preventing output losses. Following Lichetenberg and Zilberman (1986), a model including damage abatement characteristics of some input is broadly expressed as follows:

$$Q = F[X, G(Z)\,] \qquad (3\text{-}5)$$

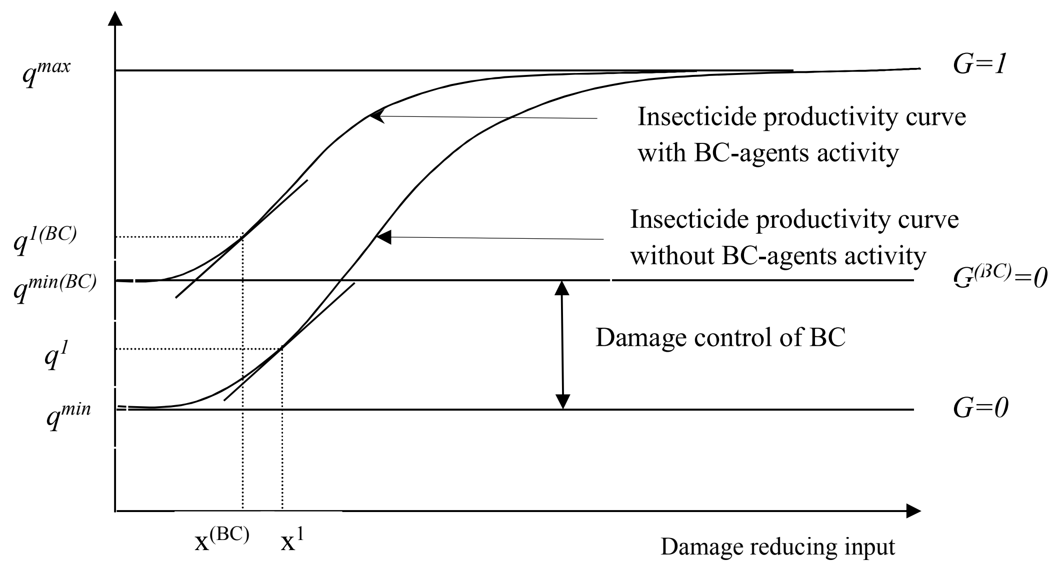
This equation expresses that production (*Q)* can be characterized as a function of directly productive inputs, *X*, and damage abatement function $G(Z)$ defined on the interval [0, 1] with extreme values $G(Z) = 0$ and $G(Z) = 1$ denoting respectively zero elimination and complete eradication of the destruction effect. *Z* is a vector of multiple damaging agents and a variety of damage control inputs to use. Following the notation of Zenghfei *et al.* (2005), and written in its simple linear form, the specification may yield:

$$q = f_1(x) + f_2(x).\,G(z) \qquad (3\text{-}6)$$

With $q \in R_+$ stands for output (maize yield), $x \in R_+^n$ is the vector of $n$ direct inputs (seed, labor, fertilizers) and $z \in R_+^m$ is the vector of $m$ damage control inputs. The function $f_1(x)$ stands for the minimum output, and $f_1(x) + f_2(x)$ is considered as the maximum output (or the attainable output - free of the damaging pest effects – as depicted in figure 3.1). The minimum output is null in most cases and this allows to get the general expression of the function to be:

$$q = f(x).\,G(z) \qquad (3\text{-}7)$$

With reference to this function and considering the two damage control factors (insecticide and BC) involved in this study, all things assumed constant elswhere, Figure 3-4 provides a graphical illustration of the effect of both factor on maize productivity. $q^{max}$ stands for the maximum attainable yield when stemborer pests are under total control and this correspond to the complete elimination of the pests (an ideal perfect control case correponding to G=1). $q^{min}$ represents the actual yield in pests' presence with no use of insecticide (G=0). $q^{min(BC)}$ represents the actual yield in without any BC-agents activity ($G^{(BC)}$=0). The evolution of the curves from $q^{min}$ and $q^{min(BC)}$ to $q^{max}$ denotes that increasing amount of insecticide or increasing level in parasitism by BC agents are associated to increasing intensity of pest control, more and more damage reduction and consequent increase in yield. The difference between the two curves stands for the intrinsic impact of BC on yield.




$q^{max}$ : Maximum attainable yield
$q^{min(BC)}$ : Maximum yield under the worst pest attack (with BC)
$q^{min}$ : Minimum yield under the worst pest attack (without BC)

**Figure 3-4** : Effect of damage-abatement inputs on yield (with and without BC)
Source: Adapted from Pemsl (2005)

From the equation 3.7, the marginal productivity of damage abating input can be expressed as:

$$\frac{\partial q}{\partial z} = \frac{q}{G(z)} * \frac{\partial G(z)}{\partial z} \quad (3.8)$$

### 3.7.2 Continous treatment approach of impact on food security and poverty

#### 3.7.2.1 Potential Outcome Framework in impact assessment

Failure of previous impact methodologies in accounting for the non-existence of the counterfactual[6] in causal effect relationship analysis often led to biased estimates which affect policy recommendations. To account for selection bias and obtain robust and reliable estimates, Potential Outcome Approach (POA) has been introduced in impact methodology (Imbens and Wooldridge, 2009). A number of methods have since been used through a quasi-experimental setting. These include selection on observables and selection on unobservable methods. The first category, including the ATE based regression, the inverse probability weighting (IPSW) and several matching methods, is used in case of overt bias, that is, the difference in the observed outcome is not only caused by the intervention but is also due to difference in observed units characteristics (Lee, 2005). The second category include among others the instrumental variable (IV) methods, switching regression, two-steps regression (2SLS), used in case of hidden bias (i.e. the difference in the observed outcome is not only caused by the intervention but is also due to difference in unobserved units characteristics) (Lee, 2005) and the non-compliance problem (also known as endogeneity problem) (Heckman and Vytlacil, 2005). The literature on impact assessment using these methods reveals that empirical application have long been focused on a dichotomous nature of intervention (with and without intervention), then classifying all treated as identical, ignoring that treatment may vary across surveys treated units.

[6] The counterfactual situation means: what would have happened if the intervention has not been implemented for the implemented area or what would have happened to non-implemented area if the intervention was implemented.

#### 3.7.2.2 Dichotomous versus continuous treatment in impact assessment

In this study, the treatment of interest is the biological control. Previous studies on BC impact (Macharia *et al.,* 2005; Asfaw *et al.*, 2011) relied on binary setting in their analysis considering BC and non-BC fields. The activity of the released natural enemies is measured through the parasitism rate which represents the biological control measurement of success (Frank, 2007). This level may spatially vary from one site to another (Le Corff *et al.*, 2000) and this led us to go beyond the consideration of binary treatment and extend this analysis using the continuous treatment impact evaluation framework. In this framework, Hirano and Imbens (2004) introduced the Generalized Propensity Score (GPS) estimator which is a generalization of the binary Propensity Score (PS). The practical implementation of the GPS proposed in Bia and Mattei (2012) was the most commonly used in empirical studies (Kassie *et al.,* 2014 and Kluve *et al.,* 2012). This approach relies on full normality distribution assumption and then excludes the zero-treated units in practice. Bia *et al.* (2014) will then proposed a semiparametric estimation of the dose response function with various distributions assumptions that should accommodate the zero-treated units but this approach does not account for the possibility of getting treatment endogeneity. Cerulli (2015) introduces a new approach which help overcoming these limitations and that should be well-suited for the biological control impact analysis. The summary of the approach is presented as follows.

#### 3.7.2.3 Accounting for heterogeneity: continuous treatment approach

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

$$\begin{cases} y_1 = \mu_1 + \mathrm{g}_1(\mathrm{x}) + \mathrm{h(b)} + \mathrm{e}_1 & w = 1 \\ y_0 = \mu_0 + \mathrm{g}_0(\mathrm{x}) + \mathrm{e}_0 & w = 0 \end{cases} \quad (3\text{-}8)$$

At individual level, the impact of biological control is measured by the Treatment Effect ( $TE = y_1 - \mathrm{y}_0$ ). Due to the missing data problem, the Average Treatment Effect for the population (ATE) is calculated conditional on x and b in the following way:

$$ATE(\mathrm{x}; b) = E(y_1 - y_0 | \mathrm{x}, b)$$

$$ATET(x; b > 0) = E(y_1 - y_0 | x; b > 0)$$

$$ATENT(x; b = 0) = E(y_1 - y_0 | x; b = 0) \quad (3\text{-}9)$$

Where E(.) is mathematical expectation operator, ATE indicates the overall impact, ATET indicates the average TE on treated and ATENT indicates the average TE on untreated units. When assuming parametric form for $\mathrm{g}_1(\mathrm{x})$ ($\mathrm{g}_0(\mathrm{x}) = \mathrm{x}\delta_0$ and for $\mathrm{g}_1(\mathrm{x})$ ($\mathrm{g}_1(\mathrm{x}) = \mathrm{x}\delta_1$), Average Treatment Effect (ATE) conditional on x and b becomes:

$$ATE(x, b, w) = w * [\mu + x\delta + \mathrm{h}(b)] + (1 - w) * [\mu + x\delta] \quad (3\text{-}10)$$

Where $\mu = \mu_1 - \mu_0$ and $\delta = \delta_1 - \delta_0$. The unconditional ATEs with regards to the model (1) is:

$$ATE = p(w = 1) * \left[\mu + \bar{x}_{b>0}\delta + \bar{\mathrm{h}}_{b>0}\right] + p(w = 0) * [\mu + \bar{x}_{b=0}\delta]$$

$$ATET = \mu + \bar{x}_{b>0}\delta + \bar{\mathrm{h}}_{b>0}$$

$$ATENT = \mu + \bar{x}_{b=0}\delta \qquad (3\text{-}11)$$

and the dose response function (DRF) representing the varying impact is function of the biological control level b and is given by:

$$ATE(b) = \begin{cases} ATET + \left[\mathrm{h(b)} - \bar{\mathrm{h}}_{b>0}\right] & \text{if } b > 0 \\ ATENT & \text{if } b = 0 \end{cases} \qquad (3\text{-}12)$$

The regression approach of estimating ATE is given as:

$$y_i = \mu_0 + w_i * ATE + x_i\delta_0 + w_i * (x_i - \bar{x})\delta_1 + w_i\left[\mathrm{h}(b_i) - \bar{\mathrm{h}}\right] + \epsilon_i \qquad (3\text{-}13)$$

Where $(\mu_0, \delta_0, \delta_1, ATE)$ are the parameters to be determined and ATET and ATENT to be deducted. However, obtaining consistent impact estimates requires additional assumptions on the biological control variable. The approach provides the estimation assuming unconfoundedness (or conditional mean independence CMI) and the estimation under treatment endogeneity.

#### 3.7.2.3.1 Model under unconfoundedness or conditional mean independence CMI

The first assumption stipulates that the treatment is exogenous given the observable characteristics $x$. In other words, the difference in outcome between BC and non-BC is not due only to experiencing the biological control in the field but conditional to other observed individual characteristics. Under this assumption the OLS regression estimation to get impact parameters and the associated consistent DRF curve are obtained as:

$E(y_i|w_i, b_i, x_i) = \mu_0 + w_i * ATE + x_i\delta_0 + w_i * (x_i - \bar{x})\delta_1 + w_i[\mathrm{h}(b_i) - \bar{\mathrm{h}}] + \epsilon_i$

(3-14)

$$\widehat{ATE}(b_i) = w\left(\widehat{ATET} + \lambda_1\left(b_i - \frac{1}{N}\sum_{i=1}^{n} b_i\right) + \lambda_2\left({b_i}^2 - \frac{1}{N}\sum_{i=1}^{n} {b_i}^2\right) + \lambda_3\left({b_i}^3 - \frac{1}{N}\sum_{i=1}^{n} {b_i}^3\right)\right) + (1-w)\widehat{ATENT} \quad (3\text{-}15)$$

Where $\lambda_1$, $\lambda_2$and $\lambda_3$ are parameters obtained from the regression (3-13) assuming a polynomial parametric form of degree 3 for the h(b) function: ($\mathrm{h}(b_i) = \lambda_1 b_i + \lambda_2 {b_i}^2 + \lambda_3 {b_i}^3$).

#### 3.7.2.3.2 Model under treatment endogeneity

The second assumption is the one of the treatment endogeneity and the semi-structural form of the corresponding function as provided in Cerulli (2015) is presented as follows:

$$y_i = \mu_0 + w_i * ATE + x_i\delta_0 + x_i + w_i * (x_i - \bar{x})\delta + w_i[\lambda_1 T_{1i} + \lambda_2 T_{2i} + \lambda_3 T_{3i}] +$$

$$\mu_i w_i^* = x_{w,i}\beta_w + \epsilon_{w,i} \quad (3\text{-}16)$$

$$b_i' = x_{b,i}\beta_t + \epsilon_{b,i} \quad (3\text{-}17)$$

Where $T_{1i} = b_i - E(b_i)$, $T_{2i} = {b_i}^2 - E({b_i}^2)$ and $T_{3i} = {b_i}^3 - E({b_i}^3)$, $w_i^*$ stands for a latent unobservable counter part of the binary variable $w_i$ (i.e $b_i = b_i'$ only when $w_i = 1$ and unobserved otherwise). $x_{w,i}$ and $x_{b,i}$ represents the sets of exogenous variables and $\epsilon_{w,i}$, $\epsilon_{b,i}$ and $\mu_i$, error terms supposed to be correlated with one another.

In this case, obtaining consistent estimates of $\mu_0, \delta_0, \delta_1, ATE, \lambda_1$, $\lambda_2$and $\lambda_3$ requires the implementation of instrumental variables (IV) method in estimating the equation, requiring then ttwo-stage least square (2SLS) instead of the OLS as previously indicated for the CMI assumption. In the response equation, we have two endogenous variables and then the estimation will require the availability of at least two IVs ($z_{w,i}, z_{b,i}$) verifying the exclusion restriction i.e directly correlated with the two endogenous variables ($w_i^*, b_i'$ ) but not with outcome variable $y_i$ and the error terms ($\mu_i$, $\epsilon_{w,i}$ and $\epsilon_{b,i}$). The direct implication for the two last equations is that their regressand variables become ($x_{w,i} = x_i$ , $z_{w,i}$ ; $x_{b,i} = x_i$ , $z_{b,i}$).

In using the 2SLS, the first step estimates the two last equations which represent a bivariate sample-selection and then require the Heckman two-step procedure. The first step consists in performing a probit of the binary treatment $w_i^*$on $x_{w,i}$ and derive the Mills'ratio which will be introduced in a second step OLS regression of the continuous treatment $b_i'$ on $x_{b,i}$. The predicted values from these two equations will be used as instruments in the first equation as part of the second step of the 2SLS to derive the overall impact estimates and deduct the DRF functions.

### 3.7.2.3.3 Endogeneity checking

In this study, the type of assumption to be considered depends on the status of the BC variable (exogenous or endogenous). As indicated earlier, the first approach option is based on the unconfoundedness assumption also known as selection on observables. This will no longer be valid in case of violation of this assumption i.e if the bio-control variable is endogenous. To verify and confirm this empirically through the collected data, we apply the two stages least square (2SLS) procedure using instrumental variables to estimate the predicted value and calculate the residuals which was integrated into a second stage augmented regression. BC variable is endogenous when the coefficient of the residuals variable is statistically significant.

### 3.7.3 Economic surplus approach in welfare-effect assessment

#### 3.7.3.1 Market equilibrium model of surplus analysis

The Economic Surplus Modeling (ESM) stems from partial equilibrium framework which is the most common approach for the evaluation of commodity-related technological progress in agriculture (Alston *et al.*, 1995; Norton and Davis, 1981). The ESM entails estimating the aggregate total monetary benefits for socio-economic agents involved in the introduction of a research innovation of development intervention in a targeted social environment (Akino and Hayami, 1975; Maredia *et al.*, 2013). In other words, estimations through this model make it possible to appreciate the variation of consumer and producer surplus attributable to intervention.

The framework has been developed in the literature under many assumptions. In most of ESA countries, the locally produced maize and sorghum are commercialized within each country. Very negligible proportion of these crops is exported, which led us to assume the closed economy[7] in the development of our framework. Under this assumption, and following the framework presented by Alston *et al.* (1995), Mensah and Wohlgenant (2010), Zhao *et al.* (1997), Maredia *et al.* (2000) and Moore *et al.* (2000) and assuming linear curves[8] of supply and demand, the determination of surplus change from the Biological Control (BC) intervention can be described as follows.

[7] Based on the FAOSTAT (2015) Data from 2000 to 2010, the estimated average proportions of exported crops relatively to the total production were 0.56% for maize and 3.37% for sorghum in Kenya

[8] The question of which functional form of supply and demand curves is to be considered. Researchers assumed that in case of parallel supply shift, linear model provides a good approximation of any other non-linear model, and then the choice of the functional form is considered as irrelevant (Mensah and Wohlgenant (2010))

The maize or sorghum supply curve before the BC-intervention is given by: $q^s = \alpha + \beta p$ (3-18)

where $q^s$ is the initial quantity supplied, $\alpha$ the intercept of the supply curve, $\beta$ the slope parameter of the supply curve and $p$ the price level. The initial demand curve is given by: $q^d = \mu + \gamma p$ ( 3-19) where $\boldsymbol{q^d}$ represents the initial quantity demanded, $\mu$ the intercept of the demand curve and $\gamma$ the slope of the demand curve. Following the economic theory, the initial market equilibrium is obtained by equating the total demand to the total supply equations, yielding the initial market equilibrium price $p^*$ before the intervention:

$$\sum q^s = \sum q^d \iff p^* = (\mu - \alpha)/(\beta + \gamma) \qquad (3\text{-}20)$$

The BC intervention induces a parallel and downward shift of the supply curve giving a new supply curve $q^s_{BC} = \alpha + \beta(p + k) = (\alpha + \beta k) + \beta p$, where $k$ stands for the shift factor treated as intercept change and $q^s_{BC}$ represents the new quantity supplied with the intervention. New market equilibrium is derived from this technology-induced supply curve and the demand curve ($q^d_T = \mu + \gamma p$), yielding a new market equilibrium price, considered as derived from the supply shift:

$$\sum q^s_{BC} = \sum q^d_{BC} \iff p^*_{BC} = (\mu - \alpha - K\beta)/(\beta + \gamma) \qquad (3\text{-}21)$$

The graphical illustration of the market equilibrium displacement provides a geometrical view of the economic surplus model (Figure 3-5). The initial supply curve $S_0$ (algebraically described by the equation (3-18)) and the demand curve D (algebraically described by the equation (3-19)) intercept at the point A ($p^*$, $q_0$) which represents the initial market equilibrium as assumed in economic theory. The point A coordinates $p^*$ and $q_0$ represent respectively the initial equilibrium price and quantity supplied or demanded.

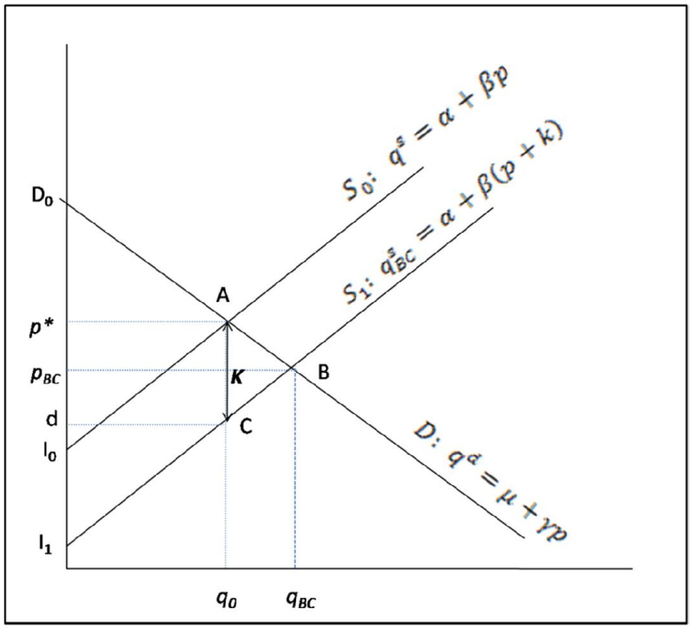



**Figure 3-5** : Change in economic surplus from a supply parallel shift induced by the BC program

Source: Adapted from Altson *et al.* (1995)

Hence, the initial surplus distribution is presented as follow: Initial Consumer Surplus $p^*AD_0$, initial Producer Surplus $p^*AI_0$ and the initial Total Surplus $D_0AI_0$ . With the BC intervention, the supply curve $S_0$ is expected to shift to $S_1$. This results in a new equilibrium point $B(q_{BC}, p_{BC})$ with the coordinates $p_{BC}$ and $q_{BC}$ representing respectively the new equilibrium price and quantity of maize or sorghum under the BC intervention. The resulting change in welfare (surplus) is then given as follow:

- Change in Consumer Surplus: $\Delta SC = p^*ABp_{BC} = p_{BC}BD_0 - p^*AD_0$
- Chance in Producer Surplus: $\Delta SP = p_{BC}BI_1 - p^*AI_0 = p_{BC}BI_1 - dCI_1 = p_{BC}BCd$
- Change in Total Surplus: $\Delta TS = p^*ABp_{BC} + p_{BC}BCd$

Following the analytical framework, the induced change in price is demonstrated to be:

$$p_{BC}^* - p^* = \frac{K\beta}{\beta+\gamma} \quad \Leftrightarrow \quad p_{BC}^* = \; p_0\{1 - (K\varepsilon)/(\varepsilon + \eta)\} \tag{3-22}$$

with $K = k/p_0$ the supply shift factor, $\varepsilon$ the supply elasticity and $\eta$ the demand elasticity. The relative reduction in price according to Alston et al. 1995 is:

$$Z = -\frac{p_{BC}^* - p^*}{p^*} = (K\varepsilon)/(\varepsilon + \eta) \tag{3-23}$$

The changes in economic surplus from a parallel supply-shift generated by the BC intervention are analytically expressed as follow:

- Change in consumer surplus:

$$\Delta CS = (p^* - p_{BC}^*)[q^* + 0.5(q_{BC}^* - q^*)] = p^* q^* Z(1 + 0.5Z\eta) \tag{3-24}$$

- Change in producer surplus

$$\Delta PS = (k + p_{BC}^* - p^*)[q^* + 0.5(q_{BC}^* - q^*)] = p^* q^* (K - Z)(1 + 0.5Z\eta) \tag{3-25}$$

- Change in total surplus

$$\Delta TS = \Delta CS + \Delta PS = p^* q^* K(1 + 0.5Z\eta) \tag{3-26}$$

The change in surplus induced by intervention may vary with the nature of the demand and supply curves (elastic or inelastic), and the nature of the innovation induced shift (pivotal or parallel) (Alston et al., 1995). An inelastic demand and an outward shift of the supply curve will result in producers selling more commodities but at a lower price leading to a decrease in their revenue as supply increases. With a pivotal outward shift of the supply and inelastic demand curve, producers are likely to experience higher revenue losses (Alston et al., 1995; Zhao et al., 1997).

#### 3.7.3.2 Potential surplus-based poverty-reduction at country level

The welfare effects were evaluated as total monetary value associated with the BC of maize and sorghum stemborers. This total generated social benefit can also be seen as accrued surplus that allow households to escape poverty. Indeed, the BC intervention can reduce poverty by raising the income of farmers' households, by reducing purchasing price for consumers' households or by creating new employment in the maize or sorghum value chains. Alene *et al.*, (2009) provided a formula that allows deriving the number of poor people lifted out of poverty from the change in surplus due to new technology introduction. The increase in number of persons that could be shifted from the group of poor (under the poverty line) to the group of non-poor (above the poverty line) due to the *icipe'* biological control program is given by:

$$\Delta P = \left(\frac{\Delta TS}{AgGDP} * 100\%\right) * \frac{\partial ln(N)}{\partial ln(AgGDP)} * N \qquad (3\text{-}27)$$

Where $\Delta P$ is the number of poor lifted out of poverty, $\Delta TS$ is the change in economic surplus due to the biological control program, $AgGDP$ is agricultural gross domestic production in year t and N is the total number of poor. The term $\frac{\partial ln(N)}{\partial ln(AgGDP)}$ represents the poverty elasticity that stands for percentage reduction of total number of poor due to 1% increase in agricultural productivity. This term is found to be equal to 0.72 for Sub-Saharan Africa (Thirtle *et al.,* 2003) and was used for this study.

#### 3.7.3.3 Return to investment and benefit-cost analysis

In general, the welfare benefits are compared to the monetary investments in order to appreciate the efficiency of the program or research through the measure of its return to investment. Economic benefit of the research is usually extended to the estimation and analysis of the Net

Present Value (NVP), the Internal Rate of Return (IRR) and Benefit-Cost Ratio (BCR) (Masters *et al.*, 1996; Zeddies *et al.,* 2001).

**NPV** measures surplus from profit *($B_t$)* compared with costs *($C_t$)* of the BC intervention based on a given interest rate r. The intervention is profitable and acceptable if the NPV exceeds zero.

$$NPV = \sum_{t=0}^{T} \frac{(B_t - C_t)}{(1+r)^t} \qquad (3\text{-}28)$$

**IRR** measures the interest rate at which, current value of costs is equal to current value of profits. IRR can then relate to any other rate of interest, in particular the one charged by commercial banks or interest rates of private investments. Greater IRR entails that investment in BC-intervention is efficient.

$$NPV = \sum_{t=0}^{T} \frac{(B_t - C_t)}{(1+IRR)^t} = 0 \qquad (3\text{-}29)$$

**BCR** The benefit-cost ratio (BCR) measures the relative value of benefit generated per investment unit. It is expressed as a ratio of the sum of a BC intervention's discounted benefits to the sum of discounted costs of research and releases. A ratio greater than one, will justify the relevancy of investment in BC program.

$$BCR = \frac{\sum_{t=0}^{T} B_t / (1+r)^t}{\sum_{t=0}^{T} C_t / (1+r)^t} \qquad (3\text{-}30)$$

The sensitivity analysis will hold on the important assumptions of the model (elasticity, change in yield and the diffusion of the pests' natural enemies).

#### 3.7.3.4 Sensitivity and stochastic dominance analysis

The above-described economic method stems from the static or deterministic part of the economic surplus approach, as most of the parameters used in the model were based on their unique values. The choice of the parameters is based on published estimates used to compute a point estimate of welfare change (Zhao *et al.*, 2000). For the purpose of taking into account the variations associated with the parameters used, as well as the correlation between parameters, we performed probabilistic analysis or stochastic analysis, which allows one to perform a more rigorous sensitivity analysis and then account for the variability of values found in the literature, and some limitations often cited for the methodology (Falck-Zepeda *et al.,* 2013). We used the Monte Carlo simulation approach for the probabilistic analysis based on the variability of price elasticity of supply and demand, yield gain due to the presence of the natural enemies, and the interest rate used in the estimation of the NPV and the BCR.

## 3.8 Empirical procedures

### 3.8.1 Productivity-effect of biological control using damage abatement function

#### 3.8.1.1 Reduced form of the damage abatement function

Most of plant control strategies including pest control using the bio-agents contribute to yield losses reduction unlike the growth-inducing input such as fertilizers, seeds, etc. Hence, assessing the productivity of biological control of maize stemborers requires the application of the damage control framework of Lichtenberg and Zilberman (1986) for which the reduced form is represented by the equation (3-5). Translating this equation in its empirical form requires different functional specifications for the productive input function ( $f(x)$ ) and the damage control function ($G(z)$ ). Cobb-Douglas function has traditionally and widely been used in the specification of the production function ( $f(x)$  (Asfaw *et al*., 2011; Carpentier and Waiver, 1997; Pemsl, 2005). Under this specification, the equation (3-5) can be written as:

$$q = a\left[\prod_{i=1}^{n}(x_i)^{\beta_i}\right] * G(z_{BC}, z_{Ins}) \quad (3\text{-}31)$$

Or in its logarithmic form:

$$lnq = a + \sum_{i}^{n} \beta_i \ln x_i + \ln\left(G(z_{BC}, z_{Ins})\right) \quad (3\text{-}32)$$

The Cobb-Douglas functional is however criticized in the literature for its lack of flexibility as it implicitly imposes some *a priori* restrictions on parameters estimation that appear untenable (Lyu *et al*., 1984; Zhengfei *et al*, 2005). It imposes all elasticity to be equal to one and does not allow the possibility of interaction between the input factors. The translog functional and other flexible forms have more attractive properties and do not deal with these *a priori* restrictions.

For these reasons, the translog functional form was considered in this study for the productive input function.

$$lnq = a + \sum_i^n \beta_i \ln x_i + \frac{1}{2}\sum_i^n \sum_j^n \alpha_{ij} \ln x_i ln x_j + \ln(G(z_{BC}, z_{Ins}) \quad (3\text{-}33)$$

With respect to the damage control function component ($G(z)$ ), different functional forms have been assumed in the literature. In the damage control framework as developed by Lichtenberg and Zilberman (1986), the damage reducing feature should be understood as a reduction proportion and then its value is imposed to lie between [0 1] interval. A number of functional forms has been cited to fit this imposition and include the exponential, logistic, Weibull and Pareto distributions (Linchtenberg and Zilberman, 1986) completed with rectangular hyperbola, linear response plateau and Square root response plateau by Fox and Weersink (1995).

The first three (exponential, logistic, Weibull) distributions are the most used in the literature (Praneetvatakul *et al.*, 2002; Pemsl 2006) and their mathematical expressions can be defined as follows:

Exponential: $$G(z_{BC}, z_{Ins}) = 1 - \exp(-\gamma_1 z_{BC} - \gamma_2 z_{Ins} - \gamma_3 z_{BC} z_{Ins}) \quad (3\text{-}34)$$

Logistic: $$G(z_{BC}, z_{Ins}) = [1 + \exp(\mu - \gamma_1 z_{BC} - \gamma_2 z_{Ins} - \gamma_3 z_{BC} z_{Ins}]^{-1} \quad (3\text{-}35)$$

Weibull: $$G(z_{BC}, z_{Ins}) = 1 + \exp(-(z_{BC})^{\gamma_1} - (z_{Ins})^{\gamma_2} - (z_{BC} z_{Ins})^{\gamma_3}) \quad (3\text{-}36)$$

where $z_{BC}$ stands for the biological control variable represented by rate of parasitism, $z_{Ins}$ the quantity of chemical insecticide used in (kg/ha) and the term $z_{BC} z_{Ins}$, the interaction of the two damage control factors. $\mu$, $\gamma_1$, $\gamma_2$, $\gamma_3$ are the coefficients to be estimated for each of the specification.

The overall model from the two above-described functional forms for the productive input function ( $f(x)$ ) and the damage control function ($G(z)$ ) can be expressed as follows:

$$lnq = a + \sum_i^n \beta_i \ln x_i + \frac{1}{2}\sum_i^n \sum_j^n \alpha_{ij} \ln x_i ln x_j + \sum_k^m \lambda_k\, d_k + \ln[(1 - \exp(-\gamma_1 z_{BC} - \gamma_2 z_{Ins} - \gamma_3 z_{BC} z_{Ins})] + \varepsilon \tag{3-37}$$

For the exponential functional form and

$$lnq = a + \sum_i^n \beta_i \ln x_i + \frac{1}{2}\sum_i^n \sum_j^n \alpha_{ij} \ln x_i ln x_j + \sum_k^m \lambda_k\, d_k + \ln\left[(1 + \exp\left(\mu - \gamma_1 z_{BC} - \gamma_2 z_{Ins} - \gamma_3 z_{BC} z_{Ins}\right)\right)^{-1}\right] + \varepsilon \tag{3-38}$$

for the logistic functional form.

The parameters$\beta$, $\alpha_{ij}$, $\lambda_k$, $\mu$, $\gamma_1$, $\gamma_2$, $\gamma_3$ are to be estimated. The set of variables $x_i$are productive input use, with i=1 for labor, 2 for seed, 3 for mineral fertilizer, 4 for material cost. $d_k$ is the set of farming characteristics and region dummy. $z_{BC}$ and $z_{Ins}$ represent respectively the bio-control variable (the parasitism rate) and the quantity of used insecticide. ε stands for the error term.

#### 3.8.1.2 Derivation of marginal productivity of the damage control agent

By definition, the marginal productivity is the increase in output arising from a unit increase of a certain input. It is obtained by considering the first derivative of the production function with respect to that input. The general expression of its calculation is given by the following equation:

$$\frac{\partial q}{\partial z_{BC}} = \frac{q}{G(z_{BC}, z_{Ins})} * \frac{\partial G(z_{BC}, z_{Ins})}{\partial z_{BC}} \tag{3-39}$$

Substituting $G(z_{BC}, z_{Ins})$ according to the specification of the functional form of damage abatement allows having:

$$MPV_{BC} = \frac{\partial q}{\partial z_{BC}} = q * \frac{(\gamma_1 + \gamma_3 z_{Ins}) \exp(-\gamma_1 z_{BC} - \gamma_2 z_{Ins} - \gamma_3 z_{BC} z_{Ins})}{1 - \exp(-\gamma_1 z_{BC} - \gamma_2 z_{Ins} - \gamma_3 z_{BC} z_{Ins})} \quad (3\text{-}40)$$

for the exponential functional form and

$$MPV_{BC} = \frac{\partial q}{\partial z_{BC}} = -q(-\gamma_1 - \gamma_3 z_{Ins})[(1 + \exp(\mu - \gamma_1 z_{BC} - \gamma_2 z_{Ins} - \gamma_3 z_{BC} z_{Ins}))^{-1}] \quad (3\text{-}41)$$

for the logistic functional form

### 3.8.1.3 Estimation procedure

In our previous development of the empirical models, the specifications did not consider one of the critical problems in econometrics and statistics which is the endogeneity of regressors in production function. Indeed, the insecticide use by farmer in our case may be endogenous to production causing the existence of a relationship between plant pests, insecticide use and crop yield (Pemsl, 2005). This causes insecticide use variable to be correlated with the production function residuals. Not accounting for this problem could lead to biases in estimates and errors in the functions interpretation even for the coefficient of biological control. To overcome this possible bias, the two-stage least squares (2SLS), as suggested in econometrics literature, was adopted. The procedure entails using valid instrumental variables (IV) to predict the value of insecticide use through an insecticide use function in a first stage. In this stage, instrument variables that are correlated with insecticide use but not with residuals need to be chosen. In a second stage, the predicted values of insecticide use can be inserted in lieu of the insecticide variable in the final estimation of the production functions. The defined specifications for the damage production function are nonlinear, and then non-linear least square (NLS) regression was used for the parameters' computation.

#### 3.8.1.4 Overview on the variables used in the models

The quantitative and qualitative variables used for the estimation of insecticide use and damage control models are summarized in the Table 3-1. For the productive inputs, the physical value has been considered except the material cost for which the monetary value was used. All the variables are presented with their description and quantitative variables are shown with their unit, mean and standard deviation. Maize yield is the dependent variable and represents the harvested quantity by the farmer per hectare. Maize yield is found to average 1500 kg/ha for the sampled farms. Labor input is referred to as the number of man-days used to grow and harvest one hectare of maize land. The number of persons and duration of work of each operation have been recorded and assuming eight hours for man-day and using man converting factor, the total labor have been calculated and average 136 man-days. The quantity of seed, fertilizers, insecticides used on maize field have reported and converted for one hectare. Cost is the depreciation of all the material used in maize farm for the cropping year. Parasitism rate is biological control measure provided by the entomology researchers team and represented the proportion of parasitized pests at vegetative stage. The parasitism represents the biological control activity variable. Among other quantitative variables, we have experience that states the number of years the farmer has practiced maize farming, age, number of years in formal school and insecticide price.

The models also used various qualitative variables including among others, improved varieties, agro-ecological dummy variables were included as proxy for rainfall, temperature and altitude distribution. The highland tropical and moist mid-altitude zones are expected to be significantly positively correlated to maize productivity because of their highest rainfall level and best soil quality compared to the reference which is the lowland tropical zone. The relevance of considering agro-ecological zones as influencing factor of agricultural productivity was demonstrated in Kassie *et al.* (2009). Location-specific variables were also considered in the models and included the country administrative regions dummies for which we expected an indeterminate relationship with productivity for the varying potentialities even inside regions. Position of the villages compared to the release points were chosen to capture BC gradient or diversity. Participation to training, contact with extension agents, farmers'group membership as well as the perceptions of farmers on infestation level were also considered in the models.

**Table 3-1** : Overview of the variables used in the models

| Variable | Variable description | Unit | Mean | Std.Dev |
|---|---|---|---|---|
| **Output variable** | | | | |
| Maize productivity | Maize yield | Kg/ha | 1.48 | 1.61 |
| **Household characteristics** | | | | |
| Age | Age of the household head (hhld0) | Years | 48.40 | 14.11 |
| Gender | Gender of the hhld0 (1=Man; 0=Woman) | 0/1 | 0.72 | |
| Residence | Number of years of residence in the village | Years | 33.86 | 18.99 |
| Education | Number of years of formal school | Years | 7.73 | 4.36 |
| Experience | Experience in agriculture | Years | 21.54 | 13.36 |
| Can read and write | hhld0 can read or not (1=yes, 0=no) | 0/1 | 0.82 | 0.38 |
| Experience in maize | Experience in maize production | Years | 20.79 | 13.30 |
| Household size | Total household size (number) | | 6.05 | 2.55 |
| Livestock | Number of livestock (tropical livestock unit) | TLU | 2.04 | 3.23 |
| Salaried employment | Hhld0 member has salaried employment (1=yes, 0=no) | 0/1 | 0.33 | |
| Main activity crop | Crop production as main activity (1=yes, 0=no) | 0/1 | 0.61 | |
| Cropped area | Total crop area | Acre | 3.53 | 3.83 |
| Available land | Total available land | Acre | 4.81 | 6.20 |
| **Standard inputs** | | | | |
| Labor | Total labor used for maize production | Man-day/ha | 136.18 | 118.69 |
| Seed | Quantity of seed used | Kg/ha | 21.48 | 17.47 |

| Variable | Variable description | Unit | Mean | Std.Dev |
|---|---|---|---|---|
| Mineral fertilizer | Quantity of mineral fertilizer used | Kg/ha | 43.33 | 84.63 |
| Capital | Production equipment | Ksh/ha | 1410.14 | 2460.17 |
| **Damage abatement inputs** | | | | |
| Insecticide | Quantity of insecticide use | Kg/ha | 1.58 | 3.86 |
| BC level | Biological control rate of parasitism | Percent | 23.49 | 18.35 |
| Use insecticide | Have use insecticide (1=yes, 0=no) | 0/1 | 0.34 | |
| **Plot characteristics** | | | | |
| Low fertility | low soil fertility level (1=yes, 0=no) | 0/1 | 0.18 | |
| Medium fertility | Medium soil fertility level (1=yes, 0=no) | 0/1 | 0.71 | |
| High fertility | High soil fertility level (1=yes, 0=no) | 0/1 | 0.10 | |
| Improved variety | Used improved maize varieties (1=yes, 0=no) | 0/1 | 0.64 | |
| Traditional variety | Used traditional maize varieties (1=yes, 0=no) | 0/1 | 0.29 | |
| **Access to development services** | | | | |
| Extension | Distance to the extension office | Km | 5.62 | 4.68 |
| Distance to 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 | Participated in training (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) (1=yes, 0=no) | | 0.30 | |
| Agroecology2 | Dry Mild altitude (DM) (1=yes, 0=no) | | 0.27 | |
| Agroecology3 | Moist Mild altitude (MM) (1=yes, 0=no) | | 0.13 | |
| Agroecology4 | Dry Transitional (DT) (1=yes, 0=no) | | 0.06 | |
| Agroecology5 | Moist Transitional (MT) (1=yes, 0=no) | | 0.15 | |
| Agroecology6 | Highland Tropical (HT) (1=yes, 0=no) | | 0.10 | |
| Release point (RP) | Where bio-agent were released (1=yes, 0=no) | | 0.25 | |

| Variable | Variable description | Unit | Mean | Std.Dev |
|---|---|---|---|---|
| 15 km from the RP | 15 km from the release point (1=yes, 0=no) | | 0.25 | |
| 30 km from the RP | 30km from the release point (1=yes, 0=no) | | 0.27 | |
| 45 km from the RP | 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 | |
| Western region | Western region (1=yes, 0=no) | | 0.05 | |
| Nyanza region | Nyanza region (1=yes, 0=no) | | 0.15 | |

Source : Author's household survey.

### 3.8.2 Poverty and food security impacts of biological control

#### 3.8.2.1 Estimation procedure

In order to implement the continuous treatment effect analysis and deduct impact parameters, the ATE-regression using the equation 3-13 in the theorethical framework was estimated. The outcome variables ($y_i$) comprises poverty indicators (expenditure/income, headcount, poverty gap and poverty severity) and food security indicators (access, stability and utilization indicators). Control variables $x_i$include household and plots characteristics as presented in Table 3-1.

#### 3.8.2.2 Treatment and outcome variables

##### 3.8.2.2.1 Treatment variable: BC level

The treatment variable is the biological control level expressed by the rate of parasitism by the released natural enemies provided by entomologists at village level. For purpose of description, four classes were created based on the first, second and third quartiles got from the sample (Table 3-2).

**Table 3-2**: Classes of Biological Control level

| Class of BC level | BC level interval (%) | Number of Households |
|---|---|---|
| 1 | [0 – 12] | 188 |
| 2 | ]12 – 21] | 142 |
| 3 | ] 21 – 36] | 126 |
| 4 | > 36 | 144 |
| Total | | 600 |

Source : Author’s computation base on entomololy survey results 2015

### 3.8.2.2.2 Poverty outcome variables

With respect to the poverty outcome variables, household income, expenditures as well as poverty measures were considered. The most conventional approach of poverty estimation is monetary metric involving the use of income or expenditures (Haughton and Khandker; 2009). Expenditures have been indicated to be a better indicator of poverty measurement compared to income (Coudouel *et al.*, 2002; Haughton and Khander; 2009). In this study, we considered both indicators for comparison purposes. In addition, the use of per capita income or expenditure that represent the total income or expenditure divided by the household size is frequently subjected to criticism as the per capita income does not always reveal the intra-household diversity and does not take into account economies of scale in consumption and the existence of difference in child and adult needs. To account for this, the adult equivalent scale is used instead of the household size to compute the income and expenditure per adult equivalent. To convert demographic composition for a household into an equivalent number of adults (AE), literature provides many adult equivalent scales that comprise among others the OECD ( $AE = 1 + 0.7(A - 1) + 0.5C$), the OECD-modified ($AE = 1 + 0.5(A - 1) + 0.3C$) and the Cutler &Katz formula ($AE = (A + \alpha C)^{\beta}$); where A stands for the number of adults, C the number of children, $\alpha$ coefficient reflecting the needs for a child relative to an adult and β representing the overall economies of scale in a household. The Cutler&Katz formula was considered in this study beacause it relative flexibility.

From the equivalent adult income and expenditure outcomes, we derived poverty indices using the Foster-Greer-Thorbecke (FGT) class of poverty measures (Foster *et al.*, 1984) which is formulated as follows:

$$P_\alpha(w,z) = \frac{1}{n}\sum_{i=1}^{m}\left[max\left(\frac{z-w_i}{z},0\right)\right]^\alpha \qquad (3\text{-}42)$$

Where w is the vector of household income or expenditure, z is the poverty line; $z - w_i$ is the income or expenditure shortfall for the ith household, m is the number of poor households, n total number of households, $\alpha$ is the poverty aversion parameter. Its simplified form used here for household level poverty is expressed as follows:

$$P_\alpha(w,z) = \left[max\left(\frac{z-w_i}{z},0\right)\right]^\alpha \qquad (3\text{-}43)$$

The two key parameters in this formula are the poverty line ($z$) and the poverty aversion ($\alpha$). The poverty line stands for a threshold that separates poor from non-poor households. The poverty line of Ksh 1562 per month used in this study is from the general value for Kenya found in the Kenya National Bureau of Statistics report (KBS, 2015). The value of $\alpha$determines the type of poverty index and higher values express greater sensitivity of the poverty measures. When $\alpha = 0$, the index yields the poverty headcount which in this case is equal to 1 if the household income or expenditure is less than the poverty line and 0 otherwise. When $\alpha = 1$, the index is the poverty gap index which is a measure of depth of poverty or the distance separating the poor from the poverty line. When $= 2$ , we obtain the squared poverty gap which is a measure of the poverty severity that consider the inequality among the poor. The computed values for the per adult equivalent income and expenditure as well as the different poverty indexes distributed across the classes of biological control are presented in Table 3-3. The one-way test using Kolmigorov Smirnov specification shows statistically significant differences for expenditure-base poverty indexes. However, these findings are just descriptive and could not have causal effect interpretation, since many other potential factors could be responsible for the observed differences and have to be controlled for for robustness.

**Table 3-3**: Average income, expenditure and poverty profile of household per BC classes

| Class of BC level | Income per year (000 Ksh) | Poverty (income-base) | | | Expenditure per year (000 Ksh) | Poverty (expenditure-base) | | |
|---|---|---|---|---|---|---|---|---|
| | | Headcount index (%) | Poverty gap index (%) | Poverty severity | | Headcount index (%) | Poverty gap index (%) | Poverty severity |
| 1 | 76.62 | 0.34 | 0.15 | 0.09 | 41.88 | 0.38a | 0.12ac | 0.05ac |
| | (195.48) | (0.48) | (0.26) | (0.18) | (69.98) | (0.49) | (0.19) | (0.11) |
| 2 | 48.54 | 0.30 | 0.13 | 0.08 | 38.10 | 0.20a | 0.05b | 0.02b |
| | (59.44) | (0.46) | (0.25) | (0.18) | (26.12) | (0.40) | (0.13) | (0.06) |
| 3 | 42.01 | 0.25 | 0.10 | 0.05 | 38.32 | 0.21a | 0.07c | 0.04c |
| | (31.27) | (0.44) | (0.21) | (0.14) | (30.59) | (0.41) | (0.18) | (0.11) |
| 4 | 54.29 | 0.35 | 0.15 | 0.09 | 36.84 | 0.28b | 0.10c | 0.05c |
| | (77.80) | (0.48) | (0.26) | (0.20) | (35.42) | (0.45) | (0.21) | (0.14) |
| Total | 57.35 | 0.32 | 0.13 | 0.08 | 39.03 | 0.28 | 0.09 | 0.04 |
| | (120.82) | (0.47) | (0.25) | (0.18) | (46.78) | (0.45) | (0.18) | (0.11) |

( ) = Standard deviation of the mean. Figures with different letters are statistically significantly different at 5% level

Source : Author's household survey.

#### 3.8.2.2.3 Food security outcome variables

Examining whether the spread of the BC agents and food security at household level are interrelated is of key importance in this study. Food security is conceived as a combination of four major components namely accessibility, availability, utilization and stability of food and being food insecure is to lack or not achieve one of these components (FAO, 2002). Measuring food security has evolved along with the concept and has become challenging as it is difficult to find a single indicator that could jointly capture all the above-cited dimensions of the concept. Literature provides a wide range of indicators to measure food security. For example, Hoddinot (1999) points out the existence of approximately 450 indicators of food security. In this study, we covered various indicators to reflect the multi-dimension features and the four above-cited components of food security at household level.

The availability component which involves the different ways of making food available to the household (production, food donation or aid, etc) can be considered as the supply side of food security (Magrini and Vigani, 2016). A comprehensive analysis of productivity-effect was provided in the first objective of this dissertation research.

For the accessibility which concerns the ability of the household to access food in adequate quantity and quality with the purpose of ensuring a safe and nutritious diet (FAO, 2006), the following indicators were considered:

- *Household per capita food expenditure*: This represents the total expenses on food in the household on the household size expressed in adult-equivalent units following. This indicator was also used in Kassie *et al.* (2014) and Shirefaw *et al.* (2014) in impact assessment of agricultural technology on food security.
- *Per capita daily calorie intake*: This indicator measures the total calorie consumption in the household. The quantities of the different food obtained from the household consumption survey were converted in calorie using the standard caloric conversion tables in Hoddinot (1999). The number of calories available in a type of food was computed by multiplying the quantity of the food by its corresponding number of calorie in 1 kg. The total calorie intake at household level was divided by the household size in adult-equivalent to obtain the per capita daily calorie intake.
- *Food insecurity indexes*: The indexes comprise the food insecurity headcount, the food insecurity gap and the squared food insecurity gap as defined in Dutta *et al.* (2007). The indexes represent members of class measures provided in Foster *et al.* (1984) and consequently the method of computation is analogous to the Foster-Greer-Thorbreek formulas (3-43) used in this study for poverty analysis. The corresponding food insecurity line (cut-off value between food-secure and food-insecure households) is the

required quantity of calorie sufficient to maintain an active and healthy life. The FAO defined this to amount 2250 Kcal per adult daily (Agola and Awange, 2014)

For the food utilization which concerns the household's ability to make use the food accessibility, the following indicators were considered:

- *Simple dietary diversity* (SDD): It is an attractive proxy indicator that reflects the quality of diet as it represents the number of food groups consumed during a determined period of time (Swindale and Billinsky, 2005). This indicator is a simple sum of the number of different foods eaten in a household in 30 days (Hoddinot, 1999).
- *Weighted Dietary Diversity* (WDD): The difference between the WDD and the SSD is that the former is calculated as a weighted sum, where the weights reflect the frequency of consumption, and not merely the number of different foods. Following Hoddinott (1999), the weights considered for this study are 24, 10, 3 and 0 for whether the food group is eaten in 16 to 30 days; 4 to 15 days; 1 to 3 days and 0 day respectively.

For the stability component which seeks to comprehend the ability of household to reduce their vulnerability to food insecurity, these indicators were considered:

- *Simple coping strategies* (SCS): This indicator was proposed by Maxwell (1996) to divert from the largely existing food consumption based indicators and incorporate elements of vulnerability in food security concept. Coping strategy encompasses the mechanisms of facing short term declining in food availability (Davies 1993). The index is computed from answers ("often", "from time to time", "rarely" and "never") to a series of six questions from a seven-days recall survey. The questions include "Eating food that are less preferred", "Limiting portion size", Borrowing food or money to buy food", "Maternal buffering", "Skipping meal" and "Skipping eating for whole days".

SCS is equal to the number of strategies that the household used often, from time to time, or rarely (Hoddinott, 1999).

- *Weighted coping strategies* (WCS): This indicator is obtained through the same calculation method as the SCS but weights reflecting the frequency of use of strategies are applied. Hence, coefficients 4, 3, 2 and 1 are affected to the answers “often”, “from time to time”, “rarely” and “never” respectively.
- *Weighted coping strategies* (WCS2): For this indicator, weights reflecting frequency of use but also severity of the household responses are applied. Coefficients 1, 2 and 3 are ascribed to the answers of questions 1 to 4, 5 and 6 respectively

The higher the indicators, the more food-insecure is the household. This implies that a negative coefficient of the treatment will suggest an improvement in the ability of the household to adapt to short term food shortage.

We extended these set of indicators to two new others which take into account the household hunger, uncertainty about the household food supply, insufficient food quality, insufficient food intake, and its physical consequences.

- Household Hunger Scale (HHS): This indicator was developed and validated for cultural use to measure the household hunger in food insecure area and is useful in evaluating policy and programmatic interventions (Ballard *et al*., 2011). The computation of this indicator is based on a series of answers to some survey questions following Ballards *et al.* (2011).
- Household Food Insecurity Access Scale (HFIAS): Introduced by Coates *et al*. (2007) in the series of Food and Nutritional Technical Assistance (FANTA) indicators, the HFIAS score is a continuous measure of the degree of food insecurity (access) in the household. It was designed to capture household behaviors signifying insufficient

quality and quantity, as well as anxiety over insecure access (Maxwell *et al.*, 2014). This is generated through answers from a series of nine occurrence questions that ask whether a specific condition associated with the experience of food insecurity ever occurred during the previous four weeks (30 days).

The higher the score (HFIAS, HHS), the more food insecurity (access) the household experienced. The lower the score, the less food insecurity (access) a household experienced.

The computed values for the food security outcomes and distributed across the classes of biological control are are summarized in Table 3-4. The one-way test using Kolmigorov Smirnov specification shows statistically significant differences between classes for food expenditure, the dietary diversity indicators and the coping strategy indices. However, these findings on differences could not be given causal effect interpretation, since many other potential factors could be responsible for the observed differences and have to be controlled for for robustness.

**Table 3-4**: Average values of food security indicators by BC class

| **Classes of BC (N)** | **Class 1 (188)** | **Class 2 (142)** | **Class 3 (126)** | **Class 4 (144)** | **Pooled sample (600)** | **F-stat** | |
|---|---|---|---|---|---|---|---|
| ***Per equivalent adult food expenses (x000 Ksh)*** | 14.47 | 20.39 | 17.35 | 14.61 | 16.51 | 7.16 | *** |
| | (11.51) | (14.77) | (11.87) | (13.10) | (13.00) | | |
| ***Household caloric acquisition*** | | | | | | | |
| Per equivalent adult calories intake (Kcal) | 2037.06 | 2193.65 | 2087.94 | 2162.72 | 2114.96 | 0.27 | |
| | (1910.37) | (1846.41) | (1436.27) | (1590.85) | (1726.43) | | |
| Food insecurity headcount | 0.69 | 0.68 | 0.65 | 0.60 | 0.66 | 0.59 | |
| | (0.46) | (0.47) | (0.48) | (0.49) | (0.48) | | |
| Food insecurity gap | 0.30 | 0.29 | 0.27 | 0.29 | 0.29 | 0.17 | |
| | (0.28) | (0.30) | (0.28) | (0.32) | (0.29) | | |
| Food insecurity severity | 0.17 | 0.17 | 0.15 | 0.186 | 0.17 | 0.45 | |
| | (0.22) | (0.26) | (0.22) | (0.28) | (0.24) | | |
| ***Dietary diversity*** | | | | | | | |
| Simple dietary diversity | 33.28 | 34.98 | 30.79 | 32.56 | 32.99 | 2.49 | * |
| | (12.54) | (13.35) | (12.67) | (12.55) | (12.81) | | |
| Weighted dietary diversity | 496.70 | 451.02 | 421.25 | 433.33 | 454.84 | 8.88 | *** |
| | (119.07) | (162.76) | (146.10) | (145.63) | (145.20) | | |
| Household hunger scale | 0.89 | 0.78 | 0.60 | 0.66 | 0.75 | 2.55 | * |
| | (1.22) | (1.21) | (0.68) | (0.80) | (1.04) | | |
| Household Food Insecurity Access Scale | 5.63 | 5.51 | 4.07 | 4.19 | 4.93 | 2.68 | ** |
| | (6.93) | (7.07) | (4.96) | (5.24) | (6.24) | | |
| ***Indices of household coping strategies*** | | | | | | | |
| Simple coping strategies | 1.78 | 1.66 | 1.42 | 1.47 | 1.60 | 0.91 | |
| | (2.23) | (2.32) | (2.10) | (1.89) | (2.15) | | |
| Weighted coping strategies | 8.51 | 8.28 | 7.64 | 7.83 | 8.11 | 2.30 | * |
| | (3.65) | (3.56) | (2.52) | (2.70) | (3.21) | | |
| Weighted coping strategies | 12.37 | 12.00 | 11.02 | 11.15 | 11.71 | 3.17 | ** |
| | (5.32) | (4.94) | (3.35) | (3.61) | (4.52) | | |

( ) = Standard deviation of the mean.
Source : Author's computation from household survey data.

### 3.8.3 Welfare effect analysis from the biological control

#### 3.8.3.1 Biological control induced supply shift parameter

While referring to the theoretical framework and the formula obtained for the producers, consumers and total surplus in equations (3-24; 3-25; 3-26), the $K_t$ parameter representing the BC research-induced supply shift parameter is found to be critical in determining the benefits from the BC spread. The supply shift parameter was estimated by Alston *et al.* (1995) to be equal to:

$$K_t = \left(\frac{j_t}{\varepsilon}\right) - c_t \qquad (3\text{-}44)$$

where $j_t$ is the proportionate change in production due to BC intervention at time t, $\varepsilon$ the price supply elasticity of the product and $C_t$, the cost increase incurred by the presence of the BC agent. Biological control is a self-spreading and self-sustained technology that prevents farmers from spending any additional cost. This implies that the total cost of production remains unchanged and rending the parameter $c_t$ in Equation (3-44) to be equaled to zero. Therefore, the expression of the supply shift equation is reduced to the ratio ( $\frac{j_t}{\varepsilon}$ ).

While $\varepsilon$ is provided by the literature on maize and sorghum supply studies, the parameter $j_t$ still need to be estimated. The parameter represents the total increase in production attributable to the BC intervention. It's given by the following equation:

$$J_t = \sum_i^n (\Delta BC_{it} * S_{it} * A_t) \qquad (3\text{-}45)$$

With $\Delta BC$ accounting for yield increase due to the presence of a biological control agent or combination of agents, $i$ the released and established species of the bio-agents and their combination. *C. flavipes* (Cf), *and X. stemmator* (Xs) as well as their combination (Cf, Xs). *S* is the rate of BC area coverage which is the ratio of the total area covered by a released BC agent (or combination of agents) $i$ and the total acreage under considered crop (maize or sorghum), $A$ is the total acreage under considered crop and *t* represents the time. The parameter $j_t$ is then derived from the equation (3-44) as proportion of total production at the year t as ($j_t = J_t/Y_t$) where $Y_t$ stands for the total production of maize or sorghum at the defined year t. Therefore, the overall formula for estimating the BC-research supply shift becomes:

$$K_t = \frac{1}{\varepsilon * Y_t}\left(\sum_i^n(\Delta BC_{it} * S_{it} * A_t)\right) \qquad (3\text{-}46)$$

#### 3.8.3.2 Yield gains attributable to the BC intervention ($\Delta BC$)

The yield gains due to each of the released bio-agents have been sourced from results on exclusion experiments conducted by entomologists. Researchers conduct the so-called exclusion experiments to determine the intrinsic gain due to the parasitism by the bio-agents (Kfir, 2002; Cugala, 2007). These trials entail setting plots in fully protected, unprotected and exclusion plots as treatments. The unprotected plots are those let without any plant protection and then represent where the BC activities occurred naturally. The exclusion plots were sprayed with selected insecticide to partially eliminate the natural enemies and then were referred to as the non-BC plots. On the fully protected plots, natural enemies and stemborers pests have been totally removed. Yield losses due to the stemborers attack in the absence of the natural enemies were obtained from the difference between the expected yield from the fully protected and exclusion plots. The difference between the yield from unprotected and exclusion plots is of high interest for the present study and represent the yield gain due the biological control at plot level. Hence, the yield gain due to BC was 26.1% in Chokwe, 11.2% in Machipanda and 7.6% in Lichinga in Mozambique (Cugala, 2007). The mean of these three percentages (14.96%) has been considered in this study for *X. stemmator*. Zhou *et al.* (2001) estimated the yield gain due to *C. flavipes* at 10% and this proportion has been considered for *C. flavipes* in the present study. In addition, based on the findings from Zhou *et al.* (2001) on the impact of bio-agent pests parasitism[9] over time, we assumed the BC-induced gain not be constant along the timeframe of our analysis. Following the parasitism rate trends, we consider 5% of the above-found yield-gain for the first three years, 18% for the fourth year, 50% for the fifth year and the constant 100% from the sixth year.

#### 3.8.3.3 Evolution of the BC-covered area

The biological control is a self-spreading technology and consequently the evaluation of its impact largely depends on the extent to which the released natural enemies really spread. The measurement of the area covered by BC in this impact evaluation constitutes a challenge as data on the follow-up and yearly monitoring of the spread are missing and mostly for the most recent releases. However, models on the organism spreading are available in the literature: Waage's function $A_t = 4D\pi r_m t^2$ where $A_t$ is the area occupied at time t, $D$ is the population diffusion coefficient and $r_m$ the intrinsic rate of the population growth; Chock's exponential function $A_t = f * e^{gt}$ where $A_t$ is the proportion of acreage where the biocontrol agent is established in year t after release, $f$ is the intercept coefficient, g is a constant specific to the dispersal rate, and e is the base of the natural logarithm (≈ 2.718).

These functions do not integrate the complexity that can imply a time-variant and multiple agents-based BC program. In other words, the possibilities of multiple points of release, the possibility of diversity in the released bio-agents and the overlapping probability of the spread of two or more different bio-agents are of high importance in spread modeling. Hence, to approximate the area covered by the BC-spread annually, spatial analysis using geo-processing tools of GIS software has been used. All the GIS coordinates of the release points were first checked and documented. I then modeled the spread around each release benchmark site in the

[9] Based on host-parasite interaction model, the impact study by Zhou *et al* (2001) demonstrated the trends of stemborer-pest parasitism by bio-agent to show a latent period (first three year) an uptake period (three years) and a plateau (maximum) during the remaining period. And then, higher impact from BC-agent is really effective after several years following the release.

four encompass directions using the method of concentric circles respecting the year of release and the appropriate specific dispersal rate.

In this assessment, the annual spread rates were taken from various sources. In fact, the literature on the dispersal rate provides many figures for the first released species *C. flavipes.* Base on this species' recovery in Northern Tanzania where no release has been made before, Omwega *et al.* (1997), assuming the origin to be the inadvertent escape from Mbita, estimated the spread rate of *Cotesia* to be 60 kilometers per year. In another study conducted by Assefa *et al.* (2008) in Ethiopia, the dispersal rate of *Cotesia* was found to be higher than 200 kilometers per year. Another recent study estimates the spread distance at 11.23 kilometers per year. The principle of the "least favorable assumption case" led us to select the minimum distance found in the literature. The dispersal rate was estimated at 8.3 km per year for *X. stemmator* (from Cugala, 2007).

Based on these spread distances, the BC covered area was modeled for all of release points for specified years and the area under BC spread (Figure 3-6) has been calculated using the GIS software functions. The spread modeling has been made using the agricultural land map. The appropriate coefficients were then used to calculate the annual maize and sorghum cultivated area under BC and we finally derived the proportions of maize and sorghum cultivated land under BC.

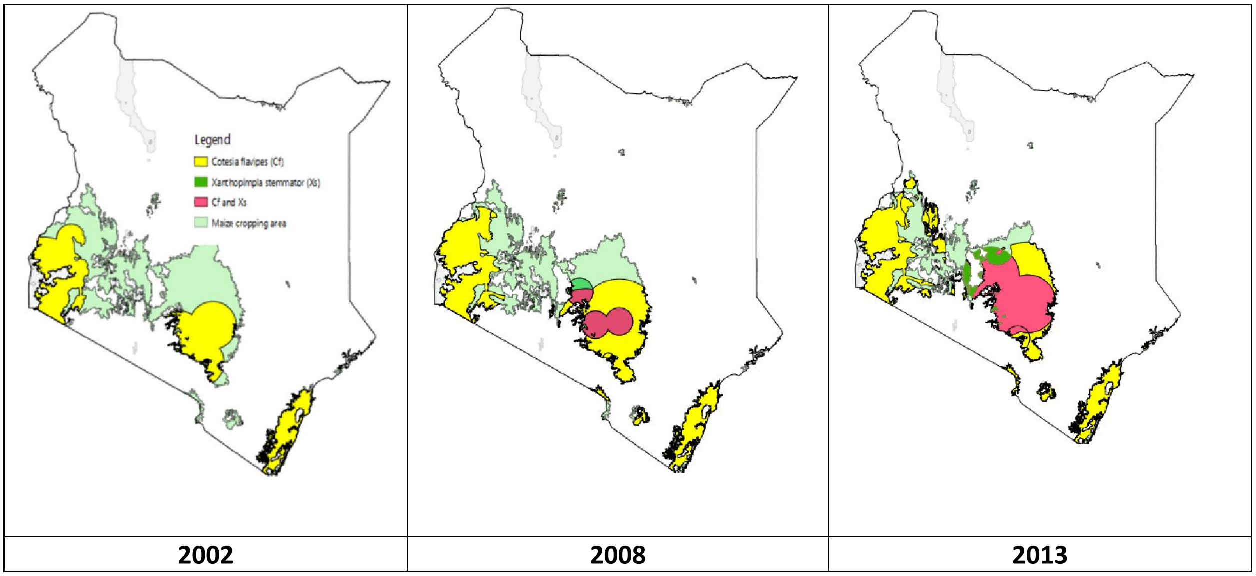



**Figure 3-6** : Spread of parasitoids in the study areas in 2002, 2008 and 2013

Source: Author's computation (2015)

#### 3.8.3.4 Price elasticity of supply and demand and prices data

As previously demonstrated in the section on the economic surplus model, price elasticity of supply and demand (ε and ŋ) are key determinants in the estimation of consumer, producer and the overall social benefits. The estimates of price supply elasticities are found to equal 0.11 in Olwande *et al.* (2009), 0.36 in Onono *et al.* (2013), 0.53 (short run) and 0.76 (long run) in Mose *et al.* (2007). According to Alston *et al.* (1995), when data on supply elasticities is lacking, it becomes expedient to rely on the unit price elasticity of supply. The most closed figure to the unit elasticity supply, that is 0.76, has been referred to in this assessment. On the other hand, all the price elasticities of demand found in the literature (Table 3-5) with value lower than one have been considered in the assessment as they confirmed the necessity nature of maize and sorghum.

Maize and sorghum time-series data on prices have been accessed from FAO database and other documents and compiled in curves shown in Figure 3-7. Maize and sorghum prices steadily increased from 1990 to 2013. The highest price for each curve is observed in 2008 or 2009 and this confirms the rise in price following the 2008 world food crisis. In the estimation of the total product value, these prices were converted to real using the food consumer price indexes assessed from the FAO and African Development Bank (AfDB) databases.

**Table 3-5:** Prices elasticity values used in the surplus calculation

| Parameter | Value | Crop | Source |
|---|---|---|---|
| Supply elasticity | 0,76 | Maize | Mose *et al.* (2007) |
| | 0,2 | Sorghum | Diao *et al.* (2008) |
| Demand elasticity | - 0,8 | Maize | Nzuma and Sarker (2008) |
| | -0,42 | Sorghum | Diao *et al.* (2008) |

Source: Author's household survey.

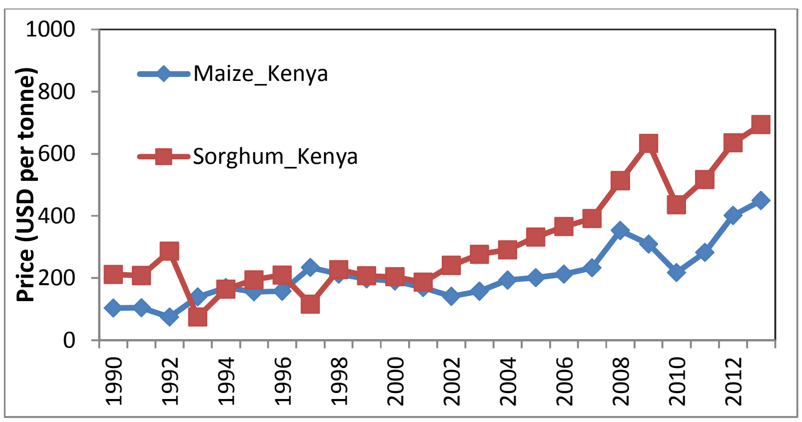



**Figure 3-7**: Trends in maize and sorghum prices in Kenya

Source : FAO, 2014

#### 3.8.3.5 BC – research investments

The BC research undergoes a series of processes including pests identification through its occurrence and intensity of damage, determination of their distribution extent and potential impact, identification and study of appropriate beneficial organisms and foreign exploration of the appropriate and potentially efficient parasitoids. Once identified, the shipment of the parasitoids is organized with all requirements (permit for importation, acquisition of material for handling and escape avoidance, etc.). The quarantine of imported parasitoids is then set to avoid premature escape and contamination by local species or strains. The bio-agents mass rearing follows and is found to be a determinant step in the success of biological release in that it provides the required number of individuals with effective and high performance in pest's parasitism. The field-releases of the natural enemies are performed and followed by the recovery studies for follow-up. Evaluations comprising frequent extensive sampling for the spread analysis and exclusion experiments are conducted to measure the success or failure of the release program.

This set of activities has been implemented by *icipe* as part of its BC program which implied investments in personal including scientists, administrative, technicians and dissertation scholars. This program also invested in laboratory equipments and vehicles for the projects, importation and mass rear natural enemies, basic surveys, studies and consultations, training of national scientists, extensionists and farmers. Data on the annual total cost of these activities have been assessed from project documents and evaluations reports. Basically, the Biological Control program is made of a series of four projects that have been implemented from 1990 to 2005: the first from 1990 to 1992 with a cost of USD 0.6 millions, the second from 1993 to 1996 with a total cost of DFI[10] 3.87 million the third from 1997 to 2001 with a total cost of DFI 7.5 million and the fourth from 2002 to 2005 with a total cost of USD 5.52 million. The total annual expenses have been partitioned base on the 10 countries (Kenya, Eritrea, Madagascar, Malawi, Mozambique, Somalia, Tanzania, Uganda, Zambia, and Zimbabwe) that benefited from the program and the share of the study country was considered.

[10] DFI is the "Dutch Guilders", former currency of the Netherlands (1 unit worth 0.56 USD, value of 23.02.2015)

# CHAPTER FOUR: EMPIRICAL RESULTS AND DISCUSSIONS

## 4.1 Socio-economic characteristics and farmers knowledge of biological control of stemborers

### 4.1.1 Household characteristics

**Error! Reference source not found.** reports summary statistics of some selected characteristics of the surveyed households at region level. For the numerical characteristics, I conducted one-way ANOVA test and subsequently performed the multiple comparison tests between regions using the Bonferroni adjustment procedure. For the categorical characteristics, the chi-square and Fisher's exact tests were used for the overall significance, and to test the significance of proportions between regions, the multiple comparisons based on Marascuilo procedure was used. Regions were compared with respect to some thirty-one variables. Out of these, five were not significant while differences were observed between the regions for all the other remaining variables. The average household size was approximately 6 persons and this size differs significantly between regions. Households in Coastal and Western regions present the highest size (almost 7 persons) while there was no statistically significant difference in household size between the other regions, as each of them had an average of 5 persons. Regarding the number of years of residence in the surveyed villages, households in the Eastern region had significantly higher dwelling duration than the other regions. The number of years of residence is a potential determining factor in the knowledge of stemborer pests' patterns including their dynamics in infestations as well as knowledge of the released bio-agents and the effectiveness of the biological control in a particular area. For the experience, farmers had an average of 22 years in agricultural activities and farmers of Eastern have more experience than those from the other regions.

**Table 4-1 :** Descriptive statistics of the surveyed household characteristics

| | Regions | | | | | Pooled (600) | F-stat / Pearson Chi2/ Fisher's exact |
|---|---|---|---|---|---|---|---|
| | Coast (N=210) | Eastern (N=180) | Rift (N=90) | Western (N=30) | Nyanza (N=90) | | |
| Age of the household head (years) | 48.83a (13.56) | 49.87a (14.43) | 47.51a (14.00) | 47.67a (14.74) | 45.59a (14.43) | 48.40 (14.11) | 1.54 |
| Female-headed household (%) | 27.62a | 25a | 27.78a | 33.33a | 35.56a | 28.33 | 3.73 |
| Household size | 7.09a (2.88) | 5.37b (1.96) | 5.27b (2.19) | 6.67a (2.59) | 5.48b (2.32) | 6.04 (2.56) | 17.21*** |
| Residence in the locality (years) | 34.10a (19.16) | 39.87b (17.59) | 30.23ac (16.33) | 25.67a (22.37) | 27.84a (19.32) | 33.87 (19.02) | 9.41*** |
| Experience in agriculture (years) | 22.11ac (12.29) | 23.93a (13.67) | 18.77bc (13.52) | 18.63ac (13.62) | 19.03c (14.19) | 21.51 (13.38) | 3.7*** |
| Can read and write (%) | 70a | 87.78b | 90b | 96.67b | 87.78b | 82.33 | 35.34*** |
| Years of formal schooling | 6.10a (4.67) | 8.68b (3.66) | 9.20b (4.42) | 9.97b (3.56) | 8.03b (3.35) | 7.82 (4.31) | 15.72*** |
| Primary | 49.52a | 50.56a | 43.33a | 46.67a | 64.44a | 51 | 9.049* |
| Junior Secondary | 6.19a | 27.78bc | 23.33bcd | 10abd | 16.67abd | 17 | 35.816*** |
| High school | 14.29a | 2.78b | 11.11ab | 20ab | 6.67ab | 9.5 | 20.014*** |
| Received training (%) | 40a | 32.78a | 46.67a | 46.67a | 33.33a | 38.17 | 7.08 |
| Training on pest control (%) | 16.67a | 6.11b | 10.00ab | 13.33ab | 4.44b | 10.50 | 15.97*** |
| Contact with extension (%) | 43.33b | 29.44a | 31.11a | 23.33a | 30a | 34.33 | 12.23** |
| Distance to extension office (km) | 6.10a (4.53) | 4.92ac (4.72) | 6.40ac (6.09) | 4.33bd (6.14) | 5.90acd (3.61) | 5.68 (4.84) | 2.53* |
| Contact with research (%) | 10.95a | 22.91b | 10b | 8b | 19.51b | 15.53 | 14.95*** |
| Contact with other program (%) | 27.14ac | 15.82abc | 9.09b | 11.54abc | 27.16ac | 20.27 | 18.71*** |
| Belong to farmers association (%) | 30.48ab | 28.33ab | 21.11ab | 56.67a | 25.56b | 29 | 14.65*** |
| Distance to the nearest market (km) | 4.42 (4.37) | 3.06 (2.93) | 4.07 (4.78) | 1.08 (0.38) | 2.51 (2.47) | 3.51 (3.80) | 9.11*** |
| Distance to the nearest tarmac road | 14.64 (16.44) | 8.98 (10.09) | 1.94 (2.03) | 1.08 (0.44) | 3.15 (3.99) | 8.71 (12.48) | 30.09*** |
| Matrimonial status (Married) (%) | 83.81a | 81.67a | 76.67a | 83.33a | 82.22a | 81.83 | 0.694 |
| *Agro-ecological zones* | | | | | | | |
| Lowland Tropical LT (%) | 86.19 | 0 | 0 | 0 | 0 | 30.17 | 1700*** |

| | Regions | | | | | Pooled (600) | F-stat / Pearson Chi2/ Fisher's exact |
|---|---|---|---|---|---|---|---|
| | Coast (N=210) | Eastern (N=180) | Rift (N=90) | Western (N=30) | Nyanza (N=90) | | |
| Dry Mildaltitude DM (%) | 7.14 | 80 | 0 | 0 | 0 | 26.5 | |
| Moist Mildaltitude MM (%) | 0 | 0 | 0 | 0 | 83.33 | 12.5 | |
| Dry Transitional DT (%) | 0 | 20 | 0 | 0 | 0 | 6 | |
| Moist Transitional MT(%) | 6.67 | 0 | 33.33 | 100 | 16.67 | 14.83 | |
| Highland Tropics HT (%) | 0 | 0 | 66.67 | 0 | 0 | 10 | |
| Land holding (acres) | 4.85 (4.81) | 4.67 (6.38) | 6.58 (8.72) | 2.64 (3.45) | 3.95 (6.11) | 4.81 (6.20) | 9.98*** |
| Livestock own (TLU) | 2.06 (3.43) | 2.14 (3.55) | 2.37 (3.30) | 0.70 (0.75) | 1.93 (2.32) | 2.04 (3.23) | 1.6 |
| Crop production as main activity | 63.81a | 55a | 58.89a | 76.67a | 62.22a | 60.83 | 6.724 |
| Livestock as main activity | 1.9 | 0 | 0 | 0 | 5.56 | 1.5 | 14.820*** |
| Commerce as main activity | 6.67ac | 18.89b | 18.89abc | 3.33ac | 8.89abc | 12.33 | 20.204*** |

Statistically significance at *p < 0.1, **p < 0.05, ***p < 0.01; Means or percents in rows with similar letters are not significantly different at 10% ; ( ) = std. dev. of means. TLU=Tropical Livestock Unit

Source : Author's survey (2014-2015)

In general, most (82%) of the surveyed household heads could read and write, the highest percentage (97%) for this characteristic was found in Western and the lowest percentage (70%) in the Coastal region. Most of them attended school for an average of 8 years, with the Western having the highest average (10) in number of years of formal school and the Coastal region having the lowest (6 years). In average half of the surveyed household heads stopped their formal education at primary level and just few of them reached the junior secondary level (17%) and high school level (less than 10%). The role of literacy and formal education is well known in capacity building and skill enhancement and the farmers with higher level of education would likely be able to know more and better use information from innovations (Knight *et al.*, 2003).

Farmer's skill and likelihood to know about innovation also depends on the degree of exposure which can be reinforced by having attended training. In average, only 38% of the surveyed households once received training in agriculture. These proportions were not statistically significantly different across regions showing that the prevailing level of training was still low throughout the regions. This level was revealed to be worse with the training on pest control. In fact, only 11% of the total surveyed households received training on pest control. Although small, this percentage varied with the region, Nyanza region having the lowest proportion of trained farmers (4%) while the highest proportion was recorded in the Coastal region (17%).

The other characteristics that stand for potential drivers for exposure, knowledge and right perceptions of technology or innovation are access to public services such as extension and research as well as membership to farmers association where information can be shared. 34% of the surveyed households were in contact with extension officers, the highest proportion being recorded in the Coastal region (43%) and the lowest (23%) in the Western region. The distance from the household to the nearest extension office was in average 6 km and the one-way ANOVA test showed that there was a significant difference between these distances across region. Households in the Rift-valley region were located at the furthest distance (6.40 km) while households in Western were the closest (4.33 km) to extension office. With regards to relationship with research organizations, in average only 16% of the surveyed households were in contact with researchers and the highest percentage was found in Eastern region.

With regards to the distance to market and nearest tarmac road which can play a role in information sharing and contribute to knowledge and perception, the surveyed households were located in average at 4 km to the nearest market and 9 km to the nearest tarmac road. These distances varied across regions with the households in the coastal region located at the farthest distance from the market (4 km) and the nearest tarmac road (15 km) while the households of the Western region were at the shortest distance (1 km) from the two types of infrastructures.

The distribution across the agro-ecological zones shows that the households of the Coastal region were predominantly in the lowland tropical zone while the Eastern ones are predominantly in dry mildaltitude zone. Households of the Rift-valley are mostly in the highland tropics while the households in Western are mostly in the moist transitional zone and the Nyanza households mostly in moist mildaltitude zone. With respect to asset ownership, the average landholding per household is 5 acres with huge variation in regards of the standard deviation of 6 acres. The land ownership varied across regions, Rift-valley being the region where households have the widest acreage (7) while Western region households got the shortest landholding (3 acres). Livestock ownership is generally low (2 TLU) and is not statistically significantly different across region. Regarding the main source of household's revenue, higher percentage of farmers (more than 55%) have crop production as main activity and few farmers have commerce (12%) or livestock rearing (2%) as main activity.

### 4.1.2 Knowledge of the economically important stemborers

During the survey, farmers were shown picture cards displaying the life stages and symptoms of attacks and damage by the economically important stemborers. Test tubes containing the living larvae were also shown and they were asked to identify the different pests. The results from this process (Figure 4-1) showed that majority of interviewed farmers recognised the pests and the knowledge rate vary with regions for *C.partelus* ($\chi^2$ = 22.99, df=4, Pr=0.000) and *B. fusca* ($\chi^2$ = 39.68, df=4, Pr=0.000). The first pest is mostly known in Coastal Eastern and Nyanza regions while the second is mostly known in Coast, Rifth-valley and Western. Knowledge rates was found not to vary accros regions for *S.calamstis* ($\chi^2$ = 7.48, df=4, Pr=0.113). The knowledge rates reflect the ecological distribution of the pests. C*.partelus* is found in lowland area which is dominant in Coast Eastern and Nyanza regions and *B.fusca* in highland area which is dominant in Western, Rift-Valley and Taita-taveta (Coastal) whereas *S.calamistis* can be found in both ecologies.

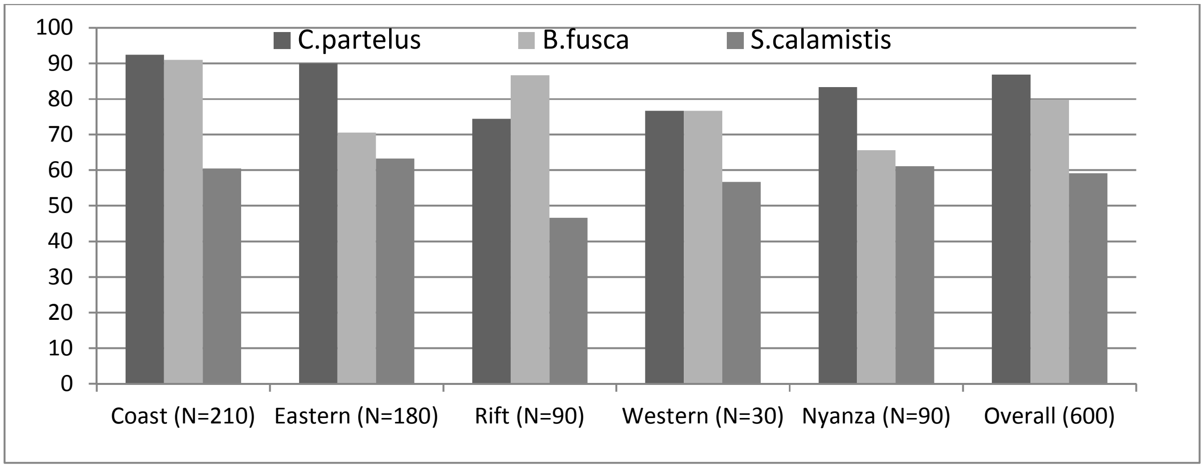



**Figure 4-1**: Knowledge of economically important stemborers pests

Source : Author's survey (2014-2015)

### 4.1.3 Knowledge of biological control of cereal stemborers

During the survey, farmers were questioned on their knowledge of the existence of leaving organisms that can control stemborers. Approximately 49% of them had knowledge of a bio-control mechanism with the highest knowledge rate (68%) in Nyanza and the lowest (41%) in Coast region (Table 4-2). The stemborers predators cited included among others ant, birds, poultry, millipedes and wasps. Farmers were also asked about their knowledge of released natural enemies (showing picture cards and glass vials with the living insects). Results showed that in general less than 25% of the interviewed farmers knew the released bio-control agents, the knowledge rates varying with regions and type of agents (Figure 4-2).

**Table 4-2 :** Knowledge of biological control

| | Regions | | | | | | Pearson Chi2/Fisher's exact |
|---|---|---|---|---|---|---|---|
| | Coast (N=210) | Eastern (N=180) | Rift (N=90) | Western (N=30) | Nyanza (N=90) | Total (600) | |
| Farmers with knowledge on existence of Biocontrol | | | | | | | |
| | 41.4 | 44.4 | 57.8 | 43.3 | 67.8 | 48.8 | 22.16*** |
| Farmers that cited these livings organisms as controlers of stemborers | | | | | | | |
| Ant | 13.8 | 0.0 | 3.3 | 3.3 | 0.0 | 5.5 | 44.70*** |
| Bird | 12.4 | 37.2 | 33.3 | 26.7 | 61.1 | 31.0 | 75.93*** |
| Poultry | 2.9 | 8.3 | 27.8 | 33.3 | 26.7 | 13.3 | 64.32*** |
| Wasp | 15.7 | 5.0 | 6.7 | 0.0 | 1.1 | 8.2 | 27.27*** |
| Milipede | 1.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 5.60 |
| Others | 0.5 | 1.7 | 0.0 | 0.0 | 1.1 | 0.8 | 2.93 |

Source : Author's survey (2014-2015)

Apart from the coastal region where 38% of farmers knew of *C. flavipes*, the majority of farmers in other regions were not aware of the insects displayed to them. This limited knowledge of biological control calls for intense education[11] training and involvement of farmers in future release programs to optimize their impacts. This also justifies the reliance on entomology survey data in identifying the presence and intensity of biological control in this economic impact assessment research.

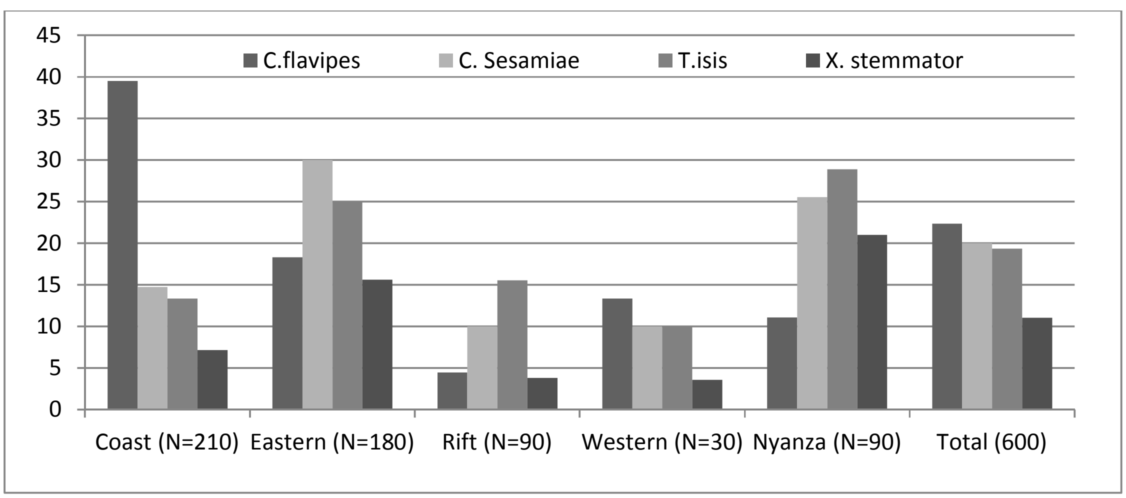



**Figure 4-2 :** Knowledge of released biological control agents

Source : Author's survey (2014-2015)

[11] Experiences in educating farmers on BC show that farmers integrate the natural enemies in their decision-making and spray less and achieve more efficient and sustainable food production (Ooi, 1996 ; Ooi and Kenmore, 2005)

## 4.2 Analyzing the productivity-effect of BC: use of production function with the damage abatement model

### 4.2.1 Insecticide use function and biological control

As previously indicated, this study used two-stage least-square estimation (2SLS) to establish the production functions because of the potential econometrical problem of endogeneity of insecticide use. However, verifying the necessity of sound utilization of this procedure seems important because when endogeneity is not a significant problem, the least squares estimator is more efficient than the two stages-least square (Wooldridge, 2015). To check the endogeneity suspicion about the insecticide use, we conducted a Hausman test (Hausman, 1978) with the conventional production function specification. This test assumes the null hypothesis of no endogeneity. The results are presented in Appendix A. Wu-Hausman F-test and the Durbin-Wu-Hausman Chi-square test gave the same results for the test on insecticide use. Both tests yield scores that are significantly different from zero at 1% level and this suggests the strong rejection of the null hypothesis of no endogeneity. This justifies statistically the use of the 2SLS estimator. Furthermore, the overidentifying restrictions test of Sargan and Basman gives non-significant score, stipulating that the considered instruments were not correlated with the error of the main regression and are valid instruments.

As a first step in this BC productivity effect assessment, the insecticide use function was established through the OLS regression of the applied amount of insecticide on maize (dependent variable) over some explanatory variables. These latters include household socio-economic characteristics (Age, formal school, experience in maize production, membership to association), the BC parasitism, the level of pest infestation (medium and high), insecticide price and the agro-ecology dummies.

Both linear and log-log functional specifications were estimated and the corresponding results summarized in Table 4-3. The log-log form shows a good explanatory power as the adjusted R square equal 0.87. Both models were globally significant as *Fstat* were significant at 1% level. Most of the coefficients show their expected signs. According to the results, labor use is statistically significant at 5% and this means, the more labor intensive the production, the more amount of insecticide is applied. Rotation was found to be positive and significant at least at 10% denoting that the use of insecticide is higher if maize is plant on the same plot for longer period. This is in line with results from Pemsl (2005) and translates the disadvantage known for the monoculture practice which favor pest development and enable for applying huge amount of pesticide. The medium to higher infestation level is associated to higher use insecticide. Farmers in the Agro-ecological zones 1, 2 and 3 were found to use much insecticide on maize production compared to the others.

Most importantly, in both models, the coefficient of parasitism is found to be negative and significant at 10% level at least, illustrating an important role of the Biological Control in insecticide use reduction. This suggests that the higher the parasitism or biological control activity, the less insecticide is applied to maize. This might mean that farmers, who are likely to be aware of the existence of the natural bio-agents, set the use of insecticide accordingly. This is in line with the results by Asfaw *et al*. (2011) who found a negative relationship between the biological control and pesticide use in cabbage production in Kenya and Tanzania. Significant reduction of pesticide use with another crop protection technology (Bt-varieties) was also reported in cotton production in China (Huang *et al.*, 2002) and in Argentina (Qaim and De Janvry, 2005). The indirect effects that may be associated to this advantage of BC include savings on cost of crop protection, potential reduction of environmental pollution risks and spending on human health.

These findings have many implications with respect to the role of the biological control in environment protection.

The substitutability of the pesticide use with Bio-agent may entail a significant reduction in quantity of chemical used and then substantially lower the direct costs associated to plant protection. When referring to the indirect costs associated with pesticide use as human health impairments, livestock product losses, lost of beneficial arthropods and birds, pesticide resistance of pests (Macharia *et al.,* 2011), the BC as alternative to pesticide use offers the possibility of lowering these detrimental effects on the environment and human health.

**Table 4-3**: Estimated coefficients for insecticide use function

| | Linear | | | Log-Log | | |
|---|---|---|---|---|---|---|
| | **Coefficient** | | **Std. error** | **Coefficient** | | **std. error** |
| Age of hhold head | -0.01 | | 0.02 | 0.00 | | 0.00 |
| Years of formal school | 0.00 | | 0.04 | 0.01 | | 0.01 |
| Association | 0.05 | | 0.36 | -0.07 | | 0.07 |
| Crop as princ. activity | 0.39 | | 0.37 | 0.06 | | 0.07 |
| Experience in maize | -0.02 | | 0.01 | 0.00 | | 0.00 |
| Hybrid variety | 0.11 | | 0.33 | 0.00 | | 0.08 |
| Labor | 0.36 | ** | 0.15 | 0.07 | ** | 0.03 |
| Rotation | 0.20 | | 0.12 | 0.04 | * | 0.02 |
| Maize yield | 0.81 | *** | 0.24 | 0.14 | *** | 0.04 |
| Low fertility | -0.32 | | 0.41 | -0.13 | * | 0.07 |
| Med. and high infest. | 0.70 | * | 0.41 | 0.23 | ** | 0.10 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Agroecology1 | 3.18 | *** | 0.67 | 0.45 | *** | 0.17 |
| Agroecology4 | 0.42 | | 0.45 | -0.06 | | 0.11 |
| Agroecology3 | 1.40 | ** | 0.64 | 0.37 | *** | 0.11 |
| Agroecology2 | 2.02 | *** | 0.72 | 0.24 | ** | 0.10 |
| BC level | -0.03 | *** | 0.01 | 0.00 | * | 0.00 |
| Price | 0.00 | ** | 0.00 | 0.52 | *** | 0.02 |
| Intercept | -6.83 | *** | 2.46 | -3.66 | *** | 0.33 |
| Number of obs | 589 | | | 589 | | |
| F(17, 571) | 8.22 | *** | | 157.27 | *** | |
| R-squared | 0.21 | | | 0.8686 | | |

*, ** and *** imply statistical significance at 10, 5 and 1% level, respectively
Source: Author's computation 2015

### 4.2.2 Production function with damage abatement specification

As second stage estimation, the production function with maize yield as dependant variable and the independent variables including the predicted values of insecticide use and biological control was estimated. Results for models of conventional (no damage-reducing consideration) specifications of production function as well as for models of production function with damage abatement specifications are presented in Table 4-4. The most often used specification form for production function in the literature is Cobb-Douglas (CD) but we chose to use translog for its flexibility and best comparative advantages. To ascertain this, a statistical test was performed to find out whether the translog form was more appropriate than the Cobb-Douglas form. Wald test of the joint significance of interaction terms in the translog ($\alpha_{ij}$in equation 3-38) form shows that the null hypothesis is rejected (*p=0.0042*, see Appendix B) indicating that translog specifications were better than Cobb-Douglas ones in fitting the collected data. Furthermore, the results of the two types of specifications of the production function show a slight improvement of the adjusted R-square[12] for translog meaning that it best fitted the empirical data. The translog as well as the CD function showed the expected signs for some productive inputs (Mineral fertilizer and seed). Most of the variables related to the farm characteristics and biological parameters were found to be statistically significant. The level of pest pressure represented by the infestation level was negative and significant at 5% level and then indicates that higher pest presence was associated with reduction in maize yield. The BC variable was positive and significantly different from zero. Hence, even with the conventional production function models, maize productivity increases with the level of parasitism by the released bio-agents showing a potential positive impact of the biological control on production.

[12] Gayawan and Ipinyomi (2009) empirically demonstrated ajusted R-square to the best criteria (compared to AIC and SIC) in the selection model based on goodness of fit

**Table 4-4:** Production functions with and without damage-abatement functions

| | Conventional functions | | Production function with damage-abatement function | | | |
|---|---|---|---|---|---|---|
| **lnyieldha** | **Cobb-Douglas** | **Translog** | **Exponential 1** | **Exponential 2** | **Logistic 1** | **Logistic 2** |
| Intercept | 5.44 *** | 5.74 *** | 14.31 | 14.83 | 7.13 *** | 7.10 *** |
| | (0.23) | (0.89) | (75.28) | (15.20) | (0.79) | (0.78) |
| Labor | -0.04 | 0.02 | -0.07 | -0.15 | -0.20 | -0.19 |
| | (0.04) | (0.26) | (0.21) | (0.22) | (0.23) | (0.23) |
| Seed | 0.35 *** | -0.20 | -0.15 | -0.18 | -0.28 | -0.27 |
| | (0.05) | (0.33) | (0.28) | (0.29) | (0.30) | (0.30) |
| Min. fertilizer | 0.11 *** | 0.14 | 0.17 | 0.15 | 0.17 | 0.18 |
| | (0.02) | (0.13) | (0.11) | (0.12) | (0.12) | (0.12) |
| Cost | -0.01 | -0.03 | -0.03 | -0.04 | 0.00 | 0.00 |
| | (0.02) | (0.11) | (0.09) | (0.09) | (0.10) | (0.10) |
| Training | -0.03 | -0.03 | -0.00 | 0.02 | 0.03 | 0.02 |
| | (0.09) | (0.09) | (0.07) | (0.08) | (0.08) | (0.08) |
| Extension | 0.18 ** | 0.22 ** | 0.20 *** | 0.21 *** | 0.23 *** | 0.22 *** |
| | (0.09) | (0.09) | (0.08) | (0.08) | (0.08) | (0.08) |
| Variety (hybrid) | 0.07 | 0.08 | 1.35 *** | 1.22 *** | 0.76 *** | 0.75 *** |
| | (0.08) | (0.08) | (0.17) | (0.15) | (0.15) | (0.15) |
| Agroecology6 | 0.77 *** | 0.58 *** | 1.51 *** | 1.45 *** | 1.07 *** | 1.07 *** |
| | (0.18) | (0.19) | (0.14) | (0.12) | (0.12) | (0.12) |
| Agroecology5 | 0.64 *** | 0.58 *** | 0.18 * | 0.13 | -0.14 | -0.14 |
| | (0.15) | (0.15) | (0.10) | (0.08) | (0.09) | (0.09) |
| Agroecology2 | -0.30 *** | -0.34 *** | 0.71 *** | 0.58 *** | 0.14 | 0.14 |
| | (0.11) | (0.11) | (0.14) | (0.11) | (0.11) | (0.11) |
| Agroecology3 | -0.12 | -0.23 | 1.16 *** | 1.18 *** | 0.91 *** | 0.91 *** |

| lnyieldha | Conventional functions: Cobb-Douglas | Conventional functions: Translog | Production function with damage-abatement function: Exponential 1 | Exponential 2 | Logistic 1 | Logistic 2 |
|---|---|---|---|---|---|---|
| | (0.14) | (0.14) | (0.17) | (0.14) | (0.16) | (0.16) |
| Agroecology4 | 0.22 | 0.18 | 0.00 | 0.01 | 0.05 | 0.05 |
| | (0.17) | (0.17) | (0.07) | (0.07) | (0.08) | (0.08) |
| High pest pressure | -0.20 ** | -0.16 ** | -0.18 *** | -0.17 *** | -0.19 ** | -0.19 ** |
| | (0.08) | (0.08) | (0.07) | (0.07) | (0.07) | (0.07) |
| Squared labor | | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 |
| | | (0.02) | (0.02) | (0.02) | (0.02) | (0.02) |
| Squared seed | | 0.14 *** | 0.12 *** | 0.12 *** | 0.13 *** | 0.12 *** |
| | | (0.05) | (0.04) | (0.04) | (0.05) | (0.05) |
| Squared Min.fertilizer | | 0.01 | -0.00 | -0.00 | -0.00 | -0.00 |
| | | (0.02) | (0.01) | (0.01) | (0.01) | (0.01) |
| Squared Cost | | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 |
| | | (0.00) | (0.01) | (0.01) | (0.01) | (0.01) |
| Labor X Seed | | -0.04 | -0.04 | -0.03 | -0.00 | -0.00 |
| | | (0.05) | (0.04) | (0.05) | (0.05) | (0.05) |
| Labor X Min.fert | | -0.03 | -0.02 | -0.02 | -0.02 | -0.02 |
| | | (0.02) | (0.01) | (0.02) | (0.02) | (0.02) |
| Labor X Cost | | 0.00 | 0.00 | 0.00 | -0.00 | -0.00 |
| | | (0.02) | (0.02) | (0.02) | (0.02) | (0.02) |
| Seed X Min.fert | | -0.01 | -0.02 | -0.01 | -0.01 | -0.01 |
| | | (0.02) | (0.02) | (0.02) | (0.02) | (0.02) |
| Seed X Cost | | -0.023 | -0.01 | -0.01 | -0.02 | -0.02 |
| | | (0.03) | (0.02) | (0.02) | (0.02) | (0.02) |

| | Conventional functions | | Production function with damage-abatement function | | | |
|---|---|---|---|---|---|---|
| lnyieldha | Cobb-Douglas | Translog | Exponential 1 | Exponential 2 | Logistic 1 | Logistic 2 |
| Min. fert X Cost | | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| | | (0.01) | (0.01) | (0.01) | (0.01) | (0.01) |
| Labor X Insecticide | | -0.02 | | | | |
| | | (0.03) | | | | |
| Seed Insecticide | | -0.01 | | | | |
| | | (0.03) | | | | |
| Min.fert X Insecticide | | -0.00 | | | | |
| | | (0.01) | | | | |
| Cost X insecticide | | 0.01 | | | | |
| | | (0.01) | | | | |
| Squared Insecticide | | 0.06 *** | | | | |
| | | (0.02) | | | | |
| Insecticide (predicted) | 0.00 | 0.13 | | | | |
| | 0.02) | (0.15) | | | | |
| Parasitism2 | 0.01 *** | 0.01 *** | | | | |
| | (0.00) | (0.00) | | | | |
| **Damage abatement input** | | | | | | |
| Intercept | | | 0.00 | 0.00 | | |
| | | | (0.10) | (0.00) | | |
| BC | | | 0.00 | 0.00 | 0.01 ** | 0.01 ** |
| | | | (0.00) | (0.00) | (0.00) | (0.00) |

| lnyieldha | Conventional functions: Cobb-Douglas | Translog | Production function with damage-abatement function: Exponential 1 | Exponential 2 | Logistic 1 | Logistic 2 |
|---|---|---|---|---|---|---|
| Insecticide (predicted) | | | 0.00 | 0.00 | 0.99 *** | 0.93 *** |
| | | | (0.04) | (0.00) | (0.01) | (0.12) |
| BC X Insecticide | | | 0.00 | | -0.00 | |
| | | | (0.00) | | (0.01) | |
| Number of obs | 589 | 589 | 589 | 589 | 589 | 589 |
| R-squared | 0.45 | 0.49 | 0.59 | 0.599 | 0.56 | 0.56 |
| Adj R-squared | 0.44 | 0.46 | 0.56 | 0.58 | 0.536 | 0.54 |

*, ** and *** imply statistical significance at 10, 5 and 1% level, respectively; ( ): Standard errors in parenthesis

Source: Author’s computation (2015)

As for the production functions including damage control functions, several specifications were tested but only two (Exponential and logistic) were reported, the other not converging or yielding weird results after thousands of iterations. For both specifications, the form with and without interaction terms (respectively exponential1, exponential2, logistic1 and logistic2) were reported. The adjusted R-square ranges from 0.5552 to 0.5931 with the higher coefficients for the exponential functional forms. However, neither the exponential1 nor the exponential2 present positively statistically significant coefficients for the BC and insecticide variables in the damage function and then favor the symmetric model (conventional models). Hence, only both logistic models gave significant damage-abatement variables confirming the theory on asymmetry in input use for BC and insecticide.

Both models depicted many significant coefficients with signs in concordance with prior expectations. Within farming characteristics, hybrid variety is revealed as an important influencing factor in maize production, as its coefficient is positively and statistically significant at 1% level. This indicates maize production was higher with hybrid varieties compared to the traditional varieties. Environment with pest pressure above the medium is associated with reduction in productivity as the coefficient of the higher-pressure variable is negative and statistically different from zero at 5% level. The agro-ecological zones dummies display positive and significant at 1% level coefficients for Agro-ecology 6 and 3 (highland tropical and moist-mid altitude) confirming the higher potential in maize production of these regions compared to the reference agro-ecology 1 (the lowland tropics). Being in contact with extension service is statistically significant at 1% level indicating that farmers who benefit from the services of extension agents from the Ministry of Agriculture have higher productivity compared to their counterparts without access to such services.

For the damage-abatement input, in the logistic2 model, both were positive and significantly different from zero at 10% level for BC coefficient and 1% level for the insecticide. This indicates that the presence of the released bio-agents is playing an important role in maize production. In other words, biological control of stemborers pests has positive impact on maize yield. This corroborates the results from Asfaw *et al*. (2011) who found the same significant relationship between the reliance on biological control in cabbage production in Kenya and Tanzania. Evidence of productivity increase using biological control was demonstrated in many other studies on other crops (Bauer *et al*., 2003; Lv *et al*., 2010; Neuenschwander *et al*., 1989; Otsman *et al.*, 2003).

The other damage-abating input that significantly contributes to the yield was insecticide use. In summary, the two damage reducing factors effectively contribute to the reduction of yield loss in the studied region. But the extent of their contribution is also important to be specified in order to appreciate their *Ceteris paribus* intrinsic values and this involves the determination of the marginal effect of the damage-abating inputs.

### 4.2.3 Marginal physical product of abatement inputs and damage function value

Marginal physical products (MPP) of the BC and insecticide were derived from the estimated models through equations 3-40 and 3-41. Marginal effect of a targeted variable measures the product instantaneous rate of change and will provide a good approximation to the amount of change in productivity response that will be produced by a 1-unit change in the target variables. Table 4-5 shows the marginal physical product for the two damage controlling agents (BC and insecticide). The MPP varies with the specification as found in many previous studies using damage abatement methodology (Carrasco and Moffit, 1992; Pemsl, 2005; Praneetvatakul *et al.,* 2002). BC productivity results got from the conventionnal approach (Cobb-Douglas and Translog) were lower compared to those of the damage abatement framework confirming the underestimation of results when using conventionnal approaches of production function as noticed in Affognon (2007), Ajayi (2000) and Lichtenberg and Zilberman (1986).

But when referring to the logistic1 and logistic2 models for which coefficients are significant, the MPP for the BC is found equal to 12 kg/ha and 16 kg/ha respectively. This means that each change of 1% in pest parasitism or BC level results in adding 12 or 16 kg/ha to maize yield, holding all other input unchanged or constant.

The predicted value of $G(z_{BC}, z_{Ins})$ based on the average values of the damage-abatement variables yielded the damage control function term. This factor represents the proportion of the attainable production due to the use of the damage abating factors. The factor has its value bound between zero and one. For instance, a term of 0.86 means that the abatement factors succeeded in preserving 86% of the attainable yield and the remaining 14.3% represented the uncontrolled damage. Values on this factor from different specifications are summarized in the Table 4-5. The damage function value varies from 0.86 for logistic model to 0.94 for the exponential model. For the logistic (for which the two damage control variables were significantly different from 0), the remaining unabated yield or the actual output loss is still relatively higher (14.3%) and call among others for the improvement of the BC parasitism level or integrated management which should involve other control strategies.

**Table 4-5 :** Marginal physical product of abatement inputs and damage function value

| | **Conventionnal** | | **With damage abatement specification** | | | |
|---|---|---|---|---|---|---|
| | ***Cobb-Douglas*** | ***Translog*** | ***Exponential1*** | ***Exponential2*** | ***Logistic1*** | ***Logistic2*** |
| ***Marginal physical product (Kg/ha)*** | | | | | | |
| *Parasitism (BC)* | 0.76 | 0.71 | 3.69 | 3.74 | 11.77 | 16.17 |
| *Insecticide* | 3.34 | 121.44 | 4.5 | 5.37 | 1201.41 | 1170.10 |
| ***Damage function*** | | | | | | |
| *Value* | | | 0.94 | 0.94 | 0.86 | 0.85 |
| *Actual output loss* | | | 0.06 | 0.06 | 0.14 | 0.15 |

*, ** and *** imply statistical significance at 10, 5 and 1% level, respectively
Source: Author's computation (2015)

Based on the econometric estimates of the damage control function, the evolution of the damage control coefficient at different insecticide use level with and without BC was plotted (See Figure 4-3) to estimate the relationship between insecticide, BC and damage control. The curves were obtained holding the BC level at its average and maximum rates as shown on the figure for two logistic functional forms. The curves show an increasing trend of the damage control with insecticide use level. The with-BC curve displays this tendency as well and thus confirms the role of intensity of insecticide and BC in yield loss reduction in maize farming. The figure also helped establishing that the distance between the curves (with and without BC) reduces gradually with increasing insecticide use, translating that the yield effects will be higher with less applied insecticide. Moreover, the highest distance between the curves is at zero insecticide level, suggesting that those who were mostly benefiting from the BC program are farmers who do not use insecticides. This confirms the BC intervention to be mostly for small-scale and resource-poor households who have limited possibilities of purchasing pesticides. In addition, the gap is higher for the maximum BC level than the mean, meaning that higher presence of the natural enemies is associated to higher benefit in term of yield effect.

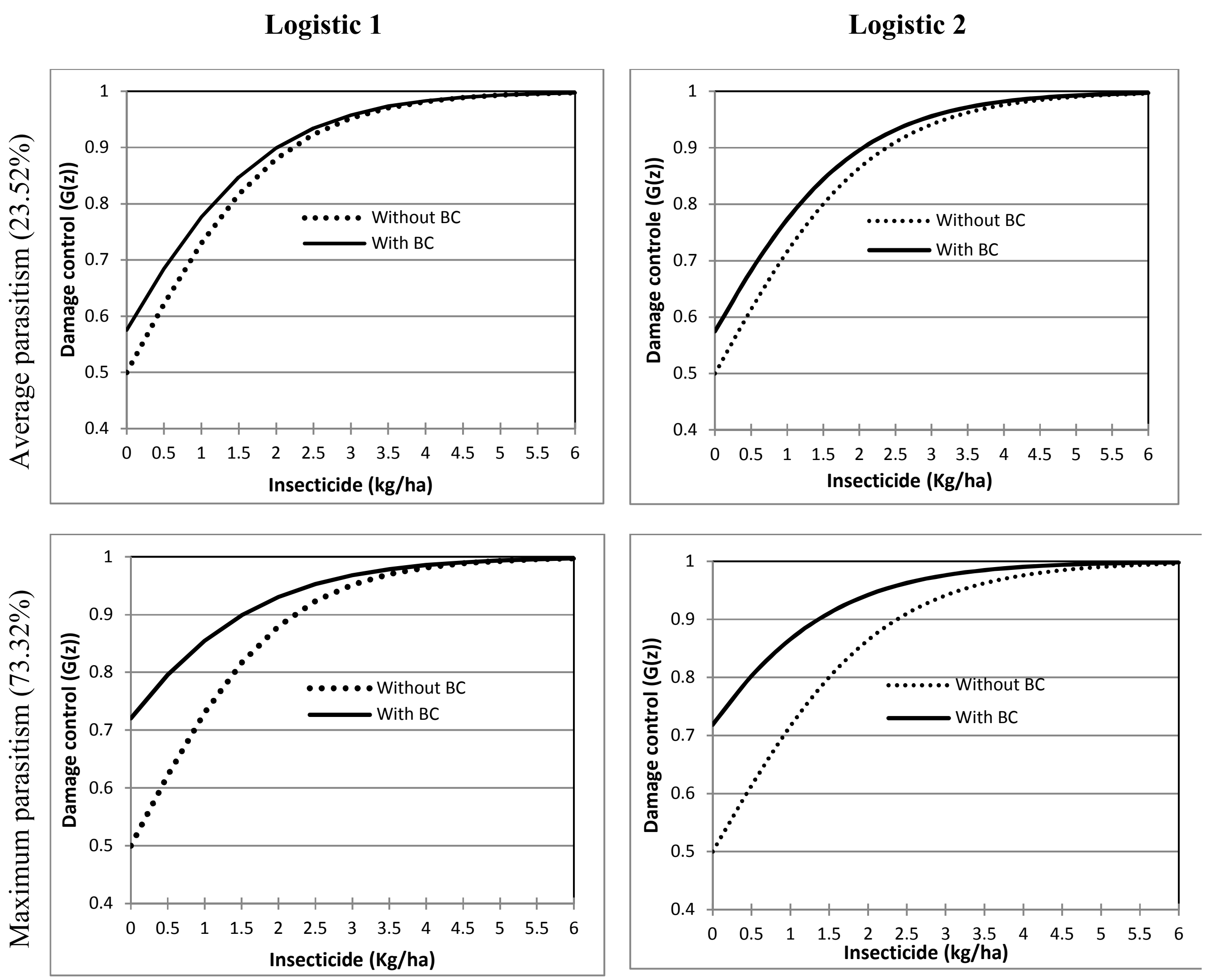



**Figure 4-3 :** Relationship between insecticide use and damage control with and without BC

Source: Author’s computation 2015

## 4.3 Impact of the biological control on poverty and food security

### 4.3.1 Explaining factors affecting BC and endogeneity checking

To provide unbiased impact estimates, the endogeneity of the BC variable was checked to give credence to the proposed method of impact analysis. In the first stage, the model of biological control level was estimated, considering on-farm level and village level variables as instruments. For the estimation, the first step regression is commonly performed using the ordinary least square (OLS) in the econometrics literature. Given the nature of the dependent variable (rate or proportion) Papke and Wooldridge (2008) suggested to use what they termed as the fractional logit (flogit) model which is one of the generalized linear models (GLM) families. Table 4-6 exhibits the estimation results of the first-stage function with both OLS and flogit models.

F-tests results show statistically significant F-value confirming the global significance of the models and the relevance of the instrumental variables used to predict the bio-control level. Furthermore, the majority of the statistically significant coefficients presented the expected direction through their signs. Even though studies usually do not focus on the interpretation of the first-stage results, they appear to be of higher importance for policy recommendation in the case of this study. Particularly, the negative and significant relation between the use of insecticide and the biological control level is of high importance. This result suggests that the use of pesticide by farmer is associated with decrease in rate of parasitism of pests by the natural enemies. This entails that pesticide use could hinder the success of the biological control. The challenges of many broad spectrum and contact insecticides are known to be directly disruptive for natural enemies. Applying sublethal dosage of pesticides is revealed to be highly susceptible to natural enemies than pest (Cugala *et al.,* 2006; Kfir *et al.,* 2002).

**Table 4-6** : Results of the first-stage estimation of the endogeneity test

Dependant variable: Bio-control level or parasitism rate

| | OLS | | FLOGIT | |
|---|---|---|---|---|
| | Coefficient | Robust Std Error | Coefficient | Robust Std Error |
| Fertilizer use | 0.04 *** | 0.00 | 0.36 *** | 0.02 |
| Insecticide use | -0.02 *** | 0.00 | -0.13 *** | 0.01 |
| Organic fertilizer | -0.01 *** | 0.00 | -0.06 *** | 0.02 |
| Medium infestation | 0.01 *** | 0.00 | 0.11 *** | 0.01 |
| High infestation index | 0.02 *** | 0.00 | 0.20 *** | 0.01 |
| High slope | -0.00 *** | 0.00 | -0.01 *** | 0.01 |
| Very high slope | 0.04 *** | 0.00 | 0.34 *** | 0.03 |
| Grass boundary | 0.03 *** | 0.00 | 0.19 *** | 0.02 |
| Perception on pest pressure | 0.02 | 0.00 | 0.11 | 0.01 |
| Edge presence | -0.01 *** | 0.01 | -0.02 *** | 0.06 |
| 15 km from release point | -0.02 | 0.00 | -0.13 | 0.01 |
| 30 km from release point | 0.00 *** | 0.01 | 0.10 *** | 0.08 |
| 45 km from release point | -0.02 *** | 0.01 | 0.46 *** | 0.09 |
| Agroecology2 | 0.01 *** | 0.01 | 0.42 | 0.11 |
| Agroecology3 | -0.07 | 0.02 | -0.06 *** | 0.15 |
| Agroecology4 | -0.04 | 0.03 | -0.62 | 0.19 |
| Agroecology5 | -0.04 *** | 0.03 | 0.11 *** | 0.17 |
| Agroecology6 | -0.15 *** | 0.02 | -0.98 *** | 0.14 |
| Maize as precedent | -0.43 | 0.03 | -3.83 *** | 0.19 |
| Low fertility index | 0.00 *** | 0.00 | 0.08 *** | 0.01 |
| Medium fertility index | -0.04 *** | 0.01 | -0.44 *** | 0.03 |
| Intercept | -0.02 *** | 0.00 | -0.10 *** | 0.02 |
| N | 600 | | 600 | |
| F/Chi- square | 93.42 *** | | 2570.98 *** | |
| R square | 0.7438 | | | |

*, ** and *** imply statistical significance at 10, 5 and 1% level, respectively

Source: Author’s computation 2015

In a context where farmers are allowed and are free to use pesticides, the sound integration of chemical control and biological control as in IPM strategies become necessary for assuring the biological control success and sustainability. Hassan and Van de Veire (2004) argued that the synergy between insecticide use and biological control can be enhanced through three key factors including: chemistry (adjusting the insecticide toxicity property specifically to the targeted pest physiology), timing (scheduling the pesticide application in a way to avoid the bio-agents) and location (spatially- distributed application of pesticides in a way to emphasis the spraying more on most infested area and let the biological control occur in places with low pest density level for instance). This required the knowledge of the effect of all available pesticides impact on the natural enemies.

Compatibility of bio-control was demonstrated to be possible with some active ingredient (Cloyd, 2005; Cloyd, 2012; Fonseca *et al.,* 2015) but at the best of our knowledge, no study reported the tolerance of insecticide used with the studied bio-agents. Hence for future BC intervention, it is suggested that prior to any bio-agent release, the strong partnership with pesticide regulation institutions is desirable to ensure the compatibility of authorized pesticides with natural enemies' development and spread. Alternatively, training of farmers on the accurate use and best timing of pesticide application, the association of BC to nonchemical and non-disruptive methods for the bio-agents such as pests-resistant crop varieties and cultural control are potential for success of the biological control.

Many other variables have statistically significant relationship with the level of biological control. A higher use of fertilizer is associated with higher rate of parasitism and this is explained by the fact that greener plants attract more pests which also attract more natural enemies. Medium and high infestations entail higher bio-control level and this is explained by the attraction of the bio-agents by the larvae and eggs of stemborers pests as well.

The positive sign depicted by the existence of grass boundary around the plot is in the same direction as grasses are known to constitute shelters for pests for passing the dry season period. On the other side, the negative relationship with the presence of edge may mean a barrier for the progression of the natural enemies. The agroecological zones dummies depicted negative and statistically significant coefficients, showing that the biological control is lower in those zones comparatively to the reference which is the lowland tropical agroecology located in the coastal region of Kenya. This region was indeed the starting point and the earliest area of implementation of the biological control in Kenya and this may justify its higher biological control level.

The second stage estimation of the endogeneity checking is reported in Table 4-7 that depicts for both outcomes (food security and poverty) the estimated coefficients of the augmented regressions. The augmented regressions were obtained by incorporating the first step BC regression estimated residuals into the outcome models. We note that the residuals variable is not significantly different from zero at 10 %. This suggests that the biological control variable may not suffer from endogeineity, confirming the self-sustaining features of this technology. This result stipulates the non-existence of biases that can stem from the unobserved heterogeneity and then the analysis could be limited to the selection on observed characteristics or conditional Mean Independence (CMI) assumption.

**Table 4-7:** Second step augmented regression results

| | **Food security** | | | **Poverty** | | |
|---|---|---|---|---|---|---|
| | **peafintakcal** | | **peafoodexpths** | **incperaeths** | **expperaeths** | |
| BC | 863.10 | ** | 0.17 | 15.35 | 27.06 | *** |
| | (407.71) | | (3.21) | (28.95) | (7.81) | |
| Age | | | -2.10 | -0.39 | 8.87 | |
| | | | (2.22) | (20.03) | (5.40) | |
| Gender | 286.39 | ** | -0.24 | -2.87 | -3.32 | |
| | (145.68) | | (1.16) | (10.50) | (2.83) | |
| Education level | -122.52 | | -0.91 | 8.21 | 4.05 | ** |
| | (81.41) | | (0.65) | (5.88) | (1.59) | |

| | Food security | | | | Poverty | | | |
|---|---|---|---|---|---|---|---|---|
| | peafintakcal | | peafoodexpths | | incperaeths | | expperaeths | |
| Residence | | | | | -3.20 | | -0.03 | |
| | | | | | (5.81) | | (1.57) | |
| Hhld size | -1614.91 | *** | -10.31 | *** | -82.53 | *** | -24.49 | *** |
| | (137.91) | | (1.09) | | (9.72) | | (2.62) | |
| Experience | 231.43 | *** | 0.82 | | -5.58 | | -1.96 | |
| | (82.57) | | (0.80) | | (7.23) | | (1.95) | |
| Cropped area | | | | | 23.512 | *** | 7.57 | *** |
| | | | | | (5.324) | | (1.44) | |
| Agriculture as main activity | -255.85 | * | -0.26 | | -30.68 | *** | -7.82 | *** |
| | (136.00) | | (1.16) | | (10.21) | | (2.75) | |
| Extension | -217.87 | ** | | | -12.62 | * | 1.62 | |
| | (98.13) | | | | (6.81) | | (1.84) | |
| TLU | | | 1.20 | | 38.32 | *** | 7.42 | *** |
| | | | (0.77) | | (7.19) | | (1.94) | |
| Have salary | | | -0.11 | | 2.54 | *** | 0.53 | ** |
| | | | (0.10) | | (0.87) | | (0.24) | |
| Have business | | | 0.10 | | 0.34 | | 0.31 | |
| | | | (0.10) | | (0.88) | | (0.24) | |
| Handicraft income | | | | | 2.28 | * | 0.46 | |
| | | | | | (1.34) | | (0.36) | |
| Access to credit | | | | | -13.02 | * | 0.14 | |
| | | | | | (7.40) | | (1.99) | |
| Market distance | 102.51 | | 0.59 | | 9.28 | | 2.25 | |
| | (115.65) | | (0.84) | | (8.22) | | (2.22) | |
| Tared road distance | | | | | 0.66 | | -0.87 | |
| | | | | | (4.13) | | (1.11) | |
| Association | | | | | -0.57 | | 2.42 | |
| | | | | | (9.85) | | (2.66) | |
| **Residuals predicted from BC equation** | **-800.30** | | **-0.65** | | **-27.38** | | **-10.56** | |
| | **(808.49)** | | **(6.36)** | | **(55.91)** | | **(15.08)** | |
| Intercept | 4426.38 | *** | 40.09 | *** | 188.67 | *** | 20.862 | |
| | (417.67) | | (7.83) | | (71.08) | | (19.17) | |
| Number of obs | 600 | | 598 | | 600 | | 600 | |
| F(12, 585) | 17.82 | *** | 8.69 | *** | 9.84 | *** | 9.98 | *** |
| R-squared | 0.21 | | 0.15 | | 0.24 | | 0.24 | |
| Adj R-squared | 0.20 | | 0.14 | | 0.22 | | 0.22 | |

*, ** and *** imply statistical significance at 10, 5 and 1% level, respectively

Source: Author’s computation 2015

### 4.3.2 Impact of biological control on poverty

#### 4.3.2.1 Average poverty impact estimates

The results on causal relationship between the biological control and poverty are presented in the Table 4-8. The analysis used both poverty measures based on household income and household expenditures. The results explanation will also focus on just the ATE represented here by the coefficients of the bio-control variable. The effect on per adult equivalent expenditure and income in the first and fifth columns of the table were examined. The estimated coefficients were positive for both measures but only the per adult equivalent expenditure was statistically significant at 5% level suggesting that controlling cereal stemborers with the released bio-agents increased the smallholders' annual expenditure by around KSh 14500 in average.

Moving on the poverty-effect of the biological control, results in Table 4-8 suggest sizeable effects. With regards to income-base poverty indexes, a statistically significant at 5% level reduction of about 18.2% in poverty is observed with the biological control. Poverty gap among households was substantially reduced at 9% while the severity of poverty has diminished by an average statistically significant proportion of 6%. This implies that the implementation of biological control has had significant impact on poverty reduction in our area of study. The ATE figures obtained for the expenditure-base poverty indexes show that the implementation of biological control of stemborers is associated with a 5% statistically significant reduction of poverty of 22% among maize smallholding farmers in Kenya. The BC intervention has also contributed in reducing the poverty gap by a significant percentage of 7.5%. In addition, reduction was noted with the BC effect on poverty severity but this result was not statistically significant at 10% at least.

**Table 4-8 :** ATE-regressions for assessing the impact of biological control on poverty

| | Per adult equivalent expenditure base | | | | Per adult equivalent income base | | | |
|---|---|---|---|---|---|---|---|---|
| | **Expenditure per year (000 Ksh)** | **Headcount index** | **Poverty gap index** | **Poverty severity** | **Income per year (000 Ksh)** | **Headcount index** | **Poverty gap index** | **Poverty severity** |
| Biological control level | 14.45 ** | -0.22 *** | -0.08 ** | -0.03 | 2.42 | -0.18 ** | -0.09 ** | -0.06 * |
| | (5.86) | (0.08) | (0.03) | (0.02) | (21.59) | (0.08) | (0.04) | (0.03) |
| Ln(age of household head) | 0.53 | -0.03 | 0.08 | 0.02 | 42.15 | -0.45 | 0.01 | -0.04 |
| | (21.94) | (0.31) | (0.13) | (0.08) | (80.81) | (0.31) | (0.16) | (0.12) |
| Gender | -4.03 | 0.02 | 0.01 | 0.05 | -5.23 | -0.05 | -0.03 | -0.02 |
| | (2.94) | (0.04) | (0.02) | (0.01) | (10.82) | (0.04) | (0.02) | (0.02) |
| Education | 0.96 | -0.14 | -0.07 | -0.04 | -6.99 | 0.10 | -0.04 | -0.04 |
| | (7.59) | (0.11) | (0.04) | (0.03) | (27.96) | (0.11) | (0.06) | (0.04) |
| Experience in agriculture | 2.32 | 0.03 | -0.00 | 0.01 | -3.83 | 0.24 ** | 0.00 | 0.01 |
| | (7.93) | (0.11) | (0.05) | (0.03) | (29.22) | (0.11) | (0.06) | (0.04) |
| Residence in the village | -3.59 | 0.03 | 0.02 | 0.01 | -15.97 | 0.03 | -0.06 * | -0.05 ** |
| | (4.49) | (0.06) | (0.03) | (0.02) | (16.56) | (0.06) | (0.03) | (0.03) |
| Ln(household size) | -12.30 | 0.31 *** | 0.14 *** | 0.07 ** | -22.74 | 0.10 | 0.19 *** | 0.15 *** |
| | (8.39) | (0.12) | (0.05) | (0.03) | (30.91) | (0.12) | (0.06) | (0.05) |
| Ln(total cultivated area) | 8.33 | -0.11 | -0.04 | -0.02 | 60.74 *** | -0.25 *** | -0.05 | -0.04 |
| | (5.90) | (0.08) | (0.03) | (0.02) | (21.73) | (0.08) | (0.04) | (0.03) |
| Cropping as main activity | 3.74 | -0.14 | -0.02 | -0.00 | -25.21 | 0.12 | 0.06 | 0.04 |
| | (10.24) | (0.14) | (0.06) | (0.04) | (37.73) | (0.14) | (0.08) | (0.06) |
| Ln(distance to extension) | 4.24 | 0.16 | 0.05 | 0.02 | 3.51 | 0.13 | -0.06 | -0.07 |
| | (8.26) | (0.12) | (0.05) | (0.03) | (30.43) | (0.12) | (0.06) | (0.05) |
| lntluliv | 2.72 | -0.15 * | -0.07 ** | -0.04 | 3.30 | -0.11 | -0.07 | -0.04 |
| | (6.52) | (0.09) | (0.04) | (0.02) | (24.00) | (0.09) | (0.05) | (0.04) |
| lnsalaryrec | -0.32 | -0.02 | 0.00 | 0.00 | 2.83 | -0.01 | -0.02 *** | -0.018 *** |

| | Per adult equivalent expenditure base | | | | Per adult equivalent income base | | | |
|---|---|---|---|---|---|---|---|---|
| | Expenditure per year (000 Ksh) | Headcount index | Poverty gap index | Poverty severity | Income per year (000 Ksh) | Headcount index | Poverty gap index | Poverty severity |
| | (0.92) | (0.01) | (0.01) | (0.00) | (3.40) | (0.01) | (0.01) | (0.01) |
| lnbusrec | 0.87 | -0.01 | -0.01 ** | -0.01 ** | -1.71 | 0.01 | -0.01 | -0.01 |
| | (0.90) | (0.01) | (0.01) | (0.00) | (3.30) | (0.01) | (0.01) | (0.01) |
| lnhandikinc | 0.26 | -0.02 | 0.01 | 0.01 | 6.01 | -0.01 | -0.01 | -0.01 ** |
| | (1.07) | (0.02) | (0.01) | (0.00) | (3.96) | (0.02) | (0.01) | (0.01) |
| crediacces | 0.26 | -0.10 *** | -0.03 *** | -0.02 ** | -10.26 | -0.02 | 0.02 | 0.02 * |
| | (2.05) | (0.03) | (0.01) | (0.01) | (7.55) | (0.03) | (0.02) | (0.01) |
| lndistmarket | -8.55 | -0.02 | 0.02 | 0.02 | -3.42 | -0.12 | -0.09 | -0.07 |
| | (11.32) | (0.16) | (0.07) | (0.04) | (41.69) | (0.16) | (0.09) | (0.06) |
| lndisttroad | 1.46 | -0.03 | -0.03 | -0.02 | -3.97 | -0.01 | -0.02 | -0.01 |
| | (7.68) | (0.11) | (0.04) | (0.03) | (28.28) | (0.11) | (0.06) | (0.04) |
| associationyes | 2.17 | -0.04 | -0.02 | -0.02 | -2.66 | -0.04 | -0.03 | -0.02 |
| | (2.72) | (0.04) | (0.02) | (0.01) | (10.01) | (0.04) | (0.02) | (0.02) |
| vilposi2 | 0.48 | 0.06 | 0.04 | 0.03 ** | 6.05 | 0.04 | 0.04 * | 0.03 * |
| | (3.37) | (0.05) | (0.02) | (0.01) | (12.42) | (0.05) | (0.03) | (0.02) |
| vilposi3 | -5.90 * | 0.14 *** | 0.05 *** | 0.02 ** | -6.41 | 0.06 | 0.06 ** | 0.04 ** |
| | (3.34) | (0.05) | (0.02) | (0.01) | (12.29) | (0.05) | (0.03) | (0.02) |
| _ws_lnage | 9.58 | 0.09 | -0.06 | 0.00 | -47.03 | 0.28 | -0.08 | -0.01 |
| | (22.63) | (0.32) | (0.13) | (0.08) | (83.35) | (0.32) | (0.17) | (0.13) |
| _ws_lnnyearsch | 2.67 | 0.10 | 0.04 | 0.02 | 13.40 | -0.11 | 0.04 | 0.05 |
| | (7.72) | (0.11) | (0.04) | (0.03) | (28.43) | (0.11) | (0.06) | (0.04) |
| _ws_lnexperagric | -4.27 | -0.08 | -0.00 | -0.01 | -2.84 | -0.23 ** | -0.01 | -0.01 |
| | (8.18) | (0.12) | (0.05) | (0.03) | (30.12) | (0.12) | (0.06) | (0.05) |
| _ws_lnresi | 3.24 | -0.03 | -0.03 | -0.03 * | 13.38 | -0.04 | 0.05 | 0.04 |
| | (4.82) | (0.07) | (0.03) | (0.02) | (17.74) | (0.07) | (0.04) | (0.03) |

| | Per adult equivalent expenditure base | | | | Per adult equivalent income base | | | |
|---|---|---|---|---|---|---|---|---|
| | Expenditure per year (000 Ksh) | Headcount index | Poverty gap index | Poverty severity | Income per year (000 Ksh) | Headcount index | Poverty gap index | Poverty severity |
| _ws_lnhsize | -14.77 * | -0.12 | -0.07 | -0.04 | -64.76 ** | 0.17 | -0.07 | -0.07 |
| | (8.87) | (0.13) | (0.05) | (0.03) | (32.68) | (0.13) | (0.07) | (0.05) |
| _ws_lntotcultivated | -0.99 | 0.03 | -0.00 | 0.00 | -39.52 * | 0.21 ** | 0.04 | 0.04 |
| | (6.08) | (0.09) | (0.04) | (0.02) | (22.41) | (0.09) | (0.05) | (0.03) |
| _ws_croproductionma | -12.65 | 0.18 | 0.04 | 0.02 | -3.06 | -0.04 | -0.02 | -0.02 |
| | (10.65) | (0.15) | (0.06) | (0.04) | (39.21) | (0.15) | (0.08) | (0.06) |
| _ws_lndistexten | -2.06 | -0.21 * | -0.09 * | -0.04 | -17.42 | -0.13 | 0.04 | 0.06 |
| | (8.45) | (0.12) | (0.05) | (0.03) | (31.13) | (0.12) | (0.06) | (0.05) |
| _ws_lntluliv | 4.88 | 0.13 | 0.06 | 0.03 | 36.58 | 0.05 | 0.04 | 0.03 |
| | (6.84) | (0.10) | (0.04) | (0.02) | (25.19) | (0.10) | (0.05) | (0.04) |
| _ws_lnsalaryrec | 0.90 | 0.010 | -0.01 | -0.00 | -0.37 | -0.01 | 0.01 | 0.01 * |
| | (0.96) | (0.01) | (0.01) | (0.00) | (3.52) | (0.01) | (0.01) | (0.01) |
| _ws_lnbusrec | -0.67 | -0.00 | 0.01 | 0.01 | 1.89 | -0.02 * | -0.00 | -0.00 |
| | (0.93) | (0.01) | (0.01) | (0.00) | (3.42) | (0.01) | (0.01) | (0.01) |
| _ws_lnhandikinc | 0.35 | 0.00 | -0.01 ** | -0.01 ** | -3.64 | -0.01 | 0.00 | 0.01 |
| | (1.14) | (0.02) | (0.01) | (0.00) | (4.21) | (0.02) | (0.01) | (0.01) |
| _ws_lndistmarket | 10.48 | -0.04 | -0.05 | -0.03 | 11.19 | 0.12 | 0.10 | 0.08 |
| | (11.54) | (0.16) | (0.07) | (0.04) | (42.50) | (0.16) | (0.09) | (0.06) |
| _ws_lndisttroad | -1.96 | 0.06 | 0.04 | 0.02 | 9.01 | -0.02 | -0.00 | -0.01 |
| | (7.81) | (0.11) | (0.05) | (0.03) | (28.75) | (0.11) | (0.06) | (0.04) |
| Tw_1 | 0.02 | -0.02 ** | -0.01 *** | -0.00 ** | -4.28 ** | -0.01 | -0.00 | -0.00 |
| | (0.51) | (0.01) | (0.00) | (0.00) | (1.87) | (0.01) | (0.00) | (0.00) |
| Tw_2 | 0.00 | 0.00 ** | 0.00 *** | 0.00 ** | 0.08 * | 0.00 | 0.00 | 0.00 |
| | (0.01) | (0.00) | (0.00) | (0.00) | (0.05) | (0.00) | (0.00) | (0.00) |
| Tw_3 | 0.00 | 0.00 ** | 0.00 ** | 0.00 ** | 0.00 | 0.00 | 0.00 | 0.00 |

| | Per adult equivalent expenditure base | | | | | | | | Per adult equivalent income base | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Expenditure per year (000 Ksh) | | Headcount index | | Poverty gap index | | Poverty severity | | Income per year (000 Ksh) | | Headcount index | | Poverty gap index | | Poverty severity | |
| | (0.00) | | (0.00) | | (0.00) | | (0.00) | | (0.00) | | (0.00) | | (0.00) | | (0.00) | |
| Intercept | 35.88 | | 0.50 | | -0.22 | | -0.05 | | -10.98 | | 1.34 | | 0.53 | | 0.59 | |
| | (73.27) | | (1.03) | | (0.42) | | (0.26) | | (269.89) | | (1.03) | | (0.55) | | (0.41) | |
| | 600 | | 600 | | 600 | | 600 | | 600 | | 600 | | 600 | | 600 | |
| | 5.61 | *** | 4.66 | *** | 4.41 | *** | 3.53 | *** | 5.82 | *** | 6.37 | *** | 5.890 | *** | 5.000 | *** |
| | 0.27 | | 0.24 | | 0.23 | | 0.19 | | 0.28 | | 0.30 | | 0.28 | | 0.25 | |
| | 0.222 | | 0.184 | | 0.174 | | 0.14 | | 0.23 | | 0.25 | | 0.23 | | 0.20 | |

Standard errors in parentheses. *, ** and *** imply statistical significance at 10, 5 and 1% level, respectively

Source: Author’s computation (2015)

#### 4.3.2.2 Heterogeneity in poverty-impact of BC

More interesting for the purposes of this research is the distribution of the impact across the level of bio-control activity. Figure 4-4 presents the plots of estimated Dose Response Function (DRF), the derivative of the DRF (or Marginal Treatment Effect - MTE), the distribution of impact parameters (ATE(x), ATENT(x), ATET(x)) and the DRF with bootstrapped standard error, accompanied by 90% confidence intervals. In the fourth column, the DRF with bootstrapped standard error performed with 20 replications display similar patterns with the estimated DRF (column one), confirming the stability of obtained results and then the reliance on their interpretation.

The DRF curves show an increasing trend for the household per capita expenditure and decreasing trend for poverty headcount and poverty gap. The household expenditures increase from 2165 Ksh at 0.5% of BC intensity to KSh 23,573 at 73.32% level while the number of poor households (poverty gap) reduces by 2.3 (0.8) and 46 (16.8) percentage point at 0.5% and 73.32 % BC level respectively. In general, on average the release of BC increases per capita expenditure by KSh 14,451 and reduces poverty headcount (poverty gap) by 22.3% (7.5%), all these figures are statistically significant at 5% level of significance. The MTE results (column 2, Figure 4-4) show a similar trend as in DRF results. A one percent increase in the intensity of BC is associated with an increase in per capita expenditure from Khs 30 at 0.5% level to Ksh 200 at 73.32% level of BC intensity. On the other hand, the poverty headcount (poverty gap) reduces by 2.3 (1.1) percentage point at 0.5% level to 1.9 (0.9) percentage point at 0.5% and 73.3% BC level respectively. The average marginal effects for per capita expenditure, poverty headcount and the poverty gap were respectively KSh119 and -0.5% (-0.09%). These results are in line with Bauer *et al.* (2003) and Waterhouse *et al.* (1998) who showed significant poverty reduction impact with the BC in banana farming in Papua New Guinea.

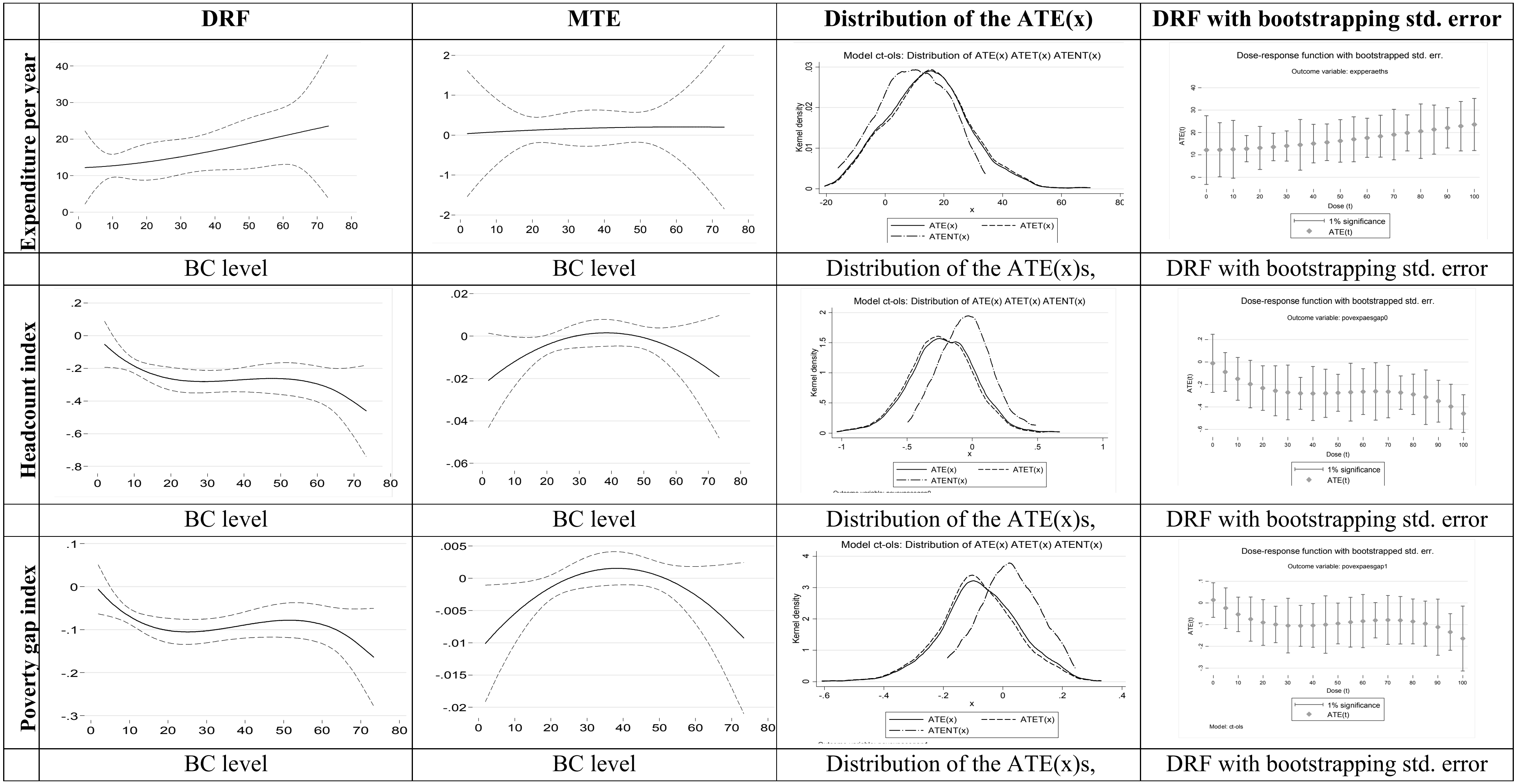



**Figure 4-4 :** Dose Response Function (DRF) and Marginal Treatment Effect (MTE) of expenditure, poverty headcount and poverty gap

Note: Solid line shows the DRF and MTE curves; dashed lines are 90 % confidence upper and lower bound intervals of the curves.

Source: Author’s computation (2015)

The distribution of ATE(x) and ATET(x) were concentrated in part on positive figures, confirming the significance of the average estimate of impact and the global positive impact of BC on household expenditures. Hence the biological control levels were associated with increasing household expenditures. As for the poverty indexes, the distribution of impact parameters ATE(x), ATET(x) and ATENT(x) was much concentrated on negative figures and then approves the tendency of poverty headcount and poverty gap reductions with the biological control implementation.

Overall, having the bio-agent spread to households' farms increased the probability of reducing poverty and higher biological control activity was associated with higher reduction in poverty. However, when examining the DRF curves, the starting and in some extent the middle figures of the BC activities were associated with lower impact responses and then lower intensity of poverty reduction. This implies that there is still potential of moving more maize farming households out of poverty by raising the level of BC activity.

These findings show that the impact varies with the intensity of BC confirming the heterogeneity in impact. The results also imply that developing and promoting biological control can contribute in the fight against poverty in the country. The relationship between BC and aggregate poverty was studied for the same program in East and Southern Africa using economic surplus method (Midingoyi *et al.*, 2016). Results showed that on average, the program can help to lift about 0.27% people (producers and consumers) out of poverty every year in Kenya. The results also corroborate the findings from a study in Papua New Guinea on causal relationship between biological control and poverty.  Indeed, the implementation of the biological control against the banana skipper pest increases farmers' income by 0.9 to 2.2% and lift 6000 to 15000 subsistence farmers out of poverty (Bauer *et al., 2003*).

### 4.3.3 Impact of biological control on food security

The causal effects of biological control on food accessibility, utilization and stability which together with the availability are the four pillars of food security (Magrini and Vigani, 2016) were estimated. Table 4-9 and Table 4-10 report the results of the OLS regressions to identify the basic parameters (including the ATE) usefull in estimating the DRF, MTE and other graphs such as the distributions of the ATE, ATET and ATENT which are the most important in view of the relevance of the used methodology. The overall significance coefficients were all statistically significantly different from zero at 1% level justifying that the models are globally significant. Apart from the average impact coefficients, these models present the advantage of providing the estimates of the determining factors of food security indicators on which we would not overemphasize although this enlarge the possibilities of policy actions of tackling food security. However, it is worth mentioning some few variables such as gender, household size, having crop production as major activity, access to extension services, livestock size and having a salaried income source that influence food security in our study area. This is in line with findings from Gebrehiwot and van der Veen (2015); Kassie *et al.* (2014), Magrini and Vigani (2014), Shiferaw *et al.* (2014) and Hundie (2012) on food security in some sub-Saharan Africa countries.

The average impact (ATE) is given by the coefficient of the BC variable in the model. With respect to the food security indicators related to the accessibility (Table 4-9), the ATE are all statistically significantly different from zero at 10% level. This suggests that biological control implementation increases in average the household per adult equivalent food expenses by KSh 4513 per year and the per adult equivalent calorie intake by 391 Kcal daily. Furthemore, the biological control has contributed to the reduction of food insecurity by 13.7% and the food insecurity gap and severity by 10.2% and 7.2% respectively.

**Table 4-9 :** ATE-regressions for impact of BC on food security (food access component)

| | Per equivalent adult food expenses (x000) | | Per equivalent adult calories intake (x000) | | Food insecurity headcount | | Food insecurity gap | | Food insecurity severity | |
|---|---|---|---|---|---|---|---|---|---|---|
| BC | 4.51 | ** | 0.39 | * | -0.14 | ** | -0.10 | ** | -0.07 | ** |
| | (1.80) | | (0.23) | | (0.07) | | (0.04) | | (0.04) | |
| lnage | -5.71 | | 0.00 | | 0.27 | | 0.17 | | 0.09 | |
| | (7.82) | | (0.00) | | (0.28) | | (0.18) | | (0.15) | |
| genderhh | -0.53 | | 0.28 | * | -0.07 | ** | -0.02 | | 0.01 | |
| | (1.15) | | (0.15) | | (0.04) | | (0.03) | | (0.02) | |
| lnnyearsch | 0.48 | | 1.02 | *** | -0.16 | | -0.05 | | -0.02 | |
| | (2.89) | | (0.37) | | (0.11) | | (0.07) | | (0.06) | |
| lnhsize | -9.05 | *** | -1.43 | *** | 0.45 | *** | 0.17 | ** | 0.06 | |
| | (3.24) | | (0.41) | | (0.12) | | (0.07) | | (0.06) | |
| lnexperagric | 2.69 | | 0.78 | *** | -0.212 | ** | -0.09 | | -0.05 | |
| | (2.91) | | (0.25) | | (0.11) | | (0.07) | | (0.06) | |
| croproductionma | -0.17 | | -0.27 | ** | 0.16 | *** | 0.08 | *** | 0.06 | *** |
| | (1.14) | | (0.14) | | (0.04) | | (0.03) | | (0.02) | |
| lndistexten | 0.00 | | -0.23 | ** | 0.07 | ** | 0.06 | *** | 0.03 | * |
| | (0.00 | | (0.10) | | (0.03) | | (0.02) | | (0.02) | |
| lntluliv | 1.85 | | 0.00 | | 0.00 | | 0.01 | | 0.01 | |
| | (2.47 | | (0.00) | | (0.09) | | (0.06) | | (0.05) | |
| lnsalaryrec | -0.13 | | 0.00 | | 0.00 | | 0.00 | | -0.00 | |
| | (0.10) | | (0.00) | | (0.00) | | (0.00) | | (0.00) | |
| lnbusrec | 0.05 | | 0.00 | | -0.01 | | -0.01 | * | -0.01 | * |
| | (0.33) | | (0.00) | | (0.01) | | (0.01) | | (0.01) | |
| lndistmarket | -5.36 | * | -0.26 | | 0.10 | | -0.05 | | -0.08 | |
| | (3.25) | | (0.41) | | (0.12) | | (0.07) | | (0.07) | |
| _ws_lnage | 5.34 | | -0.03 | | -0.27 | | -0.14 | | -0.07 | |
| | (8.10) | | (0.29) | | (0.29) | | (0.18) | | (0.16) | |
| _ws_lnnyearsch | -0.91 | | -1.21 | *** | 0.19 | * | 0.07 | | 0.04 | |
| | (2.96) | | (0.38) | | (0.11) | | (0.07) | | (0.06) | |
| _ws_lnhsize | -2.33 | | -0.30 | | -0.05 | | 0.06 | | 0.08 | |
| | (3.44) | | (0.44) | | (0.13) | | (0.08) | | (0.07) | |
| _ws_lnexperagric | -2.24 | | -0.58 | ** | 0.17 | | 0.05 | | 0.02 | |
| | (3.02) | | (0.27) | | (0.11) | | (0.07) | | (0.06) | |
| _ws_lntluliv | -0.49 | | 0.00 | | -0.08 | | -0.06 | | -0.04 | |
| | (2.59) | | (0.00) | | (0.09) | | (0.06) | | (0.05) | |
| _ws_lnbusrec | 0.06 | | 0.00 | | 0.02 | * | 0.06 | ** | 0.01 | * |
| | (0.34) | | (0.00) | | (0.01) | | (0.01) | | (0.01) | |
| _ws_lndistmarket | 6.06 | * | 0.43 | | -0.13 | | 0.03 | | 0.07 | |
| | (3.35) | | (0.42) | | (0.12) | | (0.08) | | (0.07) | |
| Tw_1 | 0.79 | *** | 0.01 | | 0.00 | | 0.00 | | 0.00 | |
| | (0.18) | | (0.02) | | (0.01) | | (0.00) | | (0.00) | |
| Tw_2 | -0.02 | *** | 0.00 | | 0.00 | | 0.00 | | 0.00 | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | (0.00) | | (0.00) | | (0.00) | | (0.00 | | (0.00) | |
| Tw_3 | 0.00 | *** | 0.00 | | 0.00 | | 0.00 | | 0.00 | |
| | (0.00) | | (0.00) | | (0.00) | | (0.00) | | (0.00) | |
| _cons | 46.57 | * | 0.70 | | -0.33 | | -0.20 | | 0.02 | |
| | (26.30) | | (1.33) | | (0.96) | | (0.56) | | 0.52) | |
| Number of obs | 598 | | 600 | | 600 | | 600 | | 600 | |
| F(21, 578) | 7 | *** | 11.61 | *** | 7.19 | *** | 6.25 | *** | 3.5 | *** |
| R-squared | 0.203 | | 0.242 | | 0.215 | | 0.192 | | 0.118 | |

Standard errors in parentheses *, ** and *** imply statistical significance at 10, 5 and 1% level, respectively

Source: Author's computation (2015)

With reference to the utilization dimension, only the estimate of the simple dietary diversity (Table 4-10) is statistically significant at 1%. With respect to the indicators of stability (simple and weighted coping strategies), all the coefficient of the treatment variable (BC) are negative and statistically different from zero at 1% significance level. This suggests that the biological control contributes to making households less vulnerable to negative shock or augment their ability of facing short-term risk of food insecurity. For both HHS and HFIAS models, the BC estimated coefficients are negative and statistically different from zero at 1% significance level implying that households experienced less food insecurity (less hunger situation, less insufficiency in quantity, less anxiety over insecure access) with the biological control implementation.

**Table 4-10 :** ATE-regressions for impact of BC on food security (food utilization and stability components)

| | Simple dietary diversity | Weighted dietary diversity | Household hunger scale | Household Food Insecurity Access Scale | Simple coping strategies | Weighted coping strategies | Weighted coping strategies |
|---|---|---|---|---|---|---|---|
| BC | 11.79 *** | 2.90 | -0.61 *** | -4.05 *** | -0.82 *** | -1.69 *** | -2.31 *** |
| | (1.82) | (20.55) | (0.15) | (0.90) | (0.32) | (0.47) | (0.66) |
| Age | -8.23 | 88.80 | -0.07 | 7.04 * | 1.86 | 3.86 * | 4.37 |
| | (7.93 | (89.41) | (0.65) | (3.84) | (1.41) | (2.09) | (2.93) |
| Gender | 1.41 | -36.90 *** | -0.17 * | -1.32 ** | -0.43 ** | -0.65 ** | -1.02 ** |
| | (1.16 | (13.05) | (0.10) | (0.56) | (0.20) | (0.30) | (0.42) |
| Education level | 0.54 | -19.10 | -0.49 ** | -2.77 * | -0.63 | -1.51 | -2.12 ** |
| | (2.93) | (33.08) | (0.24) | (1.42) | (0.51) | (0.76) | (1.06) |
| Hhld size | -0.82 | 96.59 *** | 0.18 | 2.20 | 0.96 | 1.17 | 1.54 |
| | (3.29) | (37.04) | (0.27) | (1.60) | (0.59) | (0.88) | (1.23) |
| Experience in agriculture | 1.41 | -14.38 | 0.07 | -1.58 | -0.47 | -1.20 | -1.40 |
| | (2.95 | (33.24) | (0.24) | (1.43) | (0.52) | (0.76) | (1.07) |
| Agric as main activity | 2.62 ** | 0.53 | 0.11 | 1.04 * | 0.52 *** | 0.64 ** | 0.72 * |
| | (1.15 | (12.99) | (0.10) | (0.56) | (0.20) | (0.30) | (0.42) |
| Livestock | 0.80 | -16.15 | -0.62 *** | -4.10 *** | -1.35 *** | -2.04 *** | -2.85 *** |
| | (2.50 | (28.22) | (0.21) | (1.21) | (0.44) | (0.65) | (0.91) |
| lnsalaryrec | -0.17 * | -0.36 | -0.02 *** | -0.13 *** | -0.05 *** | -0.06 ** | -0.10 *** |
| | (0.10 | (1.10) | (0.01) | (0.05) | (0.02) | (0.03) | (0.04) |
| lnbusrec | -0.08 | 4.55 | 0.01 | 0.10 | 0.01 | 0.07 | 0.08 |
| | (0.33) | (3.77) | (0.03) | (0.16) | (0.06) | (0.09) | (0.12) |
| lndistmarket | -7.16 ** | -4.80 | 0.30 | 0.96 | 0.42 | 1.37 | 2.13 * |
| | (3.30) | (37.17) | (0.27) | (1.61) | (0.59) | (0.88) | (1.23) |
| _ws_lnage | 12.35 | -61.08 | -0.33 | -9.98 ** | -2.47 * | -4.73 ** | -5.45 * |
| | (8.22) | (92.65) | (0.67) | (3.98) | (1.46) | (2.16) | (3.03) |

| | Simple dietary diversity | | Weighted dietary diversity | | Household hunger scale | | Household Food Insecurity Access Scale | | Simple coping strategies | | Weighted coping strategies | | Weighted coping strategies | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| _ws_lnnyearsch | 1.11 | | 53.34 | | 0.40 | | 1.94 | | 0.70 | | 1.56 | ** | 2.28 | ** |
| | (3.00) | | (33.82) | | (0.25) | | (1.45) | | (0.52) | | (0.77) | | (1.09) | |
| _ws_lnhsize | -0.82 | | -157.4 | *** | 0.12 | | -0.49 | | -0.67 | | -0.49 | | -0.65 | |
| | (3.48) | | (39.28) | | (0.29) | | (1.69) | | (0.63) | | (0.93) | | (1.30) | |
| _ws_lnexperagric | -3.48 | | 16.61 | | -0.04 | | 1.62 | | 0.62 | | 1.40 | * | 1.67 | |
| | (3.06) | | (34.51) | | (0.25) | | (1.48) | | (0.54) | | (0.79) | | (1.11) | |
| _ws_lntluliv | -1.25 | | 26.16 | | 0.49 | ** | 3.48 | *** | 1.07 | ** | 1.54 | | 2.12 | ** |
| | (2.63) | | (29.65) | | (0.22) | | (1.28) | | (0.46) | | (0.68) | | (0.95) | |
| _ws_lnbusrec | 0.28 | | -4.59 | | -0.02 | | -0.22 | | -0.02 | | -0.08 | ** | -0.10 | |
| | (0.35) | | (3.93) | | (0.03) | | (0.17) | | (0.06) | | (0.09) | | (0.13) | |
| _ws_lndistmarket | 5.15 | | -7.91 | | -0.29 | | -0.86 | | -0.30 | | -1.29 | | -2.11 | * |
| | (3.39) | | (38.26) | | (0.28) | | (1.65) | | (0.61) | | (0.90) | | (1.27) | |
| Tw_1 | -0.41 | ** | -6.68 | *** | -0.02 | | -0.07 | | 0.02 | | -0.01 | | -0.01 | |
| | (0.18) | | (2.02) | | (0.02) | | (0.09) | | (0.03) | | (0.05) | | (0.07) | |
| Tw_2 | 0.01 | ** | 0.15 | *** | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 | |
| | (0.00) | | (0.05) | | (0.00) | | (0.00) | | (0.00) | | (0.00) | | (0.00) | |
| Tw_3 | 0.00 | ** | 0.00 | *** | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 | |
| | (0.00) | | (0.00) | | (0.00) | | (0.00) | | (0.00) | | (0.00) | | (0.00) | |
| _cons | 57.75 | ** | 62.63 | | 2.30 | | -9.94 | | -3.17 | | -0.77 | | 2.62 | |
| | (26.67) | | (300.66) | | (2.19) | | (12.94) | | (4.79) | | (7.09) | | (9.97) | |
| Number of obs | 600 | | 600 | | 600 | | 600 | | 581 | | 581 | | 581 | |
| F( 21, 578) | 5.11 | *** | 5.45 | *** | 4.22 | *** | 5.27 | *** | 3.32 | *** | 3.92 | *** | 3.89 | *** |
| Adj R-squared | 0.126 | | 0.135 | | 0.102 | | 0.136 | | 0.078 | | 0.096 | | 0.095 | |

Standard errors in parentheses ; *, ** and *** imply statistical significance at 10, 5 and 1% level, respectively

Source: Author's computation (2015)

Most important for this impact study due to the continuous feature of biological control is the estimation of the dose response functions (DRF) and the marginal treatement effects (MTE) for the following outcomes covering these dimensions of food security: food access (Food expenditures, calorie intake, food insecurity headcount, gap and insecurity), food utilization (Simple and weighted dietary diversity) and food stability (simple and weighted coping strategies) and for household hunger scale and the household food insecurity access scale. Figure 4-5 summarises the DRF and the MTE along with the distributions of ATE, ATET and ATENT as well as the boostrapped DRF with bootstrapped standard error, accompanied by 90% confidence intervals. In the fourth column, the DRF with bootstrapped standard error performed with 20 replications display similar patterns with the estimated DRF (column one), confirming the stability of obtained results and then the reliance on their interpretation.

Observing the DRF curves for the food access indicators, it was found out that the per adult equivalent spending in food increases from 0 Ksh at 0.5 % to KSh5176 at 73.32% BC level while the per adult equivalent calorie intake increases from 262.3 Kcal at 0.5 % to 963.4 Kcal at 73.32% BC level. The number of food insecure households dropped from 14% Ksh at 0.5% to 15.47 % at 73.32% BC level whereas the food insecurity gap reductions varied from 14% Ksh at 0.5% to 15.47 % at 73.32% BC level. Regarding the causal effect between BC and food utilization indicator, the curves showed that the dietary diversity drops from 16.69 points in score at 0.5% BC level to 2.38 points in score at 73.32% BC level whereas the weighted dietary diversity drop from 74.96 points at 0.5% BC level to -150.97 points. For the stability component, the simple coping strategies score varied from -0.93 points at 0.5% to -1.73 points at 72.32% BC level whereas both weighted coping strategies scores decrease from -1.47 and -4.55 points at 0.5% BC level to -3.22 and -1.93.

| | | | | |
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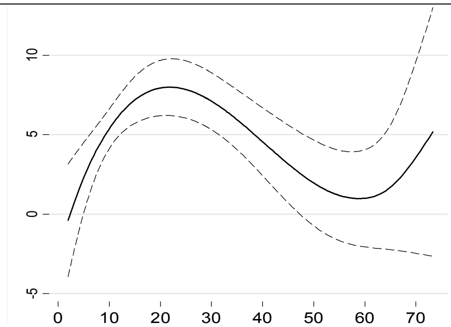
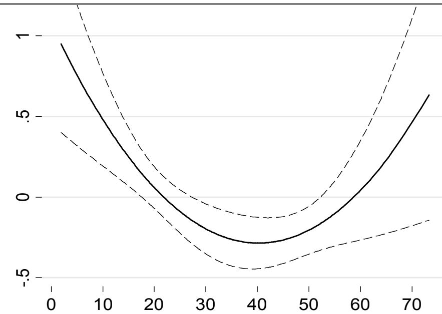
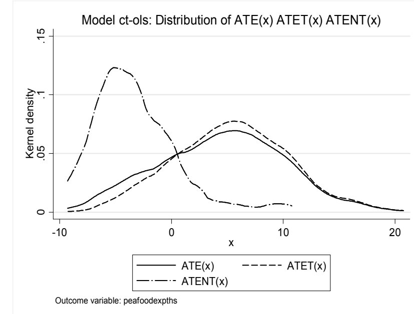
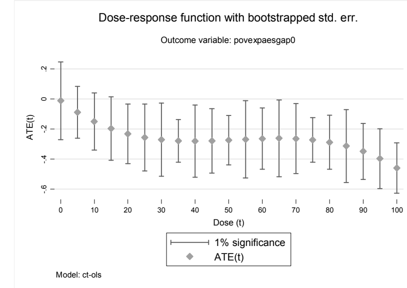
| **Perequivalent adult food** |  |  |  |  |
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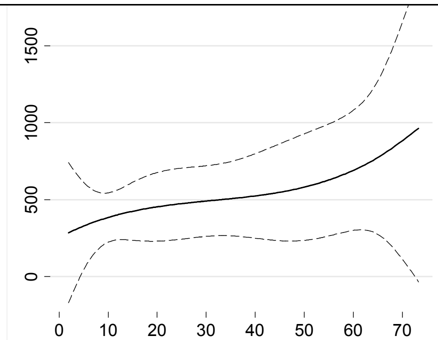
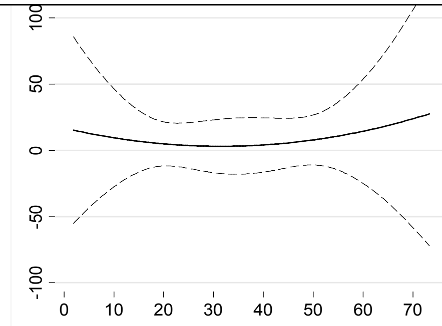
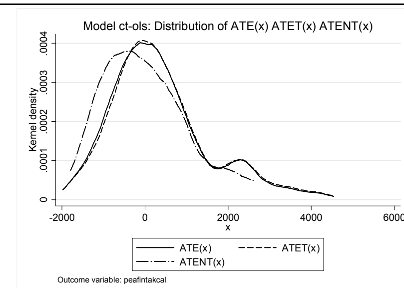
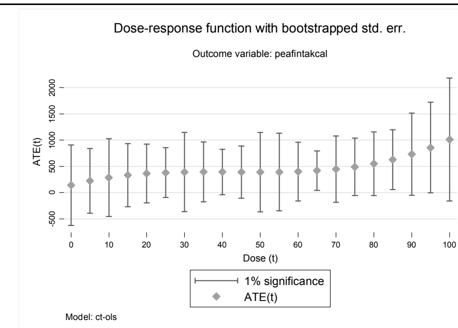
| **Per adult equivalent calorie** |  |  |  |  |
| | BC level | BC level | Distribution of the ATE(x)s, | DRF with bootstrapping std. error |

| | | | | |
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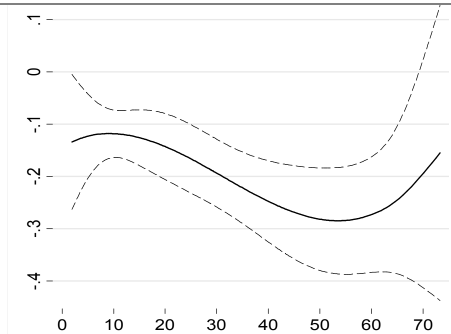
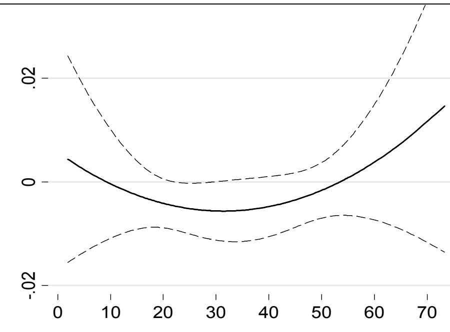
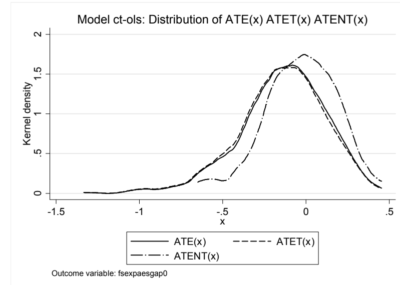
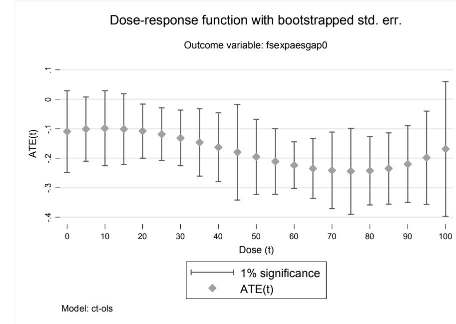
| **Headcount index** |  |  |   |   |
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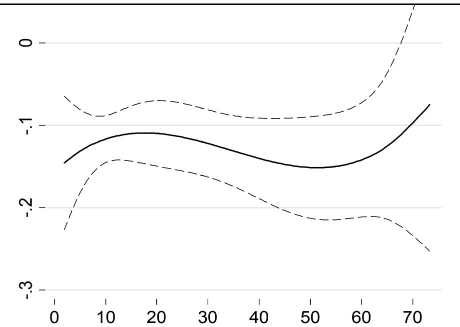
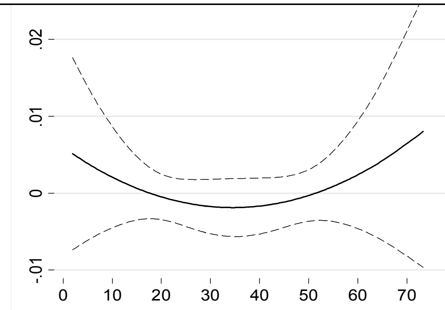
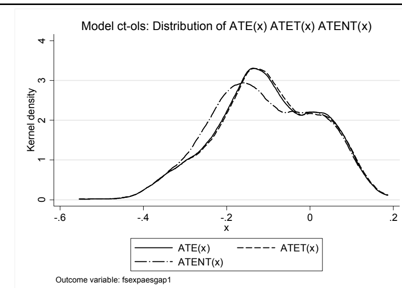
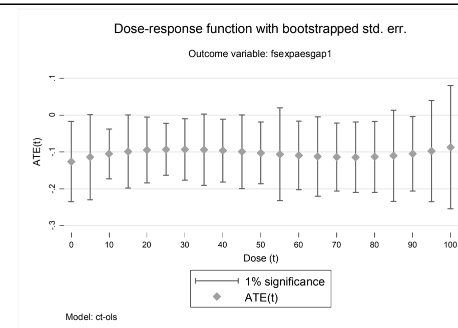
| **Food insecurity gap index** |  |  |   |   |
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| | | | | |
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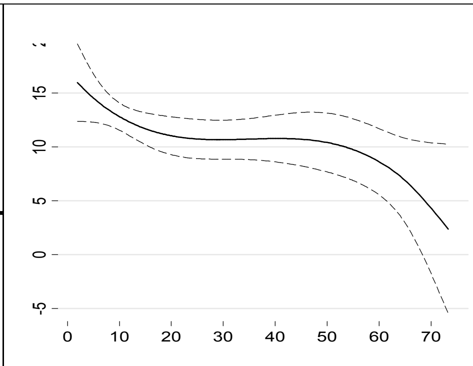
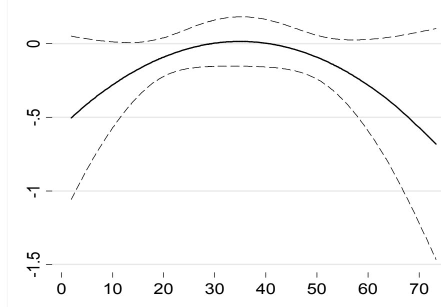
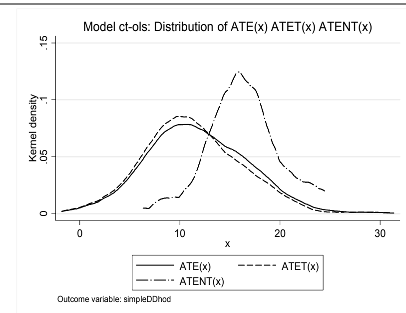
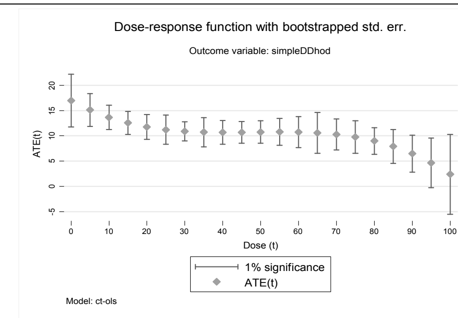
| **simplhdds** |  |  |  |  |
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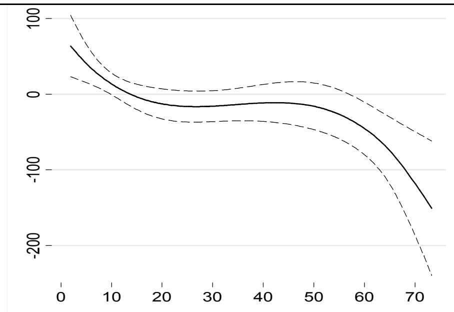
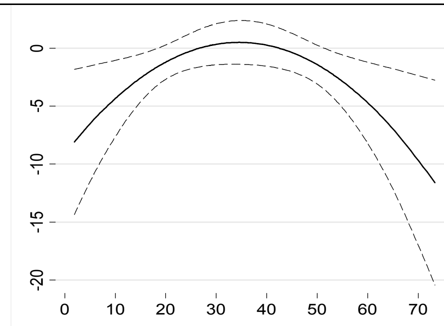
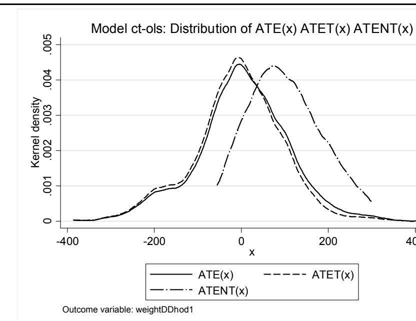
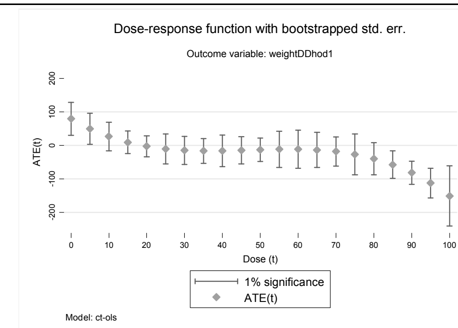
| **weightedhdds** |  |  |  |  |
| | BC level | BC level | Distribution of the ATE(x)s, | DRF with bootstrapping std. error |

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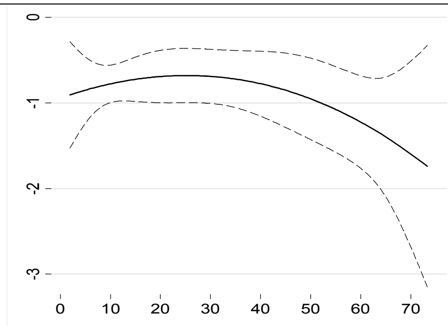
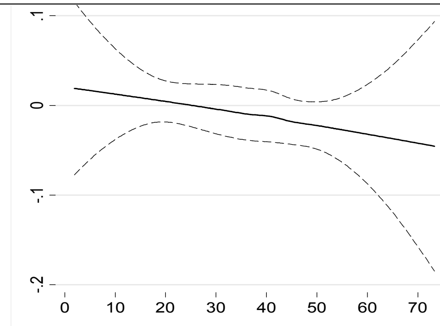
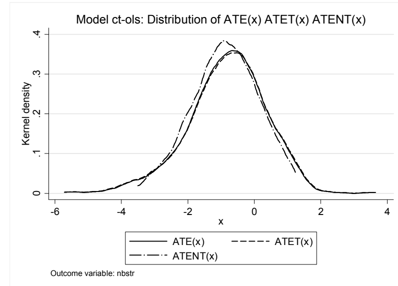
<td></td>
<td></td>
<td>
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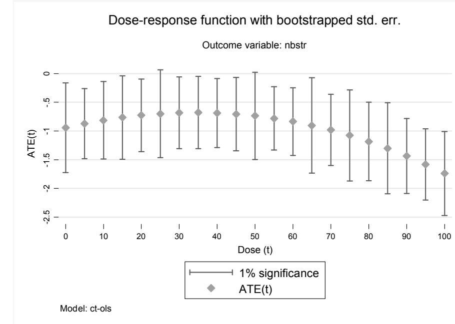
<td>
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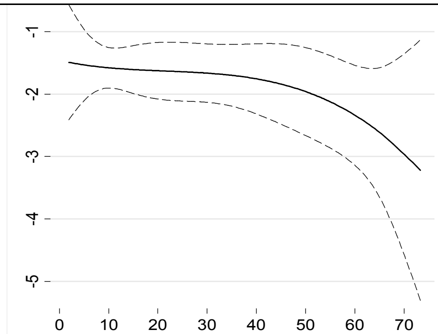
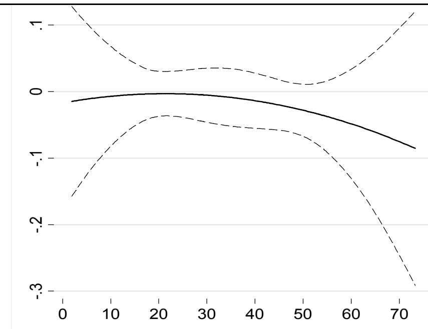
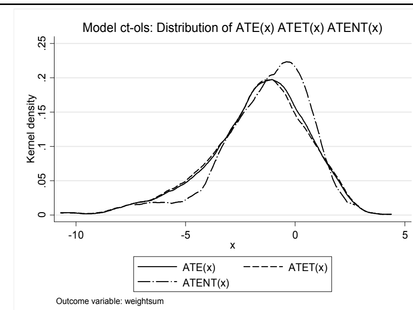
<td></td>
<td></td>
<td>
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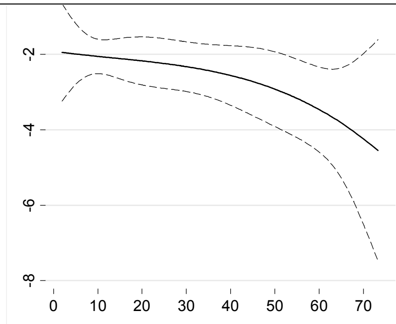
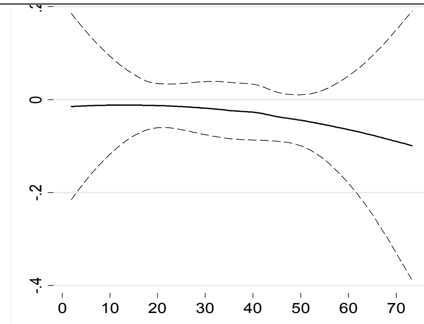
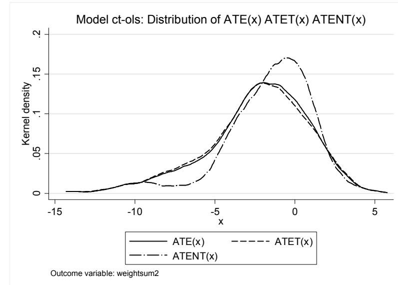
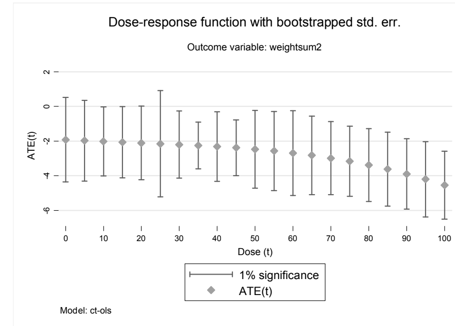
<tr><td>Weighted CS2</td><td></td><td></td><td>
</td><td>
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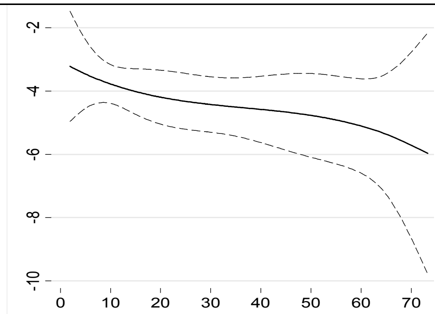
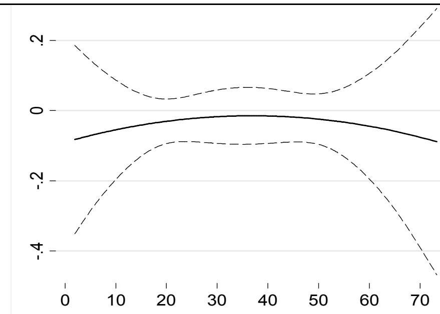
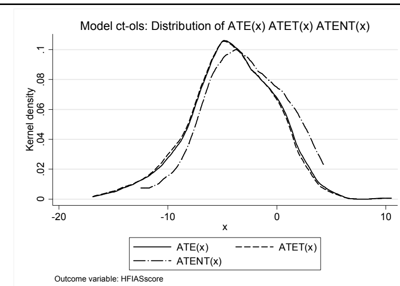
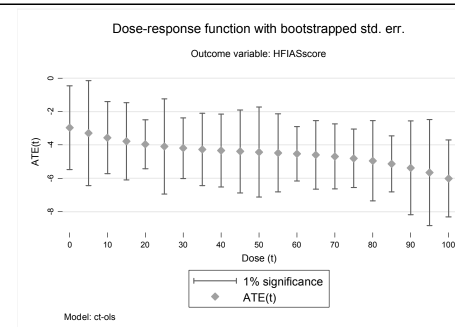
<tr><td>HFIAS</td><td></td><td></td><td>
</td><td>
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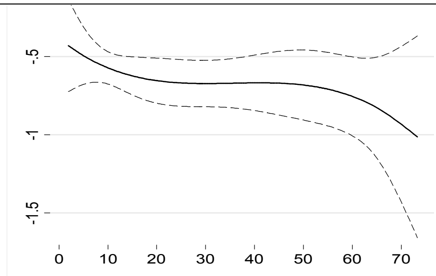
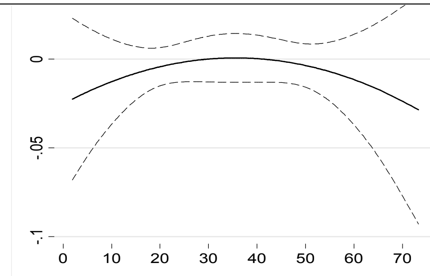
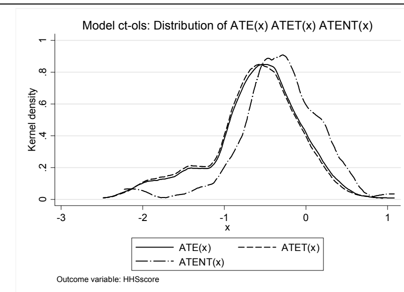
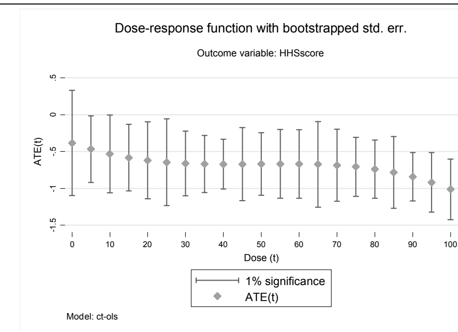
<tr><td>HHS</td><td></td><td></td><td>
</td><td>
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**Figure 4-5 :** Dose Response Function (DRF) and Marginal Treatment Effect (MTE) of food security dimensions

Note: Solid line shows the DRF and MTE curves; dashed lines are 90 % confidence upper and lower bound intervals of the curves.

Source: Author’s computation (2015)

The marginal treatment effect (MTE) functions (column 2) display the same trends as the DRF for many of the obtained results. For example, the treatment functions show that an increase of one percent in biological control level increased the calorie intake by 16.42 Kcal at 0.5% BC level to 27.48 Kcal at 73.32% BC level. Results on the average MTEs show that a one percent increase in biological control level increased the per adult equivalent food expenses and the per adult equivalent calorie intake by KSh128 and 6.94 Kcal, respectively and reduced the number of food insecure households by 0.16%. With respect to the utilization component of food security, one percent increase in BC decreased the simple and the weighted dietary diversity scores by 0.15 point and 2.3 points respectivelly. Concerning the stability component of food security, a one percent increase in BC level is associated with reduction of the simple and weighted number of strategies by 0.003, 0.01 and 0.02 points respectively. For the hunger-base indicators, a one percent increase in BC level reduced the household hunger scale and the household food insecurity access scale by 0.006 point and 0.02 point respectively.

Overall, the implementation of the biological control and its spread to many areas in Kenya contributed to improve food security through all its components except the utilization or dietary diversity which gave a negative impact with the BC. This reduction of the household's diversity in foods may be the consequence of the higher availability of maize (due to BC). Poor market access (low price) of stapple food such as maize may lead households to rely on their own production for consumption and then limiting or reducing the capacity of buying other types of food. Overall the findings suggest that promoting the biological control of cereal stemborers is a key mechanism of ensuring food security. Complementary actions to make complete the impact on food security and on the dietary diversity in particular is to promote the production diversification and market access. Evidence on the positive relationship between production diversification and dietary diversity and quality are demonstrated in the literature (Linderhof *et al.*, 2016; Shibatu *et al.*, 2015). However, Shibatu *et al.* (2015) demonstate that market access has stronger effect on dietary diversity and quality than the on-farm production diversification measure.

## 4.4 Welfare-effect from biological control

### 4.4.1 Welfare change due to biological control of stemborers

The *icipe* biological control intervention contributed to an aggregate approximate value of US$ 741 million to the economy of Kenya from 1990 to 2013 with 76.71% (US$ 568 million) from maize production and the remaining 23.29% (US$ 172 million) from sorghum production (Table 4-11).

**Table 4-11**: Welfare change from BC

| Cereal | **BC-induced change in** (USD millions) | | |
|---|---|---|---|
| | **Producer surplus (ΔPS)** | **Consumer surplus (ΔCS)** | **Total surplus (ΔTS)** |
| *Total social gain* | | | |
| Maize | 307.98 | 260.08 | 568.06 |
| Sorghum | 116.82 | 55.63 | 172.45 |
| Total | 424.80 | 315.70 | 740.50 |
| *Average annual social gain* | | | |
| Maize | 14.67 | 12.38 | 27.05 |
| Sorghum | 5.56 | 2.65 | 8.21 |
| Total | 20.23 | 15.03 | 35.26 |

Source : Author's computation (2015)

These results show that the *Icipe* Biological Control program has globally induced a highly positive impact on welfare in the three countries. Compared to other BC gain, the value is however lower than that obtained for the biological control of the cassava mealybug estimated at $US 2,205 million (Norgaard, 1988). Producers gained an average annual surplus of $US 20 million, representing 57.36% of the total surplus, confirming that they are the major beneficiaries of the BC research though their experienced reduction in price due to the higher supply in maize. This indicates that the farm level yield-effect of the BC dominates the market price-effect from the BC implementation. Maize and sorghum consumers also gained from the decrease in price due to the higher supply induced by the biological control of stemborers. Annual surplus gain was $US 13 for maize consumers and $US 2.65 for sorghum consumers in the country. Theses findings are higher than the estimated gains for Mozambique and Zambia for the same project (Midingoyi *et al.*, 2016). Although these country results are positive, they are lower than the average annual gain of $US 50 million estimated by Bokonon-Ganta *et al.* (2002) for the Biological Control program of mango mealybug in Benin.

### 4.4.2 Net benefits and rates of return to investments in BC program

We estimated the total net present value (NPV) of *icipe*'s biological control programme over the period 1990–2013 at US$ 109 million for maize and US$ 33 million for sorghum, accruing to US$ 142 million for both crops (Table 4-12). These highly positive figures translate that the flow of dicounted benefits generated by icipe BC program implimentation far outweighs the discounted value of the total fund invested in BC resaerch entailing that the icipe-BC program is highly profitable. This net benefit is higher compared to 33.02 and US$ 38.98 million found for the same program in Zambia and Mozambique, respectively (Midingoyi *et al.,* 2016). The higher net benefits for Kenya are due to the scattered release sites that allowed the natural enemies to spread and cover more extended agricultural areas. The spread started from the coastal region (Overholt *et al.,* 1994), and at Mbita, in western Kenya where the BC agents inadvertently escaped from the laboratory colony (Omwega *et al.*, 1995), followed by spread from other well-distributed release sites in Central, Eastern and the Rift Valley of Kenya. In Mozambique, the majority of the release points were concentrated in the south, and in Zambia, most releases were done near the border; consequently, the BC agents spread to the neighboring country. The earlier start of the BC programme in Kenya could also justify the higher net present value for that country.

**Table 4-12**: Net benefits and return to investment

| **Country** | **Net Present value (NPV)** (USD millions) | **Internal rate of return (IRR)** | **Benefit-Cost Ratio (BCR)** |
|---|---|---|---|
| Maize | 108.80 | 108.23% | 238.80 |
| Sorghum | 32.65 | 118.99% | 584.52 |
| Total | 141.52 | 113.08% | 276.45 |

Source : Author's computation (2015)

The internal rate of return of 113% obtained is attractive because it is above the prevailing discount rate of 10% considered for the study. This makes the investment in *icipe*'s biological control research worthwhile. The Benefit–Cost Ratio (BCR), another efficiency measure for funds used in research, was found to equal 276 meaning that each dollar invested in the biological control programme generates an additional value of 276 dollars. The findings confirm the profitability of investing in *icipe*'s biological control research. These unitary net gains are much higher than those obtained in many other BC programme impact assessments. De Groote *et al.* (2003) estimated a BCR of 124:1 for the biological control programme of water hyacinth undertaken in Southern Benin. Bokonon-Ganta *et al.* (2002) found a BCR of 145:1 for the biological control programme of mango mealybug in Benin and Norgaard (1988) estimated a BCR of 149:1 for the biological programme against the cassava mealybug in Africa.

### 4.4.3 Potential impact of biological control of stemborers on poverty reduction

To estimate the potential annual reduction of poverty due to *icipe*'s BC programme, we accessed data on the share of agricultural gross domestic product (AgGDP) and the trends in poverty incidences from the World Development Indicator (WDI) database. The calculated trends of potential poverty reduction impacts of BC research over the period 1993 to 2013 are presented in Figure 4-6 (See also Appendix D). Poverty reduction is expressed here as the proportion of poor people that could be lifted out of poverty[13], and ranged from 0.05% in 1996 to 0.81% in 2013. The reduction in poverty reached 0.1% after 6 to 7 years, confirming the long-term benefit effect of BC programme found to approximate 7 years in Zhou *et al.,* (2001).

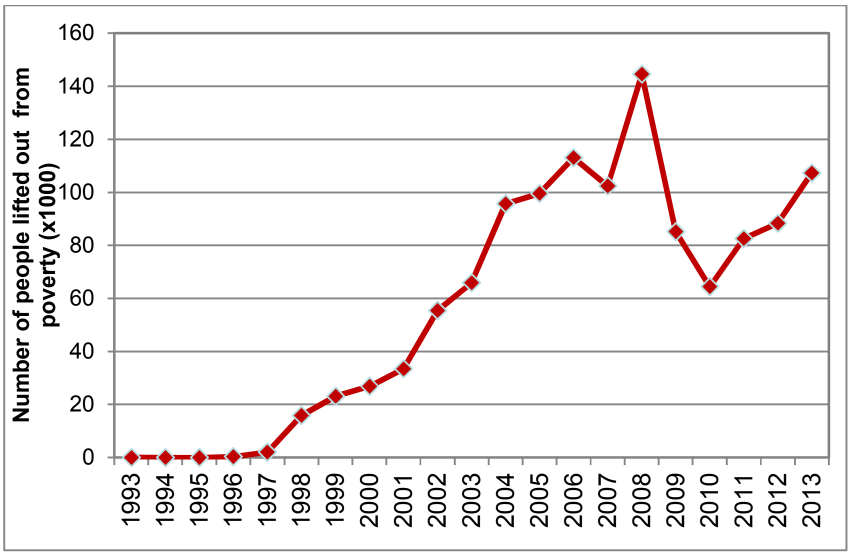



**Figure 4-6**: Trend in poverty reduction due to the BC intervention

Source : Author's computation (2015)

The average potential annual poverty reduction is presented in Table 4-13. Estimated potential impact on poverty was on average 0.35% per year from the BC of cereal stemborer in Kenya. The relatively higher poverty reduction found for Kenya compared to Mozambique and Zambia (0.25% and 0.20% respectively in Midingoyi *et al.* (2016)) is in line with the broader area covered by the BC in Kenya. The better results obtained for maize compared to sorghum confirm its importance as food crop for resource-poor people, who improved their welfare with

[13] Poor were defined as people living below the international poverty line of US$ 1.25 per day.

the yield gain resulting from BC of cereal stemborers. Poverty impacts from the BC programme have increased with time, confirming that the intervention is a sustainable course of action for promoting poverty reduction.

**Table 4-13** : Poverty reduction due to BC

| Country | Average annual number of poor (x 1000) | Potential average % of people lifted out of poverty |
|---|---|---|
| Maize | 43.98 | 0.27% |
| Sorghum | 13.42 | 0.08% |
| Total | 57.40 | 0.35% |

Source : Author's computation (2015)

### 4.4.4 Sensitivity analysis

The above discussed empirical results from the established static models were based on many assumptions on some key parameters. The models' robustness and the degree on the reliability of the results are then contingent upon the selected values of the parameters. We then performed sensitivity analysis of the base models estimates to some reasonable changes in the values of some key parameters. The sensitivity analysis consisted of changing the value of a single parameter assumption, and keeping all other values at their base values. Two groups of parameters were subjected to the sensitivity analysis: entomology-related and market-related. For the entomology-related parameters, the proportion of yield gain attributable to *icipe*'s BC programme was simulated to reduce and augment by 50% of its initial value for each released parasitoid. For the market-related parameters, the price supply elasticity and the price demand elasticity were subjected to variations. The models were estimated for both inelastic supply (0.1) and unity supply elasticity (1), and elastic demand (1.5) and inelastic demand (0.1). These values were chosen to cover the broad range of possible values found in the literature, and the possible types of slope in supply and demand elasticity theory.

Results of the sensitivity analysis (Table 4-14) show that the welfare change, the efficiency of investment in BC research, and the potential poverty reduction are sensitive to change in yield gain (or abilities of the BC agents to parasitize). Reducing the yield gain attributable to parasitism by the biological control agent *Cotesia flavipes* by 50%, results in reduction of 47% of the total social benefits and 48% of the net present value of benefits for both crops. Reduction is also observed with the internal rate of return that decreased from 113% to 29%. The potential poverty reduction also decreases by 48%. When assuming a 50% increase in crop yield gain due to each parasitoid, the welfare change, the efficiency of investment in BC research, and poverty reduction, to some extent, increase in the same proportions as in the case of 50% reduction of yield gain. The magnitude of changes according to the biological control agents shows higher changes for *C. flavipes* than for *X. stemmator*.

Change in the value of the price elasticity of supply results in a large change for surplus as well as net present value mainly for maize (Table 4-14). For a value of inelastic supply of 0.1 (initial value of 0.59), the social benefits, the net present value benefit and the potential poverty reduction increase by more than 5 times compared to their initial estimated values for maize. Shifting from the models' base values to the unitary price elasticity of supply (1: relatively elastic) reduced the benefits, research investment efficiency, and potential poverty reduction by more than 40%. For the price elasticity of demand, a slight increase was noted concerning the inelastic demand of 0.1 (Table 4-15). In addition, assuming an elastic demand (1.5) leads to a reduction in the impact estimates. The responsiveness of the supply of the studied cereals to a change in price has a larger effect on the impact results than the responsiveness of their demand. This result confirms the features of agricultural food crop commodities.

**Table 4-14**: Sensitivity analysis of the BC impact in Kenya

| Parameter | Crops | Parameter | | | Surplus | | NPV | | IRR | | BC ratio | | Poverty | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Base | Change (%) | Value | Value | Change (%) | Value | Change (%) | Value (%) | Change (%) | Value | Change (%) | Value | Change (%) |
| *Cotesia flavipes* | Maize | 10 | -50 | 5.0 | 308.3 | -45.7 | 57.0 | -47.6 | 89 | -17.7 | 125.6 | -47.4 | 0.14% | -47.5 |
| | | 10 | 50 | 15.0 | 835.0 | 47.0 | 161.9 | 48.8 | 121 | 11.5 | 354.8 | 48.57 | 0.40% | 48.7 |
| | Sorghum | 10 | -50 | 5.0 | 87.4 | -49.3 | 16.1 | -50.7 | 100 | -16.2 | 288.6 | -50.6 | 0.04% | -50.7 |
| | | 10 | 50 | 15.0 | 277.6 | 61.0 | 52.9 | 62.1 | 132 | 10.6 | 946.7 | 61.96 | 0.13% | 61.9 |
| | Aggregate | 12 | -50 | 5.0 | 395.6 | -46.6 | 73.1 | -48.3 | 93 | -17.3 | 143.4 | -48.1 | 0.18% | -48.2 |
| | | 12 | 50 | 15.0 | 1112.5 | 50.2 | 214.9 | 51.9 | 126 | 11.2 | 419.2 | 51.65 | 0.54% | 51.7 |
| *Xanthopimpla stemmator* | Maize | 15 | -50 | 7.5 | 539.1 | -5.1 | 105.2 | -3.3 | 108 | 0.0 | 230.9 | -3.3 | 0.26% | -3.2 |
| | | 15 | 50 | 22.5 | 597.3 | 5.1 | 112.4 | 3.3 | 108 | 0.0 | 246.7 | 3.326 | 0.28% | 3.2 |
| | Sorghum | 15 | -50 | 7.5 | 163.9 | -5.0 | 31.6 | -3.3 | 119 | 0.0 | 565.3 | -3.29 | 0.08% | -3.2 |
| | | 15 | 50 | 22.5 | 181.3 | 5.1 | 33.8 | 3.4 | 119 | 0.0 | 604.4 | 3.398 | 0.08% | 3.3 |
| | Aggregate | 15 | -50 | 7.5 | 703.0 | -5.1 | 136.8 | -3.3 | 113 | 0.0 | 267.3 | -3.3 | 0.34% | -3.2 |
| | | 15 | 50 | 22.5 | 778.6 | 5.1 | 146.3 | 3.4 | 113 | 0.0 | 285.7 | 3.342 | 0.36% | 3.3 |

Source : Author's computation (2015)

**Table 4-15**: Sensitivity analysis of impact of BC based on price supply and demand elasticity for Kenya

| Parameter | Crops | Parameter | | Surplus | | NPV | | IRR | | BC ratio | | Poverty | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Base | New | Value | Change (%) | Value | Change (%) | Value (%) | Change (%) | Value | Change (%) | Value | Change (%) |
| *Price elasticity of supply* | Maize | 0.59 | 0.1 | 4404.8 | 675.4 | 1018.2 | 701.4 | 169 | 141.8 | 194.1 | 673.5 | 2.10% | 673.6 |
| | | 0.59 | 1 | 430.2 | -24.3 | 95.0 | -25.2 | 62 | -11.7 | 19.0 | -24.2 | 0.21% | -24.2 |
| | Sorghum | 0.2 | 0.5 | 65.3 | -62.1 | 14.5 | -62.9 | 62 | -30.4 | 39.4 | -62.0 | 0.03% | -62.0 |
| | | 0.2 | 1 | 31.6 | -81.7 | 6.7 | -82.8 | 47 | -47.7 | 19.0 | -81.6 | 0.02% | -81.6 |
| *Price elasticity of demand* | Maize | 0.8 | 0.1 | 604.4 | 6.4 | 134.5 | 5.9 | 70 | 0.8 | 26.5 | 5.6 | 0.29% | 5.7 |
| | | 0.8 | 1.5 | 558.5 | -1.7 | 125.1 | -1.6 | 70 | -0.2 | 24.7 | -1.5 | 0.27% | -1.5 |
| | Sorghum | 0.42 | 0.1 | 247.2 | 43.4 | 55.2 | 41.6 | 91 | 2.7 | 147.1 | 41.8 | 0.11% | 40.0 |
| | | 0.42 | 1.5 | 152.1 | -11.8 | 34.6 | -11.3 | 88 | -1.3 | 91.9 | -11.4 | 0.07% | -11.1 |

Source : Author’s computation (2015)

### 4.4.5 Stochastic dominance analysis

The uncertainty in some parameters necessitated the introduction of stochasticity in this BC economic impact assessment. Monte Carlo simulations were performed using the @RISK software (Palisade Corporation, 2014). First, the probability distribution for each of the five parameters (price supply elasticity, price demand elasticity, yield gain due to *C. flavipes*, yield gain due to *X. stemmator,* and interest rate) was generated using a triangular distribution. The triangular distribution is the simplest and most often used approximation of a normal distribution showing the maximum, the mode, and the minimum. The assumed values of these three points were the same for all the models concerning yield gain due to *C. flavipes* (5%, 10%, 15%) and *X. stemmator* (10%, 15%, 20%), and the interest rate (9%, 10%, 11%). As for the assumed triangular distribution for price elasticity of supply and price elasticity of demand, the values varied depending on the initial value considered for the static analysis. For instance, the triangular distribution for the price elasticity of supply and demand was defined as (0.1, 0.7, 1) and (0.1, 0.8, 1.4) for the maize model in the case for Kenya. An *a priori* non-existence of correlation between these parameters was assumed, because no apparent relationship existed between price elasticity, yield loss abatement and interest rate.

The two models (Maize and Sorghum) were then run setting 10,000 iterations. As outputs for each of the three indicators of interest (NPV, IRR, BC ratio), the summary statistics of their distribution, their cumulative probability distribution, and the relative impact of the considered parameters' mean were derived. The results of the cumulative probability distribution are summarized in Figure 4-7. For maize models, the range of distributions of the NPV (US$ 51.7 million to US$ 936.2 million) was positive, indicating that there was no probability of getting a negative return with *icipe*'s Biological Control Programme. A similar result was obtained for the IRR (85.8% to 178.9%), indicating there was no probability of having an inferior rate to the current 10%, meaning that it will always be profitable to invest in BC interventions. As for the BCR, the minimum values of the distribution ranges (116 to 1955) are all greater than 1, indicating that each invested dollar in the biological control programme will always result in gain.

Similar results were obtained for sorghum (second column, Figure A2) as the probability of having an NPV greater than zero, an IRR greater than 10% and a BCR higher than one is higher than 98%.

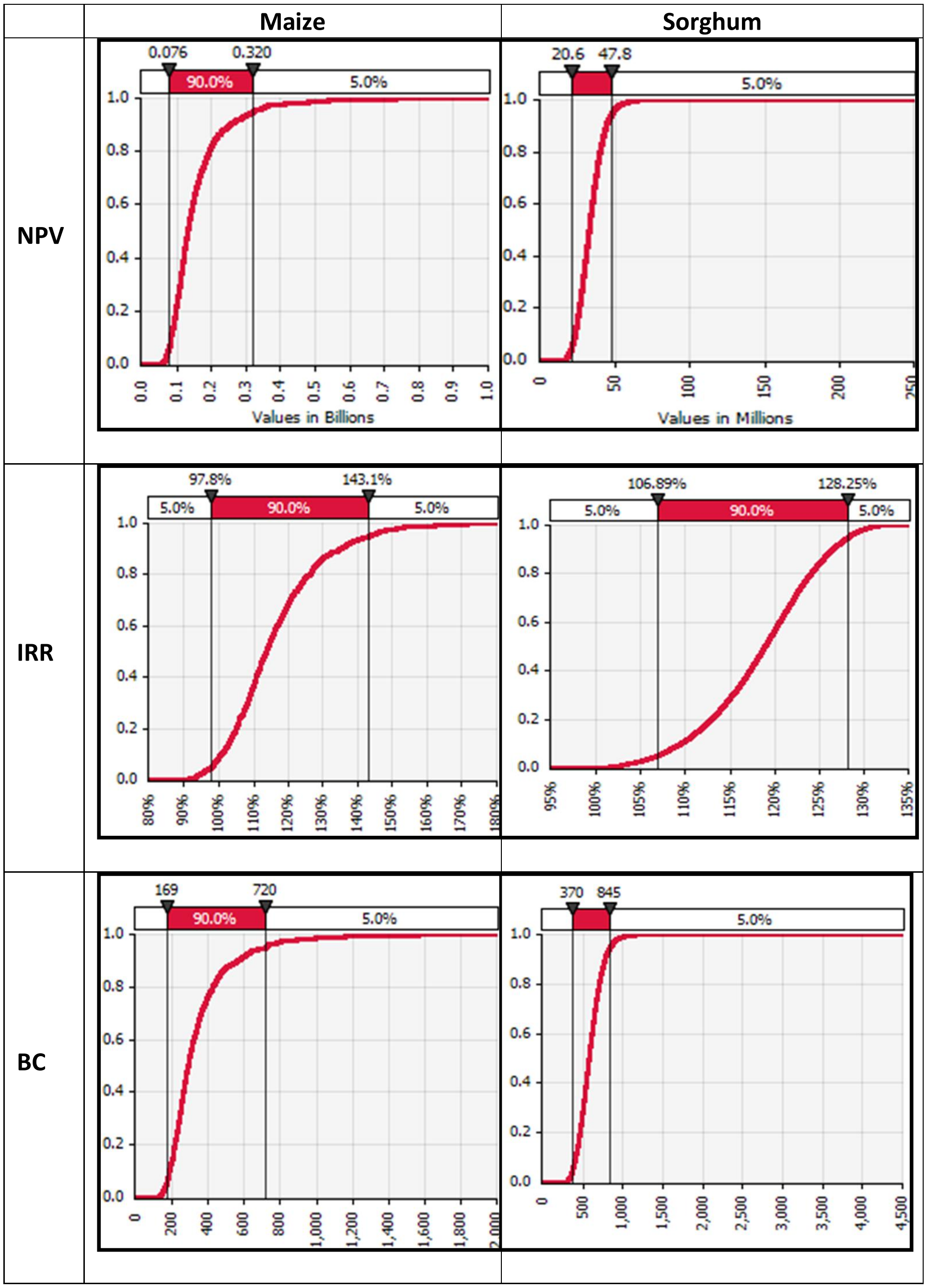



**Figure 4-7** : Cumulative probability distribution of net present value, internal rate of return (IRR) and benefit-cost ratio for maize

Source : Author’s computation (2015)

# CHAPTER FIVE: SUMMARY CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Introduction

The expectation of funding agencies, governments and other policy makers and researchers about investing fund and efforts into protection of major food crops against invasive pests such as stemborers is to ensure that their investments are efficient and contribute to improving the welfare of most vulnerable populations. This dissertation research aims to provide rigorous evidence of the impact of biological control of stemborers in cereal farming, on crop productivity, food security, poverty and global welfare. This study utilized both primary and secondary data which were collected following the analytical framework of the sustainable livelihood approach. Primary data were collected during the 2014-2015 cropping year from a representative sample of 600 households in maize producing agro-ecological zones of Kenya. A variety of methods were employed including production function integrating damage abatement model to account for the damage-abating feature of the bio-control intervention, continuous treatment regression analysis to address the heterogeneity in impact, and economic surplus modeling for casual impact estimation of welfare at global level.

## 5.2 Summary of findings and conclusions

- ***Impact of BC on productivity***

To investigate the productivity-effect of BC of cereal stemborers, this thesis employed the neo classical production theory integrating the damage abatement function framework to account for asymmetry in input contribution to production function because of the damage-reducing feature of biological control. Accounting for endogeneity of insecticide use led to the estimation of insecticide use function in a firststep regression. Results show a negative relationship between BC and pesticide use suggesting the presence of natural enemies leads to reduction in pesticide use. Moreover, estimation of the production functions using different damage function specifications indicated that farmers have significantly higher yield with the BC suggesting that the BC release program positively impacted productivity in Kenya. The marginal product derived from the models of this study demonstrates that each percent increase in parasitism results in abating maize losses by 12 kg/ha. Hence, this costless and self-sustaining control represents the best alternative for poor farmers compared to the cost of pesticide. Reducing the negative externalities from pesticides (potential hazards on environment and the expenditure in human health) adds to the advantages of the BC. These results suggest that BC is an effective and environmentally friendly tool to tackle stemborer pest problems and increase cereal production.

- ***Impact of BC on food security and poverty at household level***

To assess the impact of biological control on food security and poverty, the study adopted a parametric method for causal inference in quasi-experimental settings with continuous treatment which offers analysis under two assumptions: estimation under unconfoundedness assumption and estimation under endogenous treatment. Although exogenous by nature (a self-spreading technology and fundamentally out of control of farmer), the treatment, which is the biological control variable, was tested for its possible endogeneity through a two-stage estimation. The first stage offered opportunity of identifying the determining factors of biological control level. As results, agro-ecology, farm characteristics and practices appeared to influence the biological control level. The use of insecticide negatively influenced biological control suggesting that using pesticide is associated with decrease in rate of parasitism of pests by the natural enemies. This finding is important in terms of policy recommendation for biological control success. The second-step regression results led to confirm the exogeneity of the treatment variable and allow considering estimation under unconfoundedness or conditional mean independence for the assessment.

The findings give robust evidence for the impact of biological control on poverty in Kenya as household expenditure increased and all the observed poverty indices including the headcount index, the poverty gap declined with the intervention. A one percent increase in BC intensity is associated with a Ksh 119 (USD 1.15) increase of household expenditures and a 0.5% reduction in poor households. On average, households realized a yearly intrinsic supplementary gain of Ksh 15 thousand (USD 145.42) with the BC intervention and 22% of maize farming households were moved out of poverty, with impacts varying with the level of BC activity.

With respect to food security impact analysis, this research considered the four pillars derived from the complete and worldwide known definition for food security: availability, access, utilization and stability. Empirical findings indicate that biological control implementation significantly enhanced food access by increasing the per adult equivalent food expenditures, the per adult equivalent caloric intake and reducing of food insecurity. The results vary with the biological control level and in average, a one percent increase in bio-control level increased the per adult equivalent food expenses and the per adult equivalent calorie intake by KSh128 (USD 1.24) and 6.94 Kcal, respectively and reduced the number of food-insecure households by 0.16%. Regarding food utilization, the results show that bio-control has had negative significant impact on food diversity consumption by reducing the simple and weighted dietary diversity indexes. Empirical evidences show that bio-control has had a significant stability effect by reducing the simple and weighted number of strategies indexes and hence suggesting that the technology reduced the households' vulnerability to negative shocks that can arise from food insecurity. All these impact estimates vary with the bio-control level. Overall, in addition to the positive impact on availability (positive productivity-effect previously demonstrated), positive impacts were derived from the use of biological control for all the pillars of the food security except the utilization where a decreasing impact was found. This implies that the increase in maize production tended to reduce the diversity in food in the households.

- ***Welfare effect from the biological control***

Under the assumptions of closed economy, parallel shift of supply and demand and the linear supply and demand curves, findings from the economic surplus modeling of the BC-induced shift in maize and sorghum supply in Kenya provide evidence that producers and consumers have benefitted from the biological control of stemborer pests. The biological control intervention has contributed to an aggregate monetary surplus of $US 0.74 billion to the economy of Kenya with 76.75% ($US 0.57 billion) from maize production and the remaining 23% ($US 0.17 billion) from sorghum production. The net present benefit (including deduction of the program cost) over the period of 1993-2013 was estimated to $US 236 million for both crops suggesting the high profitability of the investment in BC program in Kenya. These estimates revealed high efficiency of the invested funds, and justified the cost-effectiveness of the BC programme. Moreover, the estimated number of people lifted out of poverty through *icipe'* BC program was in average 80,030 persons (consumer and producers) per year, representing an average of 0.49%, yearly reduction of total poor populations in the country. The key conclusion from this analysis was that biological control gives substantial benefit returns and is highly cost-effective while contributing to improved social welfare in Kenya. These results are of lower boundary as conservative parameters (dispersal rate and yield gain) were assumed in the estimations. The benefits would have increased if the advantages from the spread to neighboring countries were also considered. Additional benefits from the reduced health hazards and other benefits linked to the reduction of risks to the environment were not included.

## 5.3 Policy implications and recommendations

Some key lessons emerge from this dissertation research for *icipe*, the funding agency, governments and other policy makers and institutions interested in reducing food insecurity and poverty in a sustainable way.

Results from the estimated insecticide use function indicated a decrease in insecticide use with the biological control strategy. This reduction in pesticide appears important as BC can be seen as a safe substitute to pesticide and may be useful in anti-pesticide programs, pest-resistance management projects and policies on human and environmental health preservation. This study thus recommends that BC be included and promoted in the country plant protection systems especially in cereal farming region with high level pesticide use. Moreover, the findings of positive impact of BC on productivity suggest that it is a sound method useful in policies of yield losses reduction for more cereal availability.

Results indicate that the self-disseminating BC technology undertaken by *icipe* for reducing yield loss and consequently increasing agricultural productivity has had a positive causal effect relationship with poverty reduction and some food security components. This suggests that biological control is a pro-growth policy instrument and sustainable hunger-elimination tool. However, with respect to the negative impact on food dietary utilization, the implementation of the biological control should be combined with interventions on marketing of the production surplus generated to allow farmers having cash to purchase different types of food to ensure diversity and quality in food consumption.

Overall, these results on food security and poverty suggest that promoting biological control of stemborers is a key strategy for contributing to food availability and alleviating poverty in Kenya. However, the dose response function results show that lower and average level of BC activities are associated with lower impact responses. Therefore, there is still scope of optimizing the impact of BC in Kenya and this might require action to increase the BC-agents' presence in the infested areas. More interventions with more releases through conservative and inundative biological control program are recommended. Increasing BC activity level requires raising farmer awareness of the BC technology. Descriptive analysis revealed a low level of knowledge of the biological control and natural enemies of stemborers by farmers. For purposes of conservation, and to allow farmers to derive the full advantages from the biological control, a participatory approach in educating them on the recognition of pests and natural enemies and farming practices that favour or reduce parasitism level is of high importance. Approaches of education such as Farmer Field School (FFS) for instance might prove useful.

Findings suggest that the use of insecticides negatively impact the biological control activity. Optimizing the advantages from biological control will require that BC program implementers to include the education of farmers on farming practices that ensure the synergy between insecticide use and biological control. We also suggest institutional collaboration with the authority of pesticide regulation in order to authorize active ingredients that are compatible with the BC-agents in the perspective of an effective integrated pest management (IPM) approach.

Evidence from the economic surplus analysis shows an improvement in the welfare of producers and consumers through implementing a sustainable and cost-effective BC programme, which implies that efforts should be made to scale up BC interventions to other areas with serious stemborers problem. More funds could be invested in biological control programmes in East and Southern Africa. To optimize on the advantages from BC, activities to ensure establishment and spread of these biological control agents, especially for the control of *B. fusca* in high-altitude zones, are required.

## 5.4 Contribution to knowledge

This thesis sought to examine the impact of BC and adds to the literature and knowledge on economics of biological control through the following contriburtions.

Drawing on the theory of production economics, this thesis has extended the classical production function whereby all inputs are considered as standard by introducing the damage abatement framework which takes into account that biological control is a damage-abating factor. By incorrectly treating the BC as a growth-enhancing factor (such as fertilizers) productivity estimation may be biased and lead to erroneous policy recommendation. This thesis provides empirical findings on both considerations (classical production function and damage abatement function with appropriate functional specifications) that clearly display an underestimation of BC productivity with classical production function. The higher and consistent productivity estimates obtained when using damage abatement framework give information on the true contribution of BC in terms of yield gain.

In assessing BC effects on poverty and food security, the thesis advances the impact assessment methodology by going beyond the binary treatment (with and without BC) and considering the BC level using then continuous treatmnent approach. Ignoring the presence of diverse levels within the group of BC treated farms leads to average estimates instead of the heterogeneity in impact estimates. The present thesis provides empirical evidence of increasing impacts with BC level. Providing such information is usefull as it helps to avoid partial recommendations. In other words, it allows the consideration of not only regions without BC, but considering regions with low levels of BC that should benefit from additionnal releases of BC agents.

Food security effect analysis requires considering the complexity of the respective concept as generally recognised through its four pillars including availability, accessibility, utilization and stability. Diverting from previous studies of impact on food security, this thesis analyzes impact on each pillar of food security and provides empirical evidence that agricultural technology can contribute to improve some components of food security and not others. Results show that households have better food access, better food availability and stability with the biological control program but reduced their dietary diversity (utilization of food) with the BC.

In the welfare-effect analysis, one of the methodological innovations in this assessment was the use of GIS-based modeling to simulate the geographical spread and determine the overlapping build-up of the parasitoids from release points. This was valuable in determining the area covered by the BC intervention per year, and the cultivated cereal area under BC per year, which are important data in determining the supply shift and in computing the surplus.

## 5.5 Suggestions for future research

It is worth noting that this study is based on a single cross-section household survey. As such, it might not reflect the dynamics of biological control, productivity and poverty reduction features. Multi-season and multi-year data of household as well as biological data will help in capturing the fluctuating, uncertainty in biological control phenomena and the cyclical nature of stemborer pests' infestation. The establishment of a long run monitoring system of generating data will be useful for this concern.

This impact research is conducted in Kenya even though the BC program were implemented in ten ESA countries. Extending the research to many other countries who benefited from the program and that present non-similar agro-ecology and socio-demography with Kenya will undoubtedly help to have more complete picture on the economic impact of the icipe BC programme.

Lastly, even though this study benefited from the multi-disciplinary setting of the BC impact assessment project by using the data on biological control in economic analysis, there is still scope of integrating more pest-natural enemy's relationship data to build more accurate bio-economic models for optimality analysis. This requires the involvement of economists into the team before and during the implementation of the BC program to design a comprehensive data collection for a baseline and ex-post studies for robustness of impact estimates.

There is room for improvement in future studies, when conducting regular follow-up surveys following a BC intervention. The 'extensive survey' should be undertaken regularly to offer the possibility of testing and correcting the GIS-modeling, and enhancing the confidence on dispersal rates and spread of the biological control agents (Nordblom *et al.*, 2002). Moreover, the existence of possible variability in yield gain or loss abatement across regions (an important shortcoming in economic surplus analyses), should guide to conduct at least one exclusion experiment in each agroecological zone.

# REFERENCES


Abate, T., Mugo, S., De Groote, H., & Regassa, M.W. (2015). Maize in Kenya: Chance for Getting Back to Former Glory? DT Maize, A Quarterly Bulletin of the Drought Tolerant Maize for Africa Project. Vol.4 Number 3, September 2015.

Accadia, P., & Spagnolo, M., (2006). A bio-economic simulation model for the Italian fisheries. In *Proceedings of the Thirteenth Biennial Conference of the International Institute of Fisheries Economics & Trade (IIFET)*.

Adato, M., & Meinzen-Dick, R. S. (2003). Assessing the impact of agricultural research on poverty and livelihoods. *Quarterly Journal of International Agriculture* 42(2):149-166.

Affognon, H. D. (2007). Economic analysis of trypanocide use in villages under risk of drug resistance in West Africa (Doctoral dissertation, University of Hannover).

Agola, N. O., & Awange, J. L. (2014). Globalized Poverty and Environment: 21st Century Challenges and Innovative Solutions. Springer Science & Business Media.

Ajayi, O.C. (2000): Pesticide use, productivity and farmers' health: The case of cotton-rice systems in Côte d'Ivoire, West Africa. Pesticide Policy Project, Publication Series Special Issue No. 2, University of Hanover, Germany.

Alene, A. D., Menkir, A., Ajala, S. O., Badu-Apraku, B., Olanrewaju, A. S., Manyong, V. M., & Ndiaye, A. (2009). The economic and poverty impacts of maize research in West and Central Africa. *Agricultural Economics*, *40*(5), 535-550.

Alston, D.G., (2011). General concepts of biological control. Pests fact sheet, Utah State University, July 2011

Alston, J. M., Norton, G. W., & Pardey, P. G. (1995). *Science under scarcity: principles and practice for agricultural research evaluation and priority setting*. Cornell University Press.

Asfaw, A., Mithöfer, D., Löhr, B., & Waibel, H. (2011). Challenges for economic impact assessment of classical biological control in Kenya and Tanzania. *Vegetable Production and Marketing in Africa: Socio-economic Research, CABI, Wallingford*, 209-226.

Assefa, Y., Mitchell, A., Conlong, D. E., & Muirhead, K. A. (2008). Establishment of Cotesia flavipes (Hymenoptera: Braconidae) in sugarcane fields of Ethiopia and origin of founding population. *Journal of economic entomology*, *101*(3), 686-691.

Babcock, B. A., Lichtenberg, E., & Zilberman, D. (1992). Impact of damage control and quality of output: estimating pest control effectiveness. *American Journal of Agricultural Economics*, *74*(1), 163-172.

Baker, J. L. (2000). *Evaluating the impact of development projects on poverty: A handbook for practitioners*. World Bank Publications.

Ballard, T., Coates, J., Swindale, A., & Deitchler, M. (2011). Household hunger scale: indicator definition and measurement guide. *Food and Nutrition Technical Assistance II Project, FHI*, *360*.

Basse, B., Phillips, C. B., Hardwick, S., & Kean, J. M. (2015). Economic benefits of biological control of Sitona obsoletus (clover root weevil) in Southland pasture. *NZ Plant Prot*, *68*, 218-226.

Bauer, M., Pearce, D., & Vincent, D. P. (2003). Saving a staple crop: impact of biological control of the banana skipper on poverty reduction in Papua New Guinea. Australian Centre for International Agricultural Research, Report No (IAS-22) 26pp. 2003. Available at : http://ageconsearch.umn.edu/bitstream/113227/2/ias22.pdf (last accessed 30 December 2015).

Bento, J. M. S., Moraes, G. D., Matos, A. D., Warumby, J. F., & Bellotti, A. C. (2002). Biological control of cassava mealybug in Northeast Brasil= Controle biológico da cochonilha da mandioca no Nordeste do Brasil. *Parra, JRP; Botelho, PSM; Corrêa-Ferreira, BS*, 395-408.

Bia, M., & Mattei, A. (2012). Assessing the effect of the amount of financial aids to Piedmont firms using the generalized propensity score. *Statistical Methods & Applications*, *21*(4), 485-516.

Bia, M., Flores, C. A., Flores-Lagunes, A., & Mattei, A. (2014). A Stata package for the application of semiparametric estimators of dose–response functions. *Stata Journal*, *14*(3), 580-604.

Blackwell, M., & Pagoulatos, A. (1992). The econometrics of damage control. *American Journal of Agricultural Economics*, *74*(4), 1040-1044.

Bokonon-Ganta, A. H., de Groote, H., & Neuenschwander, P. (2002). Socio-economic impact of biological control of mango mealybug in Benin. *Agriculture, ecosystems & environment*, *93*(1), 367-378.

Bonhof, M. J., Overholt, W. A., Van Huis, A., & Polaszek, A. (1997). Natural enemies of cereal stemborers in East Africa: a review. *International Journal of Tropical Insect Science*, *17*(01), 19-35.

Brown, G.C., (1997). Simple models of natural enemy action and economic thresholds. *American Entomologist*, *43*(2), 117-124.

Bruce, Y. A., Schulthess, F., Mueke, J., & Gohole, L. (2009). Egg parasitoids of noctuid stemborers on maize in Kenya. *International Journal of Biodiversity Science & Management*, *5*(3), 174-180.

Campbell, H. F. (1976). Estimating the Marginal Productivity of Agricultural Pesticides: the Case of Tree-Fruit Farms in the Okanagan Valley. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, *24*(2), 23-30.

Cardinale, B. J., Harvey, C. T., Gross, K., & Ives, A. R. (2003). Biodiversity and biocontrol: emergent impacts of a multi-enemy assemblage on pest suppression and crop yield in an agroecosystem. *Ecology Letters*, *6*(9), 857-865.

Carpentier, A., & Weaver, R. D. (1997). Damage control productivity: why econometrics matters. *American journal of agricultural economics*, *79*(1), 47-61.

Carrasco-Tauber, C., & Moffitt, L. J. (1992). Damage control econometrics: functional specification and pesticide productivity. *American Journal of Agricultural Economics*, *74*(1), 158-162.

Cerulli, G. (2015). ctreatreg: Command for fitting dose–response models under exogenous and endogenous treatment. *Stata Journal*, *15*(4), 1019-1045.

Chambers, R. (1988) Applied production analysis. Cambridge University Press, Cambridge

Chambers, R. G. (1997). Applied Production Analysis (Cambridge University Press).

Chavez, H., Nadolnyak, D. A., & Kloepper, J. (2012). Stochastic Frontier Analysis of Biological Agents (Microbial Inoculants) Input Usage in Apple Production. In *2012*

*Annual Meeting, February 4-7, 2012, Birmingham, Alabama* (No. 119796). Southern Agricultural Economics Association.

Chock, M., Burnett, K., & Lee, D. (2010). An Economic Assessment of Biological Control for Miconia calvescens in Hawaii. *Manoa, Hawaii: University of Hawai'i Economic Research Organization (UHERO) University of Hawaii-Manoa*, 34.

Cloyd, R. (2005). Compatibility conflict: is the use of biological control agents with pesiticides a viable management strategy. In *Second International Symposium on Biological Control of Arthropods (12-16 September, Davos-Switzerland)* (pp. 546-554).

Cloyd, R.A., (2012). Indirect effects of pesticides on natural enemies. In: Soundararajan, R.P. (Ed.), Pesticides – Advances in Chemical and Botanical Pesticides. InTech, Rijeka, Croatia, pp. 127–150

Coates, J., Swindale, A., & Bilinsky, P. (2007). Household Food Insecurity Access Scale (HFIAS) for measurement of food access: indicator guide. *Washington, DC: Food and Nutrition Technical Assistance Project, Academy for Educational Development*.

Cock, M. J., Murphy, S. T., Kairo, M. T., Thompson, E., Murphy, R. J., & Francis, A. W. (2016). Trends in the classical biological control of insect pests by insects: an update of the BIOCAT database. *BioControl*, *61*(4), 349-363.

Cock, M.J.W., Brodeur, J., Barratt, B., Bigler, F., Bolckmans, K., Haas, F., Mason, P.G. & Parra, J.R.P., (2010). *The use and exchange of biological control agents for food and agriculture* (No. 47). IOBC. Paper prepared for the Commission on genetic resources for food and agriculture

Coelli, T. J., Rao, D. S. P., O'Donnell, C. J., & Battese, G. E. (2005). *An introduction to efficiency and productivity analysis*. Springer Science & Business Media.

Cook, R. J. (2007). Take-all decline: model system in the science of biological control and clue to the success of intensive cropping. *Biological Control a Global Perspective: Case Studies from Around the World. C. Vincent, M. Goettel, and G. Lazarovits, eds. CAB International, Wallingford, UK*, 399-414.

Cooke, B., Chudleigh, P., Simpson, S., & Saunders, G. (2013). The economic benefits of the biological control of rabbits in Australia, 1950–2011. *Australian Economic History Review*, *53*(1), 91-107.

Coudouel, A., Hentschel, J. S., & Wodon, Q. T. (2002). Poverty measurement and analysis. *A Sourcebook for poverty reduction strategies*, *1*, 27-74.

Cugala, D., Schulthess, F., Ogol, C. P., & Omwega, C. O. (2006). Assessment of the impact of natural enemies on stemborer infestations and yield loss in maize using selected insecticides in Mozambique. In *Annales de la Société entomologique de France* (Vol. 42, No. 3-4, pp. 503-510). Taylor & Francis Group.

Cugala, R. D. (2007). Impact assessment of natural enemies on stem borer populations and maize yield in three Agro ecological Zones in Mozambique (Doctoral dissertation, Kenyatta University, Nairobi, Kenya.).

Culliney, T. W. (2005). Benefits of classical biological control for managing invasive plants. *Critical Reviews in Plant Sciences*, *24*(2), 131-150.

Davies, S. (1993). Are coping strategies a cop out?. *IDS bulletin*, *24*(4), 60-72

De Groote, H., Ajuonu, O., Attignon, S., Djessou, R., & Neuenschwander, P. (2003). Economic impact of biological control of water hyacinth in Southern Benin. *Ecological Economics*, *45*(1), 105-117.

De Groote, H. (2002). Maize yield losses from stemborers in Kenya. *Insect Science and its Applications 22(2002): 89-96.*

De Janvry, A. (2010). Agriculture for development: new paradigm and options for success. *Agricultural Economics*, *41*(s1), 17-36.

de Lange, W. J., & van Wilgen, B. W. (2010). An economic assessment of the contribution of biological control to the management of invasive alien plants and to the protection of ecosystem services in South Africa. *Biological Invasions*, *12*(12), 4113-4124.

DeBach, P., 1974. Biological Control by Natural Enemies. Cambridge University press, London

Devorshak, C. & Neeley, A. (2012). 11 Pest Risk Assessment. *Plant Pest Risk Analysis: Concepts and Applications*, p.135.

Diao, X., Fan, S., Headey, D., Johnson, M., Pratt, A. N., & Yu, B. (2008). *Accelerating Africa's Food Production in Response to Rising Food Prices*. Washington, DC: IFPRI.

Doeleman, J. A. (1989). *Biological control of Salvinia molesta in Sri Lanka: an assessment of costs and benefits* (No. 113874). Australian Centre for International Agricultural Research.

Dutta, I., Gundersen, C., & Pattanaik, P. K. (2007). Measures of food insecurity at the household level. *Food Security Indicators, Measurement, and the Impact of Trade Openness: Series: WIDER Studies in Development Economics. Basudeb Guha-Khasnobis, Shabd S. Acharya, and Benjamin Davis, eds*, 42-61.

Eijgenraam, C. J., Koopmans, C. C., Tang, P. J., & Verster, A. C. P. (2000). Evaluation of infrastructural projects. *Guide for cost–benefit analysis, Sections I and II, The Hague: CPB, Rotterdam: NEI (changed name to ECORYS)*.

Ekesi, S. (2015). Field Infestation and Suppression of the Invasive Fruit Flies Bactrocera invadens (Drew, Trsuruta and White) on Citrus in Kenya. *Acta Hortic*, *1065*, 1019-1026. http://www.actahort.org/books/1065/1065_1127.htm.

Emana, G., Overholt, W. A., Kairu, E., MacOpiyo, L., & Zhou, G. (2002). Predicting the distribution of *Chilo partellus* (Swinhoe) and its parasitoid *Cotesia flavipes* Cameron in Ethiopia using correlation, step-wise regression and geographic information systems. *International Journal of Tropical Insect Science*, *22*(02), 123-129.

Falck-Zepeda, J. B., & Zambrano, P. (2011). Socio-economic Considerations in Biosafety and Biotechnology Decision Making: The Cartagena Protocol and National Biosafety Frameworks. *Review of Policy Research*, *28*(2), 171-195.

Falck-Zepeda, J. B., Horna, D., & Kyotalimye, M. (2013). Socioeconomic considerations in biosafety decision making: Methods and implementation, in: Horna, D., Zambrano, P., Falck-Zepeda, J. B. (Eds). International Food Policy Research Institute (IFPRI), Washington, D.C., pp. 95–128.

Ferrar, P., Forno, I. W., & Yen, A. L. (2004). Report of the Review of the Management of Biosecurity Risks associated with the Importation and Release of Biological Control Agents. *Australian Government Department of Agriculture, Fisheries and Forestry, Canberra, Australia.*

Flint, M. L., Dreistadt, S. H., & Clark, J. K. (1998). *Natural enemies handbook: the illustrated guide to biological pest control* (Vol. 3386). Univ of California Press.

Florio, M., Forte, S., Pancotti, C., Sirtori, E., & Vignetti, S. (2016). Exploring cost-benefit analysis of research, development and innovation infrastructures: an evaluation framework. *arXiv preprint arXiv:1603.03654*.

Fonseca, A. P. P., Marques, E. J., Torres, J. B., Silva, L. M., & Siqueira, H. Á. A. (2015). Lethal and sublethal effects of lufenuron on sugarcane borer Diatraea flavipennella and its parasitoid Cotesia flavipes. *Ecotoxicology*, *24*(9), 1869-1879.

Food and Agriculture Organization (FAO). (2002). *The state of food insecurity in the world.* Food and Agriculture Organization of the United Nations, Rome, Italy.

Foster, J., Greer, J., & Thorbecke, E. (1984). A class of decomposable poverty measures. *Econometrica: Journal of the Econometric Society*, 761-766.

Fowler, S.V. (2005). The successful control of *Orthezia insignis* on St. Helena Island saves natural populations of endemic gumwood trees, Commidendrum robustum. In *Second International Symposium On Biological Control Of Arthropods*.

Fox, G., & Weersink, A. (1995). Damage control and increasing returns. *American Journal of Agricultural Economics*, *77*(1), 33-39.

Frank, J. H. (2007). Biological Control of Some Insect Pests of Turfgrasses. In *Handbook of Turfgrass Management and Physiology* (pp. 281-297). CRC Press.

Gagic, V., Hänke, S., Thies, C., Scherber, C., Tomanović, Ž., & Tscharntke, T. (2012). Agricultural intensification and cereal aphid–parasitoid–hyperparasitoid food webs: network complexity, temporal variability and parasitism rates. *Oecologia*, *170*(4), 1099-1109.

Garcia, D., Prellezo, R., Sanchez, S., Andres, M., & Santurtun, M. (2012). FLBEIA: A toolbox to conduct Bio-Economic Impact Assessment of fisheries management strategies. *ICES ASC, Bergen*.

Gayawan, E., & Ipinyomi, R. A. (2009). A comparison of Akaike, Schwarz and R square criteria for model selection using some fertility models. *Australian Journal of Basic and Applied Sciences*, *3*(4), 3524-3530.

Gebrehiwot, T., & van der Veen, A. (2015). Estimating the impact of a food security program by propensity-score matching. *Journal of Development and Agricultural Economics*, *7*(1), 38-47.

Getu, E., Overholt, W. A., Kairu, E., & Omwega, C. O. (2003). Evidence of the establishment of Cotesia flavipes (Hymenoptera: Braconidae), a parasitoid of cereal stemborers, and its host range expansion in Ethiopia. *Bulletin of entomological Research*, *93*(02), 125-129.

GoK (2010). Economic Review of Agriculture 2010. Nairobi: Ministry of Agriculture.

Greathead, D. J., & Neuenschwander, P. (2003). Historical overview of biological control in Africa. *Biological Control in IPM Systems in Africa. CABI Publishing, Wallingford, UK*, 1-26.

Griffin, R. C., Montgomery, J. M., & Rister, M. E. (1987). Selecting functional form in production function analysis. *Western Journal of Agricultural Economics*, 216-227.

Groebner, D. F. & Shannon, P. W., (2005). Business statistics: A decision making approach. Upper Saddle River, NJ: Pentice Hall.

Gross, R. (2002). Food and nutrition security in poverty alleviation: Concepts, strategies, and experiences at the German Agency for Technical Cooperation. *Asia Pacific Journal of Clinical Nutrition*, *11*(s1), S341-S347.

Gutierrez, A.P., Caltagirone, L.E. & Meikle, W., (1999). Evaluation of results: economics of biological control. *Handbook of biological control*, pp.243-252.

Gutierrez, A.P., Messenger, P.S. & van den Bosch, R. (2013). *An introduction to biological control*. Springer Science & Business Media.

Habeck, M.H., Lovejoy, S.B. & Lee, J.G. (1991). December. Classical Biological Control of Insects: A Benefit-Cost Approach. In *American Journal of Agricultural Economics* (Vol. 73, No. 5, pp. 1534-1534).

Hagen, K. S., & Franz. J. M. (1973). A history of biological control. p. 433-476. In A History of Entomology (R. F. Smith, T. E. Mittler, and C. N. Smith, editors). Annu. Rev. Inc., Palo Alto, California. 517 pp.

Hajek, A. (2004). Natural Enemies: An Introduction to Biological Control. Cambridge University Press, Cambridge.

Harris, P. (1979). Cost of biological control of weeds by insects in Canada. *Weed Science*, 242-250.

Hassan, S. A., & Van de Veire, M. (2004). Compatibility of pesticides with biological control agents. *Biocontrol in protected culture*, *1*, 129-148.

Haughton, J., & Khandker, S. R. (2009). *Handbook on poverty+ inequality*. World Bank Publications.

Hausman, J. A. (1978). Specification tests in econometrics. *Econometrica: Journal of the Econometric Society*, 46(6) 1251-1271.

Headley, J. C. (1968). Estimating the productivity of agricultural pesticides. *American Journal of Agricultural Economics*, 50 (1), 13-23.

Heckman, J. J., & Vytlacil, E. (2005). Structural equations, treatment effects, and econometric policy evaluation1. *Econometrica*, *73*(3), 669-738.

Hirano, K., & Imbens, G. W. (2004). The propensity score with continuous treatments. *Applied Bayesian modeling and causal inference from incomplete-data perspectives*, *226164*, 73-84.

Hoddinott, J. (1999). *Choosing outcome indicators of household food security*. Washington, DC: International Food Policy Research Institute.

Holden, S.T., Shiferaw, B., Freeman, H.A. & Swinton, S.M. (2005). Bioeconomic modelling for natural resource management impact assessment. *Natural resource management in agriculture: methods for assessing economic and environmental impacts*, pp.175-196.

Huffaker, C.B. ed., (2012). *Theory and practice of biological control*. Elsevier.

Hundie, B. (2012). Impacts of Adoption of Improved Wheat Technologies on Households' Food Consumption in Southeastern Ethiopia. Selected Poster prepared for presentation at the International Association of Agricultural Economists (IAAE) Triennial Conference, Foz do Iguaçu, Brazil, 18-24 August, 2012.

IFAD (International Fund for Agricultural Development). 'Report and recommendation of the President to the Executive Board on proposed technical assistance grants for agricultural research and training by CGIAR' Supported international centers. (1998). Available at: from http://www.ifad.org/gbdocs/eb/64/e/eb64-r25.pdf. (last accessed 20 January 2016)

IITA [International Institute of Tropical Agriculture] Maize. (2013). http://www.iita.org/maize

Imbens, G. W., & Wooldridge, J. M. (2009). Recent developments in the econometrics of program evaluation. *Journal of economic literature*, *47*(1), 5-86.

Irz, X., Lin, L., Thirtle, C., & Wiggins, S. (2001). "Agricultural productivity growth and poverty alleviation." *Development Policy Review*, 19 (4), 449-466.

Jiang, N., Zhou, G., Overholt, W. A., Muchugu, E., & Schulthess, F. (2006). The temporal correlation and spatial synchrony in the stemborer and parasitoid system of Coast Kenya with climate effects. In *Annales de la Société entomologique de France* (Vol. 42, No. 3-4, pp. 381-387). Taylor & Francis Group.

Kabubo-Mariara, J., & Karanja, F. K. (2007). The economic impact of climate change on Kenyan crop agriculture: A Ricardian approach. *Global and planetary change*, *57*(3), 319-330.

Kairo, M. T. (2005). Hunger poverty and protection of biodiversity: Opportunities and challenges for biological control. In *Hoddle, MS, Compiler, Proceedings of 2nd International Symposium on Biological Control of Arthropods, Davos, Switzerland* (Vol. 1, pp. 228-236).

Kang'ethe, E. (2011). Situation analysis: Improving food safety in the maize value chain in Kenya. *Report prepared for FAO. College of Agriculture and Veterinary Science, University of Nairobi, Nairobi*.

Kassie, M., Jaleta, M., & Mattei, A. (2014). Evaluating the impact of improved maize varieties on food security in Rural Tanzania: Evidence from a continuous treatment approach. *Food Security*, *6*(2), 217-230.

Kassie, M., Pender, J., Yesuf, M., Köhlin, G., & Mulugeta, E. (2009). The Role of Soil Conservation on Mean Crop Yield and Variance of Yield-Evidence from the Ethiopian Highlands. *rapport nr.: Working Papers in Economics 408*.

Kfir, R. (1998). Maize and grain sorghum: southern Africa. *African Cereal Stem Borers: Economic Importance, Taxonomy, Natural Enemies and Control, CAB International: Wallingford (UK)*, 29-37.

Kfir, R. (2002). Increase in cereal stem borer populations through partial elimination of natural enemies. *Entomologia Experimentalis et Applicata*, *104*(2-3), 299-306.

Kfir, R. (2005). The impact of parasitoids on Plutella xylostella populations in South Africa and the successful biological control of the pest on the island of St. Helena. In *second international symposium on biological control of arthropods*.

Kfir, R., Overholt, W. A., Khan, Z. R., & Polaszek, A. (2002). Biology and management of economically important lepidopteran cereal stem borers in Africa. *Annual review of entomology*, *47*(1), 701-731.

Kipkoech, A. K., Schulthess, F., Yabann, W. K., Maritim, H. K., & Mithöfer, D. (2006). Biological control of cereal stem borers in Kenya: A cost benefit approach. In *Annales de la Société entomologique de France* (Vol. 42, No. 3-4, pp. 519-528). Taylor & Francis Group.

Mwadalu, R., & Mwangi, M. (2013). The potential role of sorghum in enhancing food security in semi-arid eastern Kenya: A review. *Journal of Applied Biosciences*, *71*(1), 5786-5799.

Kipkoech, A. K., Schulthess, F., Yabann, W. K., Maritim, H. K., Erick, M., & Mithöfer, D. (2009, August). The economic value of releasing parasitoid for the control of maize stemborers in East and Southern Africa. In *Contributed paper prepared for presentation at the International Association of Agricultural Economics Conference, Beijing, China*.

Kluve, J., Schneider, H., Uhlendorff, A., & Zhao, Z. (2012). Evaluating continuous training programmes by using the generalized propensity score. *Journal of the Royal Statistical Society: Series A (Statistics in Society)*, *175*(2), 587-617.

Knight, J., Weir, S., & Woldehanna, T. (2003). The role of education in facilitating risk-taking and innovation in agriculture. *The Journal of Development Studies*, *39*(6), 1-22.

Lazarovits, G., Goettel, M. & Vincent, C. (2007). Adventures in Biocontrol. pp. 1-6 in C. Vincent, M. Goettel & G. Lazarovits (Eds.). Biological Control: a global perspective. Case Histories from around the world. CABI Publishing, Wallingford, U.K., 440 p.

Le Corff, J., Marquis, R. J., & Whitfield, J. B. (2000). Temporal and spatial variation in a parasitoid community associated with the herbivores that feed on Missouri Quercus. *Environmental Entomology*, *29*(2), 181-194.

Le Rü, B. P., Ong'amo, G. O., Moyal, P., Muchugu, E., Ngala, L., Musyoka, B., Abdullah, Z., Matama, T.K., Lada V.Y., Pallangyo, B., Omwega, C.O., Schulthess, F., Calatayud, P.A., & Silvain, J. F. (2006). Geographic distribution and host plant ranges of East African noctuid stemborers. In *Annales de la Société entomologique de France* (Vol. 42, No. 3-4, pp. 353-361). Taylor & Francis Group.

Le Ru, B. P., Ong'amo, G. O., Moyal, P., Ngala, L., Musyoka, B., Abdullah, Z., Cugala, D., Defabachew, B., Haile, T. A., Matama, T.K., Lada V.Y., Negassi, B., Pallangyo, B., Ravolonandrianina, J., Sidumo, A., Omwega, C.O., Schulthess, F., Calatayud, P.A., Silvain, J. F., & Lada, V. Y. (2006). Diversity of lepidopteran stem borers on monocotyledonous plants in eastern Africa and the islands of Madagascar and Zanzibar revisited. *Bulletin of Entomological Research*, *96*(06), 555-563.

Lee, M. J. (2005). *Micro-econometrics for policy, program, and treatment effects*. Oxford: Oxford University Press.

Lichtenberg, E., & Zilberman, D. (1986). The econometrics of damage control: why specification matters. *American Journal of Agricultural Economics*, *68*(2), 261-273.

Linderhof, V. G. M., Powell, J. P., Vignes, R., & Ruben, R. (2016). The influence of household farming systems on dietary diversity and caloric intake: the case of Uganda.

Lv, J., Wilson, L. T., Beuzelin, J. M., White, W. H., Reagan, T. E., & Way, M. O. (2011). Impact of Cotesia flavipes (Hymenoptera: Braconidae) as an augmentative biocontrol agent for the sugarcane borer (Lepidoptera: Crambidae) on rice. *Biological Control*, *56*(2), 159-169.

Lyu, S. L., White, F. C., & Lu, Y. C. (1984). Estimating effects of agricultural research and extension expenditures on productivity: a translog production function approach. *Southern Journal of Agricultural Economics*, *16*(02).

Macharia, I., Löhr, B., & De Groote, H. (2005). Assessing the potential impact of biological control of Plutella xylostella (diamondback moth) in cabbage production in Kenya. *Crop Protection*, *24*(11), 981-989.

Macharia, I., Mithöfer, D., & Waibel, H. (2011). Indirect and External Costs of Pesticide Use in the Vegetable Sub-sector in Kenya. *Vegetable Production and Marketing in Africa: Socio-economic Research*, 227.

Maes K.V.N. (1998) Lepidoptera: Introduction. In Polaszek., A., 1998. (Ed.) African cereal stem borers: economic importance, taxonomy, natural enemies and control. CAB International, Wallingford, Oxon, UK, 530 pp.

Magrini, E., & Vigani, M. (2016). Technology adoption and the multiple dimensions of food security: the case of maize in Tanzania. *Food Security*, *8*(4), 707-726.

Mahr, S.E.R., Cloyd, R.A., Mahr, D.L. and Sadof, C.S., 2001. Biological control of insects and other pests of greenhouse crops. *Univ. of Wisconsin-Extension, Cooperative Extension*.

Mailafiya, D. M., Le Ru, B. P., Kairu, E. W., Dupas, S., & Calatayud, P. A. (2011). Parasitism of lepidopterous stem borers in cultivated and natural habitats. *Journal of Insect Science*, *11*(15), 1-19.

Maredia, M., Byerlee, D., & Anderson, J. R. (2000). Ex post evaluation of economic impacts of agricultural research programs: a tour of good practice. http://impact.cgiar.org/sites/default/files/pdf/99.pdf.

Masters, A.W., Coulibaly, B., Sanogo, D., Sidibé, M., & Williams, A., (1996). The Economic Impact of Agricultural Research: A Practical Guide. Department of Agricultural Economics, Purdue University, West Lafayette.

Matama-Kauma, T., Schulthess, F., Le Rü, B. P., Mueke, J., Ogwang, J. A., & Omwega, C. O. (2008). Abundance and diversity of lepidopteran stemborers and their parasitoids on selected wild grasses in Uganda. *Crop Protection*, *27*(3), 505-513.

Maxwell, D., Vaitla, B., & Coates, J. (2014). How do indicators of household food insecurity measure up? An empirical comparison from Ethiopia. *Food Policy*, *47*, 107-116.

Maxwell, D.G., (1996). Measuring food insecurity: the frequency and severity of “coping strategies”. *Food policy*, *21*(3) 291-303.

McConnachie, A. J., De Wit, M. P., Hill, M. P., & Byrne, M. J. (2003). Economic evaluation of the successful biological control of Azolla filiculoides in South Africa. *Biological control*, *28*(1), 25-32.

McIntosh, C., Sarris, A., & Papadopoulos, F. (2013). Productivity, credit, risk, and the demand for weather index insurance in smallholder agriculture in Ethiopia. *Agricultural Economics*, *44*(4-5), 399-417.

Mensah, E.C., & Wohlgenant, M.K., (2010). A market impact analysis of soybean technology adoption. Res. Business Econ. J. http://www.aabri.com/manuscripts/09228.pdf.

Mi, S., Danforth, D.M., Tugwell, N.P. & Cochran, M.J., 1998. Plant-Based Economic Injury Level for Assessing Economic Thresholds in Early-Season Cotton. *Journal of Cotton Science* 2:35-52 (1998).

Midingoyi, S.G., Affognon, H.D., Macharia, I., Ong’amo, G., Abonyo, E., Ogola, G., De Groote, H. & LeRu, B. (2016). Assessing the long-term welfare effects of the biological control of cereal stemborer pests in East and Southern Africa: Evidence from Kenya, Mozambique and Zambia’, *Agriculture, Ecosystems & Environment*, *230*, 10-23.

Mills, N., (2005). Classical biological control of codling moth: the California experience. In *Second International Symposium on Biological Control of Arthropods* (Vol. 2)

Minkenberg, O. P., & van Lenteren, J. C. (1986). *The leafminers, Liriomyza bryoniae and L. trifolii (Diptera: Agromyzidae), their parasites and host plants: a review* (No. 86-2, p. 50). Agricultural University.

Moolman, J., Van den Berg, J., Conlong, D., Cugala, D., Siebert, S., & Le Ru, B. (2014). Species diversity and distribution of lepidopteran stem borers in South Africa and Mozambique. *Journal of Applied Entomology*, *138*(1-2), 52-66.

Moonga, M.N., (2007). Assessment of infestation levels of *Chilo partellus* Swinhoe (Lepidoptera: Crambidae) on maize and the impact of its parasitoid *Cotesia flavipes* Cameron (Hymenoptera: Braconide) in Sinazongwe District of Zambia. MSc thesis, University of Zambia.

Moore, M. R., Gollehon, N. R., & Hellerstein, D. M. (2000). Estimating producer's surplus with the censored regression model: An application to producers affected by Columbia River Basin salmon recovery. *Journal of Agricultural and Resource Economics*, 325-346.

Morin, L., Reid, A.M., Sims-Chilton, N.M., Buckley, Y.M., Dhileepan, K., Hastwell, G.T., Nordblom, T.L. & Raghu, S., (2009). Review of approaches to evaluate the effectiveness of weed biological control agents. *Biological Control*, *51*(1), 1-15.

Mose, L. O., Burger, K. E. E. S., & Kuvyenhoven, A. R. I. E. (2007). Aggregate supply response to price incentives: The case of smallholder maize production in Kenya. In *African crop science conference proceedings*. 8, 1271–1275.

Myrick, S., Norton, G. W., Selvaraj, K. N., Natarajan, K., & Muniappan, R. (2014). Economic impact of classical biological control of papaya mealybug in India. *Crop Protection*, *56*, 82-86.

Naranjo, S. E., Ellsworth, P. C., & Frisvold, G. B. (2015). Economic value of biological control in integrated pest management of managed plant systems. *Annual review of entomology*, *60*, 621-645.

Neuenschwander, P. W. N. O., Hammond, W. O., Gutierrez, A. P., Cudjoe, A. R., Adjakloe, R., Baumgärtner, J. U., & Regev, U. (1989). Impact assessment of the biological control of the cassava mealybug, Phenacoccus manihoti Matile-Ferrero (Hemiptera: Pseudococcidae), by the introduced parasitoid *Epidinocarsis lopezi* (De Santis) (Hymenoptera: Encyrtidae). *Bulletin of Entomological Research*, *79*(04), 579-594.

Nordblom, T. L., Smyth, M. J., Swirepik, A., Sheppard, A. W., & Briese, D. T. (2002). Spatial economics of biological control: investing in new releases of insects for earlier limitation of Paterson's curse in Australia. *Agricultural Economics*, *27*(3), 403-424.

Norgaard, R. B. (1988). The biological control of cassava mealybug in Africa. *American Journal of Agricultural Economics*, 72: 366–371.

Norton, G. W., & Davis, J. S. (1981). Evaluating returns to agricultural research: a review. *American Journal of Agricultural Economics*, *63*(4), 685-699.

Nsami, E., Pallangyo, B., Mgoo, V., & Omwega, C. O. (2001). Distribution and species composition of cereal stemborers in the eastern zone of Tanzania. *International Journal of Tropical Insect Science*, *21*(04), 347-351.

Nwanze, K.F. (2000). IPM for sustainable food crops production in Africa. Bulletin of the African Association of Insect Scientists, Bahaha, J.W. (ed.). *Africa Science Bulletin* 3: 15.

Nwilene, F. E., Nwanze, K. F., & Youdeowei, A. (2008). Impact of integrated pest management on food and horticultural crops in Africa. *Entomologia experimentalis et applicata*, *128*(3), 355-363.

Nzuma, J. M., & Sarker, R. (2010). An error corrected almost ideal demand system for major cereals in Kenya. *Agricultural economics*, *41*(1), 43-50.

Odendo, M., Ouma, J., Wachira, S., & Wanyama, J. (2003). Economic assessmentof maize yield loss due to stem borer in major maize agro-ecological zones of Kenya. In *African Crop Science Conference Proceedings* (Vol. 6, pp. 683-687)..

OECD, (2001). *Measuring Productivity: Measurement of Aggregate and Industry-level Productivity Growth: OECD Manual*. Organisation for Economic Co-operation and Development.

Olwande, J., Ngigi, M., & Nguyo, W. (2009). Supply Responsiveness of Maize Farmers in Kenya: A Farm-Level Analysis. In *presentation at the international association of agricultural economists' conference, Beijing, China, (16-22 August)*. Contributed Paper prepared for presentation at the International Association of Agricultural Economists' 2009 Conference, Beijing, China, August 16-22, 2009.

Omwega, C. O., Kimani, S. W., Overholt, W. A., & Ogol, C. K. P. O. (1995). Evidence of the establishment of Cotesia flavipes (Hymenoptera: Braconidae) in continental Africa. *Bulletin of Entomological Research*, *85*(04), 525-530.

Omwega, C. O., Muchugu, E., Overholt, W. A., & Schulthess, F. (2006). Release and establishment of *Cotesia flavipes* Cameron (Hymenoptera: Braconidae) an exotic parasitoid of *Chilo partellus* (Swinhoe) (Lepidoptera: Crambidae) in East and southern Africa. In *Annales de la Société entomologique de France* (Vol. 42, No. 3-4, pp. 511-517). Taylor & Francis Group.

Omwega, S. W., CO, O., & WA, M. (1997). Establishment and dispersal of Cotesia flavipes (Cameron)(Hymenoptera: Braconidae), an exotic endoparasitoid of Chilo partellus (Swinhoe)(Lepidoptera: Pyralidae) in northern Tanzania. *African Entomology*, *5*(1), 71-75.

Ong'amo, G. O., Le Rü, B. P., Dupas, S., Moyal, P., Calatayud, P. A., & Silvain, J. F. (2006). Distribution, pest status and agro-climatic preferences of lepidopteran stem borers of maize in Kenya. In *Annales de la Société Entomologique de France* (Vol. 42, No. 2, pp. 171-177). Taylor & Francis Group.

Onono, P. A., Wawire, N. W., & Ombuki, C. (2013). The response of maize production in Kenya to economic incentives. *International Journal of Development and Sustainability*, *2*(2), 530-543. Ooi, P. A. C. (1996). Experiences in educating rice farmers to understand biological control. *Entomophaga*, *41*(3-4), 375-385.

Ooi, P. A. C. (1996). Experiences in educating rice farmers to understand biological control. *Entomophaga*, *41*(3-4), 375-385.

Ooi, P. A. C., & Kenmore, P. E. (2005). Impact of educating farmers about biological control in farmer field schools. In *Second International Symposium on Biological Control of Arthropods, Davos, Switzerland, 12-16 September, 2005* (pp. 277-289). United States Department of Agriculture, Forest Service.

Östman, Ö., Ekbom, B., & Bengtsson, J. (2003). Yield increase attributable to aphid predation by ground-living polyphagous natural enemies in spring barley in Sweden. *Ecological Economics*, *45*(1), 149-158.

Overholt, W. A., Maes, K. V. N., & Goebel, F. R. (2001). *Field guide to the stemborer larvae of maize, sorghum and sugarcane in Eastern and Southern Africa*. ICIPE Science Press, Nairobi, Kenya.

Overholt, W. A., Ngi-Song, A. J., Omwega, C. O., Kimani-Njogu, S. W., Mbapila, J., Sallam, M. N., & Ofomata, V. (1997). A review of the introduction and establishment of Cotesia flavipes Cameron in East Africa for biological control of cereal stemborers. *International Journal of Tropical Insect Science*, *17*(01), 79-88.

Overholt, W. A., Ochieng, J. O., Lammers, P., & Ogedah, K. (1994). Rearing and field release methods for Cotesia flavipes Cameron (Hymenoptera: Braconidae), a parasitoid of tropical gramineous stem borers. *International Journal of Tropical Insect Science*, *15*(03), 253-259.

Palisade Corporation, (2014). @RISK software version 6 NewYork, Palisade Corporation

Papke, L. E., & Wooldridge, J. M. (2008). Panel data methods for fractional response variables with an application to test pass rates. *Journal of Econometrics*, *145*(1), 121-133.

Parish, R. M., & Dillon, J. L. (1955). Recent applications of the production function in farm management research. *Review of Marketing and Agricultural Economics*, *23*(04), 215-236.

Pedigo, L.P., Hutchins, S.H. and Higley, L.G. (1986). Economic injury levels in theory and practice. *Annual review of entomology*, *31*(1), pp.341-368.

Pemsl, D. (2005). Economics of agricultural biotechnology in crop protection in developing countries: The case of Bt-cotton in Shandong Province, China. PhD thesis, University of Hanover, Hanover, Germany.

Polaszek, A., (1998). (Ed.) African Cereal Stem Borers: Economic Importance, Taxonomy, Natural Enemies and Control. CAB International, Wallingford, Oxon, UK, 530 pp.

Praneetvatakul, S., Kuwattanasiri, D. & Waibel, H., (2002). The Productivity of Pesticide use in rice production of Thailand: A damage control approach. In *Paper for the International Symposium on "Sustaining Food Security and Managing Natural Resources in Southeast Asia: Challenges for the 21st Century* (p. 14).

Pretty, J., & Bharucha, Z. P. (2015). Integrated pest management for sustainable intensification of agriculture in Asia and Africa. *Insects*, *6*(1), 152-182.

Rasmussen, S. (2012). *Production economics: the basic theory of production optimisation*. Springer Science & Business Media.

Riley, D.G., (2008). Economic injury level (EIL) and economic threshold (ET) concepts in pest management. In *Encyclopedia of Entomology* (pp. 1282-1286). Springer Netherlands.

Roth, S., & Hyde, J. (2002). Partial budgeting for agricultural businesses. *University Park, PA: Penn State University. CAT UA366*, *7*.

Ruegg, R., & Jordan, G. B. (2011). *Guide for conducting benefit-cost evaluation of realized impacts of public R&D programs*. TIA Consulting, Inc., Emerald Isle, NC (United States); Sandia National Lab.(SNL-NM), Albuquerque, NM (United States).

Sallam, M. N., Overholt, W. A., & Kairu, E. (2001). Dispersal of the exotic parasitoid Cotesia flavipes in a new ecosystem. *Entomologia Experimentalis et Applicata*, *98*(2), 211-217.

Schulthess, F., Chabi-Olaye, A., & Goergen, G. (2001). Seasonal fluctuations of noctuid stemborer egg parasitism in southern Benin with special reference to *Sesamia calamistis* Hampson (Lepidoptera: Noctuidae) and Telenomus spp. (Hymenoptera: Scelionidae) on maize. *Biocontrol Science and Technology*, *11*(6), 745-757.

Scoones, I. (1998). Sustainable rural livelihoods: a framework for analysis.

Seshu Reddy K.V. (1998). Maize and Sorghum in East Africa. In Polaszek., A., 1998. (Ed.) African cereal stem borers: economic importance, taxonomy, natural enemies and control. CAB International, Wallingford, Oxon, UK, 530 pp.

Shiferaw, B., Kassie, M., Jaleta, M., & Yirga, C. (2014). Adoption of improved wheat varieties and impacts on household food security in Ethiopia. *Food Policy*, *44*, 272-284.

Sibhatu, K. T., Krishna, V. V., & Qaim, M. (2015). Production diversity and dietary diversity in smallholder farm households. *Proceedings of the National Academy of Sciences*, *112*(34), 10657-10662.

Simmonds, F. J. (1967). The economics of biological control. *Journal of the Royal Society of Arts*, *115*(5135), 880-898.

Skevas, T., Swinton, S. M., Meehan, T. D., Kim, T. N., Gratton, C., & Egbendewe-Mondzozo, A. (2014). Integrating agricultural pest biocontrol into forecasts of energy biomass production. *Ecological Economics*, *106*, 195-203.

Sohati, P. H., Musonda, E. M., & Mukanga, M. (2001). Distribution of cereal stemborers in Zambia and release of *Cotesia flavipes* Cameron, an exotic natural enemy of Chilo partellus (Swinhoe). *International Journal of Tropical Insect Science*, *21*(04), 311-316.

Soliman, T., Mourits, M. C. M., Lansink, A. O., & Van der Werf, W. (2010). Economic impact assessment in pest risk analysis. *Crop Protection*, *29*(6), 517-524.

Songa, J. M., Guofa, Z., & Overholt, W. A. (2001). Relationships of stemborer damage and plant physical conditions to maize yield in a semi-arid zone of eastern Kenya. *International Journal of Tropical Insect Science*, *21*(03), 243-249.

Stern, V. M. R. F., Smith, R., Van den Bosch, R., & Hagen, K. (1959). The integration of chemical and biological control of the spotted alfalfa aphid: the integrated control concept. *California Agriculture*, *29*(2), 81-101.

Swindale, A., & Bilinsky, P. (2005). Household dietary diversity score (HDDS) for measurement of household food access: indicator guide. *Washington, DC: Food and Nutrition Technical Assistance Project, Academy for Educational Development*.

Takagi, M., Okumura, M., Shoubu, M., Shiraishi, A. & Ueno, T. (2005). Classical biological control of the alfalfa weevil in Japan. In *Second International Symposium On Biological Control Of Arthropods*.

Thirtle, C., Lin, L., & Piesse, J. (2003). The impact of research-led agricultural productivity growth on poverty reduction in Africa, Asia and Latin America. *World Development*, *31*(12), 1959-1975.

Tisdell, C. A. (1990). Economic impact of biological control of weeds and insects. *Critical issues in biological control.*, 301-316.

Tisdell, C.A., Mackauer, M., Ehler, L.E. & Roland, J., (1990). Economic impact of biological control of weeds and insects. *Critical issues in biological control.*, pp.301-316.

Trumble, J. T. (1998). IPM: overcoming conflicts in adoption. *Integrated Pest Management Reviews*, *3*(4), 195-207.

Trumble, J. T., & Morse, J. P. (1993). Economics of integrating the predaceous mite Phytoseiulus persimilis (Acari: Phytoseiidae) with pesticides in strawberries. *Journal of economic entomology*, *86*(3), 879-885.

Turner, C. E. (1985). Conflicting interests and biological control of weeds. Proc. 6th Internatl. Symp. Biol. Control of Weeds, Vancouver, Canada 1984. p. 203-25.

van den Berg, J., & Nur, A.F. (1998). Chemical Control. In Polaszek., A., 1998. (Ed.) African Cereal Stemborers: Economic Importance, Taxonomy, Natural Enemies and Control. CAB International, Wallingford, Oxon, pp. 319–332.

van den Berg, J., Nur, A.F., & Polaszek, A., (1998). Cultural control, in: Polaszek, A., (Ed.) African Cereal Stemborers: Economic Importance, Taxonomy, Natural Enemies and Control. CAB International, Wallingford, Oxon, pp. 333–347.

Van Ittersum, M. K., & Rabbinge, R. (1997). Concepts in production ecology for analysis and quantification of agricultural input-output combinations. *Field crops research*, *52*(3), 197-208.

Van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., & Hochman, Z. (2013). Yield gap analysis with local to global relevance—a review. *Field Crops Research*, *143*, 4-17.

Van Lenteren, J.C., (2008). IOBC Internet book of biological control. *International Organization for Biological Control, Wageningen, The Netherlands*.

Van Wilgen, B. W., & Lange, W. D. (2011). The costs and benefits of biological control of invasive alien plants in South Africa. *African Entomology*, *19*(2), 504-514.

Varela, A. M., Seif, A., & Lohr, B. (2003). *A Guide to IPM in Brassicas Production in Eastern and Southern Africa* (No. 2003: 15). The International Centre of Insect Physiology and Ecology (ICIPE). ICIPE Science Press.

Villanueva-Jiménez, J. A., Hoy, M. A., & Davies, F. S. (2000). Field evaluation of integrated pest management-compatible pesticides for the citrus leafminer Phyllocnistis citrella (Lepidoptera: Gracillariidae) and its parasitoid *Ageniaspis citricola* (Hymenoptera: Encyrtidae). *Journal of economic entomology*, *93*(2), 357-367.

Wambugu, P. W., Mathenge, P. W., Auma, E. O., & Van Rheenen, H. A. (2009). Constraints to on-farm maize (Zea mays) seed production in Western Kenya: seed vigor and viability. *Journal of New Seeds*, *10*(3), 149-159.

Waterhouse, D., Dillon, B., & Vincent, D. (1998). Economic benefits to Papua New Guinea and Australia from the biological control of banana skipper (Erionota thrax). *Canberra: ACIAR Impact Assessment Series*, (12), 36.

Wooldridge, J.M., (2015). *Introductory econometrics: A modern approach*. Fourth Edition, Nelson Education. 865 pp.

Wisniewski, M., Wilson, C., Droby, S., Chalutz, E., El Ghaouth, A., & Stevens, C. (2007). Postharvest biocontrol: new concepts and applications. *Biological control: A global perspective. United Kingdom, CABI International*, 262-273.

Yaninek, J. S., Gutierrez, A. P., & Herren, H. R. (1992). Effects of cassava green mite on drymatter production and allocation in cassava. *IITA Research*, *4*, 1-5.

Zeddies, J., Schaab, R. P., Neuenschwander, P., & Herren, H. R. (2001). Economics of biological control of cassava mealybug in Africa. *Agricultural Economics*, *24*(2), 209-219.

Zhang, W., & Swinton, S. M. (2012). Optimal control of soybean aphid in the presence of natural enemies and the implied value of their ecosystem services. *Journal of environmental management*, *96*(1), 7-16.

Zhao, X., Griffiths, W. E., Griffith, G. R., & Mullen, J. D. (2000). Probability distributions for economic surplus changes: the case of technical change in the Australian wool industry. *Australian Journal of Agricultural and Resource Economics*, *44*(1), 83-106.

Zhao, X., Mullen, J. D., & Griffith, G. R. (1997). Functional forms, exogenous shifts, and economic surplus changes. *American Journal of Agricultural Economics*, *79*(4), 1243-1251.

Zhengfei, G., Lansink, A. O., Wossink, A., & Huirne, R. (2005). Damage control inputs: a comparison of conventional and organic farming systems. *European Review of Agricultural Economics*, *32*(2), 167-189.

Zhou, G., Baumgärtner, J., & Overholt, W. A. (2001). Impact assessment of an exotic parasitoid on stemborer (Lepidoptera) population dynamics in Kenya. *Ecological Applications*, *11*(5), 1554-1562.

# APPENDICES

**Appendix A** : Test of endogeneity of insecticide use: Instrumental variables (2SLS) regression

| lnyieldha | Coef. | Std.Err | z | P>z | [95% Conf. Interval] | |
|---|---|---|---|---|---|---|
| lnqinsecticimha1 | -0.1691 | 0.0492 | -3.4400 | 0.0010 | -0.2656 | -0.0727 |
| lnlabormha1 | 0.0757 | 0.2635 | 0.2900 | 0.7740 | -0.4406 | 0.5921 |
| lnqseedmha1 | -0.1849 | 0.3413 | -0.5400 | 0.5880 | -0.8538 | 0.4841 |
| lnqminfertmha1 | 0.1831 | 0.1376 | 1.3300 | 0.1830 | -0.0867 | 0.4528 |
| lnmaterialcostha | 0.0039 | 0.1095 | 0.0400 | 0.9710 | -0.2107 | 0.2185 |
| training | -0.0775 | 0.0902 | -0.8600 | 0.3900 | -0.2543 | 0.0993 |
| extension | 0.2744 | 0.0942 | 2.9100 | 0.0040 | 0.0899 | 0.4590 |
| parasitism2 | 0.0082 | 0.0025 | 3.3500 | 0.0010 | 0.0034 | 0.0130 |
| varietyhybrid | 0.1129 | 0.0861 | 1.3100 | 0.1900 | -0.0558 | 0.2817 |
| Agroecology6 | 0.0253 | 0.2448 | 0.1000 | 0.9180 | -0.4545 | 0.5051 |
| Agroecology5 | 0.0390 | 0.2145 | 0.1800 | 0.8560 | -0.3815 | 0.4595 |
| Agroecology2 | -0.7487 | 0.1587 | -4.7200 | 0.0000 | -1.0598 | -0.4376 |
| Agroecology3 | -0.7274 | 0.2077 | -3.5000 | 0.0000 | -1.1344 | -0.3204 |
| Agroecology4 | -0.3297 | 0.2233 | -1.4800 | 0.1400 | -0.7674 | 0.1079 |
| pestpresurm3 | -0.2065 | 0.0838 | -2.4600 | 0.0140 | -0.3708 | -0.0422 |
| lnlab2 | -0.0103 | 0.0229 | -0.4500 | 0.6530 | -0.0553 | 0.0347 |
| lnseedmha2 | 0.1651 | 0.0514 | 3.2100 | 0.0010 | 0.0644 | 0.2658 |
| lnminf2 | 0.0011 | 0.0168 | 0.0700 | 0.9480 | -0.0318 | 0.0340 |
| lnmat2 | 0.0045 | 0.0064 | 0.7100 | 0.4810 | -0.0080 | 0.0171 |
| lnlabxlnseed | -0.0211 | 0.0547 | -0.3900 | 0.7000 | -0.1284 | 0.0862 |
| lnlabxlnminf | -0.0155 | 0.0187 | -0.8300 | 0.4080 | -0.0522 | 0.0212 |
| lnlabxlnmate | 0.0088 | 0.0231 | 0.3800 | 0.7050 | -0.0366 | 0.0541 |
| lnseedxlnminf | -0.0198 | 0.0254 | -0.7800 | 0.4350 | -0.0695 | 0.0299 |
| lnseedxlnmate | -0.0370 | 0.0261 | -1.4200 | 0.1560 | -0.0882 | 0.0142 |
| lnminfxlnmate | 0.0108 | 0.0095 | 1.1400 | 0.2530 | -0.0077 | 0.0294 |
| _cons | 5.7830 | 0.8888 | 6.5100 | 0.0000 | 4.0410 | 7.5250 |
| Number of obs | 586 | | | | | |
| Wald chi2(25) | 479.240 | | | | | |
| Prob > chi2 | 0.000 | | | | | |
| R-squared | 0.407 | | | | | |
| Root MSE | 0.801 | | | | | |
| Instrumented: | lnqinsecticimha1 | | | | | |
| Instruments: | lnlabormha1 lnqseedmha1 lnqminfertmha1 lnmaterialcostha training extension parasitism2 varietyhybrid Agroecology6 Agroecology5 Agroecology2 Agroecology3 Agroecology4 pestpresurm3 lnlab2 lnseedmha2 lnminf2 lnmat2 lnlabxlnseed lnlabxlnminf lnlabxlnmate lnseedxlnminf lnseedxlnmate lnminfxlnmate pestpresurm1 fertilem1 timem croproductionma associationyes expmaiz nyearsch agehh priceins00 | | | | | |

**Tests of endogeneity**
Ho: variables are exogenous
Durbin (score) chi2(1) = 18.181 (p = 0.0000)
Wu-Hausman F(1,559) = 17.8986 (p = 0.0000)

**Tests of overidentifying restrictions:**
Sargan (score) chi2(8) = 13.8886 (p = 0.0847)
Basmann chi2(8) = 13.4004 (p = 0.0988)

**Appendix B** : Wald test for choice between translog and Cobb-Douglas specifications

| **lnyieldha** | **Coef,** | | **Std, Err,** | **Coef,** | | **Std, Err,** |
|---|---|---|---|---|---|---|
| _cons | 5.4350 | *** | 0.2321 | 5.7362 | *** | 0.8907 |
| lnlabormha1 | -0.0364 | | 0.0419 | 0.0215 | | 0.2616 |
| lnqseedmha1 | 0.3482 | *** | 0.0520 | -0.2037 | | 0.3349 |
| lnqminfertmha1 | 0.1065 | *** | 0.0210 | 0.1371 | | 0.1320 |
| lnmaterialcostha | -0.0082 | | 0.0173 | -0.0304 | | 0.1072 |
| lnqinsecticimha1 | 0.0035 | | 0.0207 | 0.1292 | | 0.1486 |
| training | -0.0265 | | 0.0863 | -0.0306 | | 0.0859 |
| extension | 0.1800 | ** | 0.0894 | 0.2178 | ** | 0.0892 |
| parasitism2 | 0.0119 | *** | 0.0021 | 0.0113 | *** | 0.0022 |
| varietyhybrid | 0.0732 | | 0.0822 | 0.0847 | | 0.0821 |
| Agroecology6 | 0.7690 | *** | 0.1818 | 0.5820 | *** | 0.1868 |
| Agroecology5 | 0.6422 | *** | 0.1464 | 0.5766 | *** | 0.1474 |
| Agroecology2 | -0.3032 | *** | 0.1082 | -0.3354 | *** | 0.1107 |
| Agroecology3 | -0.1189 | | 0.1388 | -0.2290 | | 0.1447 |
| Agroecology4 | 0.2195 | | 0.1683 | 0.1836 | | 0.1690 |
| pestpresurm3 | -0.2045 | ** | 0.0808 | -0.1645 | ** | 0.0808 |
| lnlab2 | | | | 0.0097 | | 0.0221 |
| lnseedmha2 | | | | 0.1439 | *** | 0.0494 |
| lnminf2 | | | | 0.0067 | | 0.0161 |
| lnmat2 | | | | 0.0097 | | 0.0061 |
| lninsec2 | | | | 0.0575 | *** | 0.0180 |
| lnlabxlnseed | | | | -0.0404 | | 0.0524 |
| lnlabxlnminf | | | | -0.0282 | | 0.0179 |
| lnlabxlnmate | | | | 0.0004 | | 0.0227 |
| lnlabxlnqinsec | | | | -0.0178 | | 0.0250 |
| lnseedxlnminf | | | | -0.0061 | | 0.0248 |
| lnseedxlnmate | | | | -0.0231 | | 0.0253 |
| lnseedxlnqinsec | | | | -0.0079 | | 0.0292 |
| lnminfxlnmate | | | | 0.0126 | | 0.0092 |
| lnminfxlnqinsec | | | | -0.0027 | | 0.0085 |
| lnmatxlnqinsec | | | | 0.0102 | | 0.0094 |
| Number of obs | 589 | | | 589 | | |

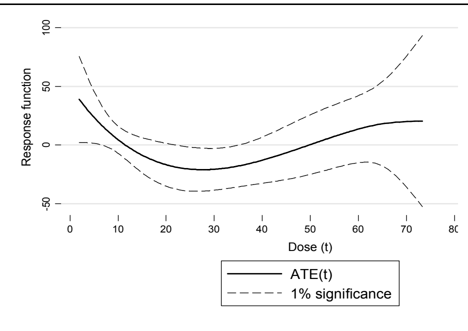
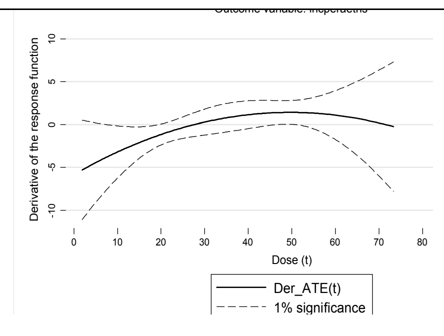
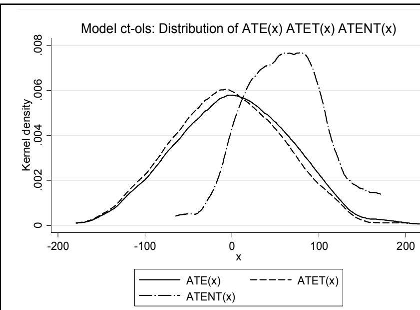
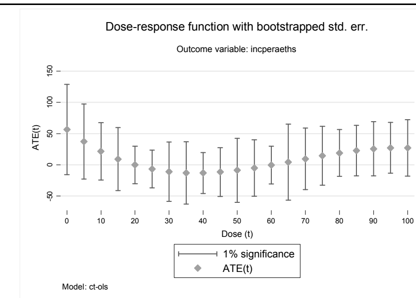
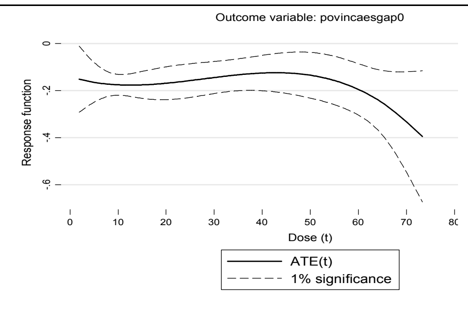
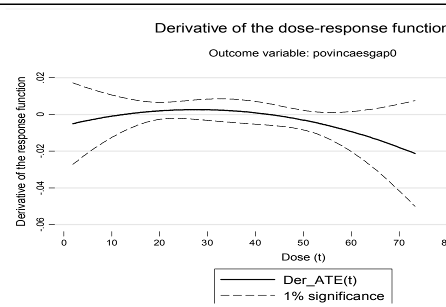
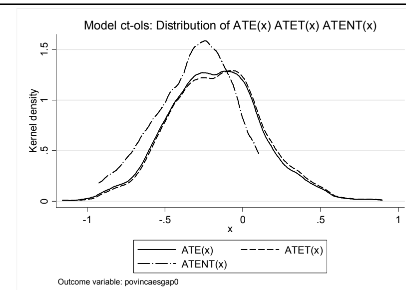
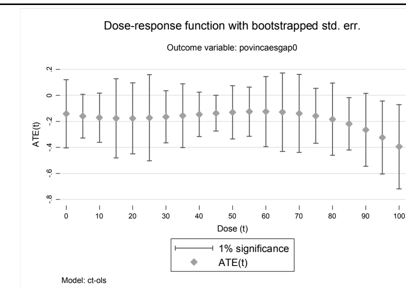
| | | | | |
|---|---|---|---|---|
| F( 15, 573) | 31.88 | *** | 17.6 | *** |
| R-squared | 0.4549 | | 0.4861 | |
| Adj R-squared | 0.4406 | | 0.4585 | |

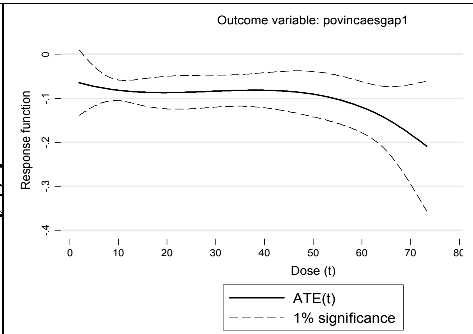
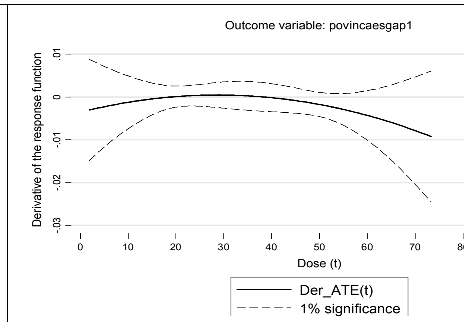
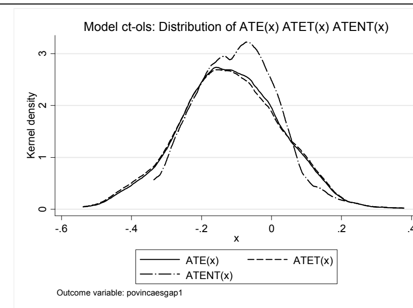
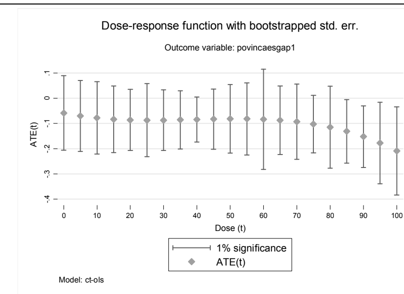
test lnlab2 lnseedmha2 lnminf2 lnmat2 lninsec2 lnlabxlnseed lnlabxlnminf lnlabxlnmate lnlabxln
> qinsec lnseedxlnminf lnseedxlnmate lnseedxlnqinsec lnminfxlnmate lnminfxlnqinsec
lnmatxlnqinse
> c

( 1) lnlab2 = 0
( 2) lnseedmha2 = 0
( 3) lnminf2 = 0
( 4) lnmat2 = 0
( 5) lninsec2 = 0
( 6) lnlabxlnseed = 0
( 7) lnlabxlnminf = 0
( 8) lnlabxlnmate = 0
( 9) lnlabxlnqinsec = 0
(10) lnseedxlnminf = 0
(11) lnseedxlnmate = 0
(12) lnseedxlnqinsec = 0
(13) lnminfxlnmate = 0
(14) lnminfxlnqinsec = 0
(15) lnmatxlnqinsec = 0

F( 15, 523) = 2.26
Prob > F = 0.0042

**Appendix C** : Dose-response function and Marginal Treatment Effect of household income, poverty headcount and poverty gap

<table>
<tr><td></td><td colspan="4">Income-base</td></tr>
<tr><td>Income per year</td>
<td>
</td>
<td>
</td>
<td>
</td>
<td>
</td></tr>
<tr><td></td><td>Dose-response function</td><td>Derivative of DRF</td><td>Distribution of the ATE(x)s,</td><td>DRF with bootstrapping std. error</td></tr>
<tr><td>Headcount index</td>
<td>
</td>
<td>
</td>
<td>
</td>
<td>
</td></tr>
<tr><td></td><td>Dose-response function</td><td>Derivative of DRF</td><td>Distribution of the ATE(x)s,</td><td>DRF with bootstrapping std. error</td></tr>
</table>

| | | | | |
|---|---|---|---|---|
| **Poverty gap index** |  |  |  |  |
| | Dose-response function | Derivative of DRF | Distribution of the ATE(x)s, | DRF with bootstrapping std. error |

Note: Solid line shows the marginal treatment effect; dashed lines are 90 % confidence upper and lower bound intervals

**Appendix D** : *icipe* biological control programme in Kenya: Impact on poverty reduction

| Years | Kenya | | | | | |
|---|---|---|---|---|---|---|
| | Maize | | Sorghum | | Total | |
| | (x1000) | % | (x1000) | % | (x1000) | % |
| 1993 | 0.0 | 0.00 | 0.0 | 0.00 | 0.0 | 0.00 |
| 1994 | 0.0 | 0.00 | 0.0 | 0.00 | 0.0 | 0.00 |
| 1995 | 0.0 | 0.00 | 0.0 | 0.00 | 0.0 | 0.00 |
| 1996 | 0.3 | 0.01 | 0.0 | 0.00 | 0.3 | 0.01 |
| 1997 | 1.9 | 0.03 | 0.1 | 0.00 | 2.0 | 0.04 |
| 1998 | 13.2 | 0.10 | 2.6 | 0.02 | 15.8 | 0.12 |
| 1999 | 19.8 | 0.15 | 3.4 | 0.03 | 23.1 | 0.17 |
| 2000 | 22.3 | 0.16 | 4.6 | 0.03 | 26.9 | 0.20 |
| 2001 | 28.2 | 0.20 | 5.2 | 0.04 | 33.4 | 0.24 |
| 2002 | 42.0 | 0.29 | 13.4 | 0.09 | 55.4 | 0.39 |
| 2003 | 48.9 | 0.33 | 17.0 | 0.12 | 65.8 | 0.45 |
| 2004 | 72.3 | 0.48 | 23.4 | 0.15 | 95.6 | 0.63 |
| 2005 | 84.6 | 0.55 | 14.9 | 0.10 | 99.5 | 0.64 |
| 2006 | 74.2 | 0.47 | 38.8 | 0.24 | 113.0 | 0.71 |
| 2007 | 78.8 | 0.48 | 23.5 | 0.14 | 102.4 | 0.63 |
| 2008 | 104.4 | 0.62 | 40.2 | 0.24 | 144.6 | 0.86 |
| 2009 | 65.8 | 0.38 | 19.4 | 0.11 | 85.2 | 0.49 |
| 2010 | 48.2 | 0.27 | 16.1 | 0.09 | 64.3 | 0.36 |
| 2011 | 63.6 | 0.35 | 18.9 | 0.10 | 82.5 | 0.45 |
| 2012 | 71.3 | 0.38 | 17.0 | 0.09 | 88.3 | 0.47 |
| 2013 | 84.0 | 0.44 | 23.2 | 0.12 | 107.3 | 0.56 |
| **Aver an** | **44.0** | **0.27** | **13.4** | **0.08** | **57.4** | **0.35** |

**Appendix E** : Published paper in peer-reviewed journal and manuscripts awaiting for submission

Midingoyi, S.G., Affognon, H.D., Macharia, I., Ong'amo, G., Abonyo, E., Ogola, G., De Groote, H. & LeRu, B. (2016). Assessing the long-term welfare effects of the biological control of cereal stemborer pests in East and Southern Africa: Evidence from Kenya, Mozambique and Zambia', *Agriculture, Ecosystems & Environment*, *230*, 10-23.

Estimating the impact of biological control of maize stemborers on productivity and poverty in Kenya: A Continuous Treatment Approach (Submitted to Journal of Rural Studies).

Productivity-effect of the Biological Control of Maize Stemborer Pests in Kenya: A Damage Control Function Approach (under revision for submission)

The impact of Biological Control of Maize Stemborer on Food Security in Kenya: Evidence from the Continuous Treatment Approach (under revision for submission)

**Appendix F** : List of conference papers and posters

Midingoyi, G.S, Affognon, H., Muriithi, B., Macharia, I., Ongamo, G. and LeRu, B. (2017). Assessment of the Economic and Poverty Impacts of Biological Control of Cereal Stemborers in Kenya using the Economic Surplus Modelling Approach. Contribution selected for oral presentation at the **5th International Symposium on Biological Control of Arthropods**, September 11-15, 2017., At Langkawi, Malaysia

Midingoyi G.S., Kassie, M., Affognon, H.D., Macharia, I., and LeRu, B. (2017). Estimating the impact of biological control of maize stemborers on productivity and poverty in Kenya: A Continuous Treatment Approach. Contribution selected for oral presentation at the **Global Food Symposium** 2017, to be held on 28-29 of April at Goettingen, Germany and as poster presentation at **Agricultural Economics Society**'s 91st annual conference to be held on 24-26 of April 2017 in Dublin, Ireland.

Midingoyi, G.S, Affognon, H., Ongamo, G. and LeRu, B. (2015) Economic Welfare Change Attributable to Biological Control of Lepidopteran Cereal Stemborer Pests in East and Southern Africa: Cases of Maize and Sorghum in Kenya, Mozambique and Zambia. Selected contribution for Oral presentation at the 29th Triennial **International Conference of Agricultural Economists (ICAE)**, August 8-14, 2015, Milan, Italy. http://ageconsearch.umn.edu/handle/212461

Midingoyi G.S, Affognon H, Macharia I., Ongamo G and LeRu B. Estimating the productivity-effect of biological control among maize farming households in the Coastal region of Kenya, Selected contribution for oral presentation at the 21st Conference of the **African Association of Insect Scientists** (AAIS), October 19-23, 2015; Cotonou, Benin

Affognon H, Midingoyi G.S, Macharia, I., Ongamo G and LeRu B. Welfare change attributable to the Biological control of maize and sorghum stem borers in East and Southern Africa, Selected contribution for oral presentation at the 21st Conference of the **African Association of Insect Scientists** (AAIS), October 19-23, 2015; Cotonou, Benin

**Appendix G** : Interview schedule for households' survey

| | |
|---|---|
| icipe African Insect Science for Food and Health | **International Centre for Insect Physiology and Ecology (ICIPE)** <br> ---------------------------- <br> **Impact Assessment of Biological Control of Stem-Borers (BCSB)** |

**ECONOMICS OF BIOLOGICAL CONTROL OF MAIZE AND SORGHUM STEM-BORERS IN EAST AND SOUTHERN AFRICA**

**Questionnaire: to be administered to the household head**

*(The household head is the person (man or woman) in charge of decision-making on production/consumption and resources management in the household. In case that the household head is not available, the most knowledgeable person about the household would be appropriate.)*

**Questionnaire N°|___|___|___|___|**

*Good morning. My name is _______________and we are conducting a survey on biological control (BC) of stemborers, agricultural production and living conditions in rural area in Kenya. The purpose is to evaluate the extent to which Icipe' BC project works in improving your activities and life conditions in order to suggest a plan for future in protecting maize and sorghum against stemborers in Kenya. I would like to give you assurance that the information you and other people give us will be kept confidential.*

## General information

| **Place** | **Enumerator** |
|---|---|
| Region:_________________________ \|___\|___\| <br> County:_________________________\|___\|___\| <br> District/Sub-county:________________\|___\|___\| <br> Division/Ward: _______________________\|___\|___\| <br> Location: _______________________\|___\|___\| <br> Sub-location: ____________________\|___\|___\| <br> Village: ________________________\|___\|___\| | Name:_____________________\|___\|___\| <br> Phone number: \|__\|__\|__\|__\|__\|__\|__\|__\|__\|__\|__\|__\| <br> Interview date: \|___\|___\| \|___\|___\| \|___\|___\| (dd\|mm\|year) <br> Interview starting-time: \|___\|___\| h \|___\|___\| min <br> End-time : \|___\|___\| h \|___\|___\| min |
| **Household Head (HH)** | **Supervisor** |
| Name: _____________________________ <br> Phone number: \|__\|__\|__\|__\|__\|__\|__\|__\|__\|__\|__\| <br> GPS Coordinates: <br> Latitude: ( ) \|__\|__\|__\| Deg.\|__\|__\|__\|. \|__\|__\|__\|Min. <br> Longitude: (E) \|__\|__\|__\| Deg.\|__\|__\|__\|. \|__\|__\|__\|Min. <br> Altitude (m.a.s.l) \|__\|__\|__\|__\| M | Name:__________________________\|___\|___\| <br> Supervision date: \|___\|___\| \|___\|___\| \|___\|___\| (dd\|mm\|year) <br> **Supervisor's comments:** |
| **Main interviewee (if different from the HH):** <br> Name: ______________________________ <br> Phone number: : \|__\|__\|__\|__\|__\|__\|__\|__\|__\|__\|__\| | |

## Section 1: Household's Characteristics

| | |
|---|---|
| 1.1 Age of the household head (years) \|__\|__\| | 1.4 Number of years of residence in the village \|__\|__\| |
| 1.2 Gender of the household head \|__\| <br> (*1=male, 0=female*) | 1.5 Can the household head read and write \|__\| <br> (*1=Yes, 0=No*) |
| 1.3 Religion of the household head \|__\| <br> *(0=none, 1=Muslim, 2=Christian, 3=Other: specify……….* | 1.6 Number of years spent in school \|__\|__\| |

1.7 Experience in agriculture (years) |__|__|

1.8 Have you received any training? |__|
(*1=Yes, 0=No*)

1.9 Types of training received |__| |__| |__|
*(1=Training on pest control, 2=Training on soil fertility 3= Training on animal protection 4=purchase of seed, 5=sales of agricultural crops, 6=technical training, 7=credit, 8=Provides equipment (agricultural equipment), 9=sales of agricultural input, 10=gift of agricultural input, 11=other (specify…………………..))*

1.10 Contact with extension services? |__|
(*1=Yes, 0=No*)

1.11 Distance from the household to the nearest extension office (Km) |__||__|

1.12 Contact with research agents? |__|
(*1=Yes, 0=No*)

1.13 Contact with any other institution/program/project in agriculture |__|
(*1=Yes, 0=No*)

1.14 Is the household head member of a farmer's association? (1=Yes, 2=No longer (has broken links); 3=Never) |__|

1.15 If no longer, give reason(s) for breaking links:
………………………………………………..
………………………………………………..

1.16 If never, give reason(s) for not belonging
………………………………………………..
………………………………………………..

1.17 Types of help received from the group |__| |__| |__|

(1= *Group sale of crops, 2=Mutual labor aid, 3=training, 4=credit, 5= Equipment, 6= group purchase of fertilizer, 7=other (specify…………………………….)*

1.18 Distance from the household to the nearest market (Km) |__||__|

1.19 Distance from the household to the nearest tarmac road (Km) |__||__|

1.20 Ethnic group: …………………………

1.21 Household's demography: list all the household members and provide the information listed bellow (begin by the household head)

| ID | Name | Sex (code1) | Age | Matrimonial status (code2) | Family relationship with the head of the household (code 3) | Contribute to the household income (percentage) | Education level (code4) | Main activity (code5) | Secondary activity (code5) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | |
| 2 | | | | | | | | | |
| 3 | | | | | | | | | |
| 4 | | | | | | | | | |
| 5 | | | | | | | | | |
| 6 | | | | | | | | | |
| 7 | | | | | | | | | |
| 8 | | | | | | | | | |
| 9 | | | | | | | | | |
| 10 | | | | | | | | | |
| 11 | | | | | | | | | |
| 12 | | | | | | | | | |
| 13 | | | | | | | | | |
| 14 | | | | | | | | | |
| 15 | | | | | | | | | |

**Code1: Sex**
1=male
0=female

**Code2: Matrimonial status**
1=married, 2= single, 3=widow/widower, 4=divorced

**Code3: *Family relationship***
1=head of the household, 2=Husband/wife of the head of the household
3=son/daughter of the head of the household,4=nephew/niece,
5=father/mother of the household head
6=brother/sister of the household head,7=laborer.
8=other (specify)

**Code4: *Education level***
1=primary, 2=Junior Secondary School, 3=High School, 4=University, 5=Islamic, 6=Illiterate, 7=other (specify)

**Code5: *Activities***
1= crop production, 2=Livestock keeping, 3=house chores, 4=commerce, 5=handicraft, 6=laborer, 7=none, 8=student, 9=other

## Section 2: Household's Constraints of maize and sorghum production, knowledge and perceptions on stem borers

2.1 Please, Help to list the challenges encountered in **maize** farming for your household and rank them according to the their economic importance for your household (Code)

| Problems | Rank | Problems | Rank |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

Code: 1=Poor soil fertility, 2=Striga (witch weed) 3=other weeds issue, 4=Insect pest, 5=Rodents, 6=Bird, 7=Drought, 8=late onset of rain, 9=Rainfall irregularity, 10=Shortness of rain period, 11=Strong wind, 12=difficult access to fertilizers, 13=quality of fertilizer, 14=Difficulty on using manure, 15=lack of farming equipment, 16=Rock problem, 17=No extension services, 18=Plant diseases, 19=Seed quality, 20=Lack of new improved varieties, 21= Lack of credit, 22= Soil erosion, 23=Shortage of labor, 24=Lack of market access, 25=Poor market prices, 26=Wild animal 27=Other (Specify),

2.2 Please, Help to list the challenges encountered in **sorghum** farming for your household and rank them according to the their economic importance for your household (Code)

| Problems | Rank | Problems | Rank |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

Code: 1=Poor soil fertility, 2=Striga (witch weed) 3=other weeds issue, 4=Insect pest, 5=Rodents, 6=Bird, 7=Drought, 8=late onset of rain, 9=Rainfall irregularity, 10=Shortness of rain period, 11=Strong wind, 12=difficult access to fertilizers, 13=quality of fertilizer, 14=Difficulty on using manure, 15=lack of farming equipment, 16=Rock problem, 17=No extension services, 18=Plant diseases, 19=Seed quality, 20=Lack of new improved varieties, 21= Lack of credit, 22= Soil erosion, 23=Shortage of labor, 24=Lack of market access, 25=Poor market prices, 26=Wild animal 27=Other (Specify),

2.3 Please provide information of the problem related to insect pests in maize and sorghum farming

| | Do you know this insect (1=Yes, 0=No) | Local name | Describe the most important damage on | | Rank in decreasing order of importance | |
|---|---|---|---|---|---|---|
| | | | Maize | Sorghum | Maize | Sorghum |
| Aphid ( ) | | | | | | |
| Stem borers (or stalk borer) | | | | | | |
| Spider mite | | | | | | |
| Cutworm | | | | | | |
| Termites (Mchwa) | | | | | | |
| Grasshopper/locust (Nzige) | | | | | | |
| Armyworms | | | | | | |
| Weevil | | | | | | |
| LGB | | | | | | |
| Other (Specify) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

2.4 Please, tell us about your knowledge and perceptions of these insects (in the pictures and test tubes)

| Stem borers | Do you know this insect (1=Yes, 0=No) | Local name | Identify it in these vials | Year of first occurr ence | Level of infestation (Code1) | | Severity of damage (Code2) | | Yield reduction due to the pest (kg/acre) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Maize | Sorghum | Maize | Sorghum | Maize | Sorghum |
| *Chilo partelus* (Picture 1) | | | | | | | | | | |
| *Busseola fusca* (Picture 2) | | | | | | | | | | |
| *Sesamia calamistis* (Picture 3) | | | | | | | | | | |

**Code1**: 1=Low, 2=Medium, 3= High. **Code2**: 1=Not severe, 2=slight severe, 3=moderate, 4=high, 5=very high

2.5 Knowledge of the cycle and symptoms of stem borers

| Stem borers | Do you know the reproduction cycle (1=Yes, 0=No) | Please, tell us about three mains symptoms/ damages of the presence of the insect (Code 1) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Maize | | | Sorghum | | |
| *Chilo partelus* (Pictures 1 and test tube1) | | | | | | | |
| *Busseola fusca* (Pictures 2 and test tube2) | | | | | | | |
| *Sesamia calamistis* (Pictures 3 and test tube3) | | | | | | | |

**Code** 1=Scar and holes on the leaves, 2="Dead heart", 3=tunnel in the stem, 4=tunnel in maize cobs, 5=weakening of stems which can break and lodge, 6=chaffy heads in sorghum; 7=several small hundred eggs in batches inserted between the sheath and the stem, 8=Other (Specify)

2.6 Please provide information on the method used in managing these stem borers pests

| Practice | Do you know this practice? (1=Yes, 0=No) | Do you know it as pests' management measure for Maize? (1=Yes, 0=No) | Do you know it as pests' management measure for Sorghum? (1=Yes, 0=No) | If yes, the first year of practice? | Yield loss reduction due to the practice for Maize (kg/acre) | Yield loss reduction due to the practice for Sorghum (kg/acre) |
|---|---|---|---|---|---|---|
| Removing attacked plants | | | | | | |
| Removing insects and their larva | | | | | | |
| Fertilization | | | | | | |
| Rotation with cowpea | | | | | | |
| Use of insecticide | | | | | | |
| Neem spray | | | | | | |
| Sawdust spray | | | | | | |
| Ash spray | | | | | | |
| Use crop residues | | | | | | |
| Burning stalks after harvesting | | | | | | |
| Tillage | | | | | | |
| Trap crop | | | | | | |
| Crop rotation | | | | | | |
| Intercropping | | | | | | |
| Playing on sowing date | | | | | | |
| Removal of alternative host plant | | | | | | |
| Water management | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| Others (specify) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

## Section 3 : Household's knowledge and perceptions on natural enemies and biological control of stem borers.

3.1: According to you are there other insects or living organisms that can control these stem borers pests? |__|
*(1=Yes or 0=No)*

3.2: If yes, list them and please help provide the following information

| Name in local language | Name in English | Year of knowledge | Does it exist on your farm (Code1) | Degree of presence (Code2) | Ability of pest reduction (Code3) | Yield gain (%) due to its presence in | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | low | Medium | High |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |

**Code1:** (1=Yes, 0=No); **Code2**: 1=Low, 2=Medium, 3= High. **Code3**: 1=Not severe, 2=slight severe, 3=moderate, 4=high, 5=very high

3.3 Are you aware of a project that released insects that control stem borer pests in your village? |__|
*(1=Yes or 0=No)*

3.4 If yes in which year|__||__||__||__| 3.5: By which institution? ……………

3.6: Have you been involved in the project (*1=Yes or 0=No*)? |__|

3.7: Have you noticed reduction of infestation of maize or sorghum after this introduction (Code) |__|
*(1=Not at all, 2=Slight reduction, 3=Average reduction, 4=significant reduction, 5=very significant reduction)*

3.8: Please provide information on these natural enemies and their presence in your farm

| | Which of these insects do you know (Code 1) | Year of knowledge | Degree of presence in your farm (Code 2) | Which stem borer does it control | Effectivness in control (Code 2) | Yield loss reduction due to their presence (%) in | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | low | Medium | High |
| *Cotesia flavipes* (Picture 1-Nat en) | | | | | | | | |
| *Cotesia Sesamiae* (Picture 2-Nat en) | | | | | | | | |
| *Telenomus Isis* (Picture 3-Nat en) | | | | | | | | |
| *Xanthopimpla Stemmator* (Picture 4-Nat en) | | | | | | | | |

**Code1:** (1=Yes, 0=No); **Code2**: 1=Low, 2=Medium, 3= High.

# Section 4: Overview on land tenure, land use and grown crops

4.1 Give details about all the land used by your household during the last 12 months. Please include land you are cultivating that belong to other households, or left fallow or used for grazing.

| | Total agricultural cultivated land | | | Own land left for fallow | Land given to other family members | | Grazing land | | |
|---|---|---|---|---|---|---|---|---|---|
| | Own land | Gift land | Rented-in | | Rented out | gift | Own | Rented-in | Obtained as gift |
| Acres | | | | | | | | | |

4.2 Please provide us with information about the share of the total cultivated land between the crops grown this last cropping year in the household

| Crops | 2014 | | | | | | | | | | | | | | 2015 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Maize | | Sorghum | | Other crops (Specify - See Code) | | | | | | | | | | Maize | | Sorghum | | Other crops (Specify - See Code) | | | | | | | |
| | LR | SR | LR | SR | LR | SR | LR | SR | LR | SR | LR | SR | LR | SR | LR | SR | LR | SR | LR | SR | LR | SR | LR | SR | LR | SR |
| 1. Crop acreage (acre) | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2. Total harvested quantity (Kg) | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3. Amount consumed (Kg) | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4. Quantity lost (Kg) | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5. Gift (Kg) | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6. Quantity stored (Kg) | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7. Quantity sold (Kg) | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 8. Selling price/ Unit | | | | | | | | | | | | | | | | | | | | | | | | | | |

**Code Crops**: 1=Rice, 2=Groundnut, 3=Beans, 4=Peas, 5=Barley, 6=Yam, 7=Sweet potato, 8=Irish potato, 9=Cocoyam, 10=Cotton, 11=Cassava, 12=Vegetable, 13=Tea, 14=Coffee, 15=Flowers, 16=Sun flower, 17=Wheat, 18=Tobacco, 19= Sugarcane, 20=Oats, 21=Linseed, 22=Other crop (Specify)

## Section 5: Sorghum and maize farming systems

Please provide information on maize and sorghum farming by the household.

| Questions | | Answer | Questions | | Answer | Questions | | Answers |
|---|---|---|---|---|---|---|---|---|
| 5.1 For how long have you been producing *(Years)* | Maize | | 5.5 Do you have contact with any other program/project/NGO? (*1=Yes, 0=No*) | Maize | | 5.9 How far is your crop plot from the household,? (km) | Maize | |
| | Sorghum | | | Sorghum | | | Sorghum | |
| 5.2 Did you ever get production training on? *(1=Yes, 0=No)* | Maize | | 5.6 If yes what is the main working relationship? (Code1) | Maize | | 5.10 What is your plot soil type? (Code 2) | Maize | |
| | Sorghum | | | Sorghum | | | Sorghum | |
| 5.3 Do you have contact with the extension agent for production? *(1=Yes, 0=No)* | Maize | | 5.7 Do you have contact with research for production *(1=Yes, 0=No)* | Maize | | 5.11 What do you do with crop residues after harvesting? (Code 3) | Maize | |
| | Sorghum | | | Sorghum | | | Sorghum | |
| 5.4 If yes what is the main working relationship? (Code1) | Maize | | 5.8 Main objective of farming *(1=Home consumption, 2=Commercialization, 3=Both)* | Maize | | 5.12 What is the rotation duration (years) on the plot? | Maize | |
| | Sorghum | | | Sorghum | | | Sorghum | |

**Code 1**: 1=Training on pest control, 2=Training on soil fertility, 3=experimentation on improved seed, 4=sales of agricultural crops, 5=technical training, 6=credit, 7=Provides equipment (agricultural equipment), 8=sales of agricultural input, 9=gift of agricultural input, 10=other (specify). **Code 2**: 1=Black cotton soil, 2=Sandy, 3=Clay, 4=loam, 5=other (specify). **Code 3**: 1=Slash and burn, 2=Slash and leave it on the surface for livestock, 3=Slash and store as forage, 4=Do nothing and leave as they are, 5=Slash and sell, 6=Slash and leave lying until the next season, 7=Slash and use for mulching, 8=Other (specify)

5.13 Please provide details on the cultivated plots of maize and sorghum the last cropping year

| **Crops** | | Acreage (Acre) | Land quality (Code1) | Slope (Code2) | Irrigated land (1=yes, 0=No) | Previous crop (Code3) | Type of land preparation (Code4) | Variety grown (Code5) | Type of seed use (Code6) | Pest pressure (Code 7) | Type of seasons (Code8) | Period of sowing (Code9 | Grass boundary near the field (1=yes, 0=No) | Number of plants intercropped (Code10) | Have edge around farms (1=yes, 0=No) | Have erosion problem (Code 11) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Maize | Plot1 | | | | | | | | | | | | | | | |
| | Plot2 | | | | | | | | | | | | | | | |
| | Plot3 | | | | | | | | | | | | | | | |
| Sorghum | Plot1 | | | | | | | | | | | | | | | |
| | Plot2 | | | | | | | | | | | | | | | |
| | Plot3 | | | | | | | | | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Code1:** 1=Fertile, 2=Moderately fertile, 3=Infertile **Code 2**: 1=Flat (0-5%), 2=Slight slope (6-12%), 3=Average (12-25%) slope 4=pronounced slope (>25%) | **Code 3** : 1=Maize, 2=Sorghum, 3=Fallow, 4=Beans, 5=Peas 6=Other crop (Specify) | **Code 4** : 1=Hand 2=Animal powered 3=Tractor 4=Burning, 5=Herbicide use | **Code5** 1=Improved 2=Traditional 3=Both | **Code 6**: 1=From previous harvest 2=Certified, 3=Non certified, 4=Mixed | **Code 7**: 1=Low 2=Medium 3=High | **Code8** 1=Rainy season 2=Dry season **Code 9**: 1=Earlier, 2=Normal 3=Late | **Code 10**: 0=no intercropping, 1=1 intercrops, 2=2intercropped, 3=other (Specify) | Code 11: 1=No, 2=Mild 3=Severe |

5.14 Please provide the following details regarding family labor or external labor and the amount paid for workers in **maize** farming.

| **Operations** | | Long rainy season | | | | | | | | | | Short rainy season | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Family labor** | | | | | **External labor used** | | | | | **Family labor** | | | | | **External labor used** | | | | |
| | | Number | | | Duration (days) | Expenses | Number | | | Duration (days) | Total cost | Number | | | Duration (days) | Expenses | Number | | | Duration (days) | Total cost |
| | | M | W | C | | | M | W | C | | | M | W | C | | | M | W | C | | |
| **Maize : Plot1** | Land preparation | | | | | | | | | | | | | | | | | | | | |
| | Ploughing/ | | | | | | | | | | | | | | | | | | | | |
| | Planting | | | | | | | | | | | | | | | | | | | | |
| | Weeding | | | | | | | | | | | | | | | | | | | | |
| | Spraying | | | | | | | | | | | | | | | | | | | | |
| | Fertilizer application | | | | | | | | | | | | | | | | | | | | |
| | Harvesting | | | | | | | | | | | | | | | | | | | | |
| | Threshing | | | | | | | | | | | | | | | | | | | | |
| | Shelling | | | | | | | | | | | | | | | | | | | | |
| | Other (Specify) | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | |
| **Maize : Plot2** | Land preparation | | | | | | | | | | | | | | | | | | | | |
| | Ploughing/ | | | | | | | | | | | | | | | | | | | | |
| | Planting | | | | | | | | | | | | | | | | | | | | |
| | Weeding | | | | | | | | | | | | | | | | | | | | |
| | Spraying | | | | | | | | | | | | | | | | | | | | |
| | Fertilizer application | | | | | | | | | | | | | | | | | | | | |
| | Harvesting | | | | | | | | | | | | | | | | | | | | |
| | Threshing | | | | | | | | | | | | | | | | | | | | |
| | Shelling | | | | | | | | | | | | | | | | | | | | |
| | Other (Specify) | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | |

M=man, W=woman, C=Child

5.15 Please provide the following details regarding family labor or external labor and the amount paid for workers in **sorghum** farming.

| Operations | | Long rainy season | | | | | | | | | | Short rainy season | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Family labor** | | | | | **External labor used** | | | | | **Family labor** | | | | | **External labor used** | | | | |
| | | Number | | | Duration (days) | Expenses | Number | | | Duration (days) | Total cost | Number | | | Duration (days) | Expenses | Number | | | Duration (days) | Total cost |
| | | M | W | C | | | M | W | C | | | M | W | C | | | M | W | C | | |
| **Sorghum : Plot1** | Land preparation | | | | | | | | | | | | | | | | | | | | |
| | Ploughing/ | | | | | | | | | | | | | | | | | | | | |
| | Planting | | | | | | | | | | | | | | | | | | | | |
| | Weeding | | | | | | | | | | | | | | | | | | | | |
| | Spraying | | | | | | | | | | | | | | | | | | | | |
| | Fertilizer | | | | | | | | | | | | | | | | | | | | |
| | Harvesting | | | | | | | | | | | | | | | | | | | | |
| | Threshing | | | | | | | | | | | | | | | | | | | | |
| | Shelling | | | | | | | | | | | | | | | | | | | | |
| | Other (Specify) | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | |
| **Sorghum : Plot2** | Land preparation | | | | | | | | | | | | | | | | | | | | |
| | Ploughing/ | | | | | | | | | | | | | | | | | | | | |
| | Planting | | | | | | | | | | | | | | | | | | | | |
| | Weeding | | | | | | | | | | | | | | | | | | | | |
| | Spraying | | | | | | | | | | | | | | | | | | | | |
| | Fertilizer application | | | | | | | | | | | | | | | | | | | | |
| | Harvesting | | | | | | | | | | | | | | | | | | | | |
| | Threshing | | | | | | | | | | | | | | | | | | | | |
| | Shelling | | | | | | | | | | | | | | | | | | | | |
| | Other (Specify) | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | |

M=man, W=woman, C=Child

5.16 Please provide information on the quantity and cost of input used during the last cropping year?

| Crops | | Seeds | | | | | | | Mineral fertilizer | | | | | | | | | | | | | Organic fertilizer | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Name of variety | Type of variety (Code 1) | Source of seed (Code 2) | Long rainy season (LR) | | Short rainy season (SR) | | LR | | | | | | SR | | | | | | LR | | SR | |
| | | | | | Quantity (kg) | Cost | Quantity (kg) | Cost | Period of application (Code 3) | Quantity (Kg) | | | | Total Cost | Period of application (Code 3) | Quantity (kg) | | | | Total Cost | Quantity | Cost | Quantity (Kg) | Cost |
| | | | | | | | | | | DA | NP | CA | Oth | | | DA | NP | CA | Oth | | | | | |
| Maize | Plot 1 | | | | | | | | | | | | | | | | | | | | | | | |
| | Plot 2 | | | | | | | | | | | | | | | | | | | | | | | |
| | Plot 3 | | | | | | | | | | | | | | | | | | | | | | | |
| Sorghum | Plot 1 | | | | | | | | | | | | | | | | | | | | | | | |
| | Plot 2 | | | | | | | | | | | | | | | | | | | | | | | |
| | Plot 3 | | | | | | | | | | | | | | | | | | | | | | | |

**Code 1**: 1=Hybrid, 2=Other improved, 3=Traditional, 4=Open-pollinated, 5=Mixed 6=Other (Specify); **Code 2**:1=Own from last harvest, 2=Bought from seed company, 3=received from neighbors, 4=newly received from NGO/Research/Extension, 5=Other (Specify); **Code 3**:1=after planting, 2=After weeding, 3=Both after planting and weeding, 4=At planting 5=Other (specify).

5.17 Please provide information on the quantity and cost of input (pesticides) used during the last cropping year?

| Crops | | Insectides | | | | | | | | | | | Herbicide | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Name of Pesticide | Type of pesticide (Code 1) | Source of Product (Code 2) | LR | | | | SR | | | | LR | | | SR | | |
| | | | | | Number of application | Quantity Q | | Cost (Ksh) | Number of application | Quantity Q | | Cost (Ksh) | Number of application | Quantity (L) | Total Cost (KSH) | Number of application | Quantity (L) | Total Cost (Ksh) |
| | | | | | | Q | Unit | | | Q | Unit | | | | | | | |
| Maize | Plot 1 | | | | | | | | | | | | | | | | | |
| | Plot 2 | | | | | | | | | | | | | | | | | |
| | Plot 3 | | | | | | | | | | | | | | | | | |
| Sorghum | Plot 1 | | | | | | | | | | | | | | | | | |
| | Plot 2 | | | | | | | | | | | | | | | | | |
| | Plot 3 | | | | | | | | | | | | | | | | | |

**Code 1**: 1=Liquid, 2=Dust 3=granules; **Code 2**:1=Bought from chemical outlet, 2=received from neighbors, 3=newly received from NGO/Research/Extension, 4=Other (Specify),

5.18 In case of irrigation, provide information on the amount and cost of water.

| **Crops** | | Water | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Source of Water | Long Raining Season | | | Short Raining Season | | |
| | | | Number of application | Quantity (L) | Cost (KSH) | Number of application | Quantity (L) | Cost (KSH) |
| Maize | Plot 1 | | | | | | | |
| | Plot 2 | | | | | | | |
| | Plot 3 | | | | | | | |
| Sorghum | Plot 1 | | | | | | | |
| | Plot 2 | | | | | | | |
| | Plot 3 | | | | | | | |

## Section 6: Household income and expenditure

6.1: Please provide for each of these crops, the income in the last two cropping year

*(Please collect the income as total value of the product (estimated market price of the product X quantity of product)*

| **Source of agricultural income** | Maize | Sorghum | Other crop | Crop 1 | Crop 2 | Crop 3 | Crop 4 | Crop 5 | Crop 6 | Crop 7 | Crop 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (Code) | | | | | | | | |
| **Income 2015** | | | | | | | | | | | |
| **Income 2014** | | | | | | | | | | | |

1=Rice; 2=Groundnut; 3=Beans; 4=Peas; 5=Barley ; 6=Yam; 7=Sweet potato; 8=Irish potato; 9=Cocoyam; 10=Cotton; 11=Cassava; 12=Vegetable; 13=Tea; 14=Coffee; 15=Flowers; 16=Sun flower; 17=Wheat; 18=Tobacco; 19= Sugarcane; 20=Oats; 21=Linseed; 22=Sesame; 23=Bananas; 24=Trees; 25= Teff ; white/black); 26=Other (specify)

6.2 Please provide information on the income from livestock and animal products during this last year

| | Type of animals | Number of head | Total estimated Value | Number of sales | Total revenue from sales |
|---|---|---|---|---|---|
| 1 | Cow | | | | |
| 2 | Bull | | | | |
| 3 | Heifer | | | | |
| 4 | Calve | | | | |
| 5 | Steer | | | | |
| 6 | Ox | | | | |
| 7 | Sheep | | | | |
| 8 | Goat | | | | |
| 9 | Pigs | | | | |
| 10 | Poultry | | | | |
| 11 | Rabbit | | | | |
| 12 | Donkey | | | | |
| 13 | eggs | | | | |
| 14 | Milk | | | | |

6.3 Please provide information on credit sources and amount during the cropping year?

| **Information** | Accessing credit?1= yes, 2=no | Source of credit (code1) | Amount of credit | Repayment period (months) | Mode of repayment 1=per installment, 2=per term | How much must you pay back in total? | What was the money used for? (code2) |
|---|---|---|---|---|---|---|---|
| **Answer** | | | | | | | |
| | | | | | | | |
| | | | | | | | |

**Code1: Source credit**: 1=local credit institution, 2=bank, 3=projects, 4=NGO, 5=traders, 6=inhabitant of the village, 7=inhabitant of another village, 8=farmers' organization, 9=other (specify)

**Code 2:** 1=For Maize/sorghum production, 2=Other agricultural activities: 3=Off-farm activities, 4=Food expenses, 5=Schooling expenses, 6=other (specify)

6.4 Please provide the following information regarding the savings done in the last 12 months

| **Information** | Have you set any money aside? 1=yes, 2=no | Where do you keep such money? (code1) | How much is the amount set aside (Ksh)? | By keeping that money there, has it yielded any annual benefits for you? 1=yes, 2=no | If yes, how much for that year (Ksh)? | Why do you keep money aside? |
|---|---|---|---|---|---|---|
| **Answer** | | | | | | |
| | | | | | | |
| | | | | | | |

**Code 1**: 1=bank, 2=on myself, 3=with relative, 4=with a third party, who is not a member of the family, 5=other (Specify)

6.5 Income from off-farm activities by all households members during the last 12 months

| Sources of income | Amount | Who provide it in the household (See code) | | |
|---|---|---|---|---|
| 1. Salary received | | | | |
| 2. Rent received | | | | |
| 3. Business or commerce | | | | |
| 4. Beekeeping activity | | | | |
| 4. Transportation | | | | |
| 5. Handicrafts | | | | |
| 6. Assistance from a third party | | | | |
| 7. Pension | | | | |
| 8. Gift | | | | |
| 9. Insurance | | | | |
| 10. Financial assistance from a relative of the household (remittance) | | | | |
| 11. Food aid received | | | | |
| Other non-agriculture income sources (Specify) | | | | |
| ……………………………………… | | | | |
| ……………………………………… | | | | |
| ……………………………………… | | | | |
| ……………………………………… | | | | |

**Code of Person in charge:** 1=head of the family, 2=husband/wife of the head of the household, 3=son/daughter of the head of the family, 4=nephew/niece, 5=father/mother of the head of the household, 6=brother, sister, brother in-law, sister in-law, 7=in-laws, 8=laborers, 9=other (specify)

6.6 Could you please provide information on all household expenses related to farming for maize, sorghum and the other crops in the last 12 months?

| Source of expenditure (if applicable) | Maize (KES) | Sorghum (KES) | Other crops (KES) |
|---|---|---|---|
| Transportation of input | | | |
| Input storage | | | |
| Land preparation | | | |
| Seed | | | |
| Fertilizer | | | |
| Herbicide | | | |
| Other phytosanitary products | | | |
| Labor cost for seeding/Transplanting | | | |
| Labor cost for herbicide and fertilizer application | | | |
| Labor for harvest and post harvest | | | |
| Packaging | | | |
| Implement hiring cost | | | |
| Other labor cost | | | |
| Other financial cost | | | |
| Fuel for farm works | | | |
| Transportation of produce | | | |
| Processing of produce | | | |
| Storing produce | | | |
| Other cost (specify) | | | |
| | | | |

6.7: Could you please provide information on expenses on livestock in the last 12 months?

| Sources of expenditure | Method of payment (1=cash, 2=kind, 3= both) | Total amount spend (where payment is done in kind, provide estimated cash value) |
|---|---|---|
| Labor for looking after animals | | |
| Feeding | | |
| Veterinary services/ medicine | | |
| Other expenses _ | | |
| | | |
| | | |
| | | |
| | | |

6. 8: Please, could you provide information on food expenditures and other household expenses in the two years.

| Expenditure source | Amount (KES) | | | Expenditure source | Amount (KES) | |
|---|---|---|---|---|---|---|
| | 2014 | 2015 | | | 2014 | 2015 |
| Food expenses (per month and then convert in year) | | | | Traditional care (treatment) | | |
| Children School fee | | | | Financial assistance/ monetary gifts (present) | | |
| Other educational expenses | | | | Voluntary contributions (gifts, remittances, transfers) | | |
| Entertainment (games, cigarettes, tobacco, alcohol, etc) | | | | Functions (marriage, funeral, local festivities) | | |
| Rent (House and other rented items) | | | | Trips (travel cost) | | |
| Clothing | | | | Taxes | | |
| Housing maintenance. | | | | Contributions to associations and groupings | | |
| Light/electric power | | | | Water | | |
| Fuel | | | | Other (Specify)……………… | | |
| Pharmaceutical products | | | | Other(Specify)……………… | | |
| Expenditure on health (traditional and modern medicine) | | | | Other(Specify)……………… | | |

## Section 7: Household assets

7.1: Please provide information on your household dwelling and basic amenities

| Questions | Answers | Questions | Answers |
|---|---|---|---|
| 7.1 Does your household own a dwelling? *(1=Yes 0=No)* | \|___\| | 7.5 What is the main source of domestic water? *(1=Own well, 2=Public well, 3=well of neighboring household, 4=Bore hole, 5=Running river, 6=Lake, 7=Trap water, 8=Other (Specify…………………)* | \|___\| |
| 7.2 What is the type of wall of your house? *1=Stone 2=Mud 3=Timber 4=Iron sheets 5=Other (specify……………. )* | \|___\| | 7.6 Type of toilet (0= No toilet/Use bush, 1=Pit latrine , 2= Flush toilet ) | \|___\| |
| 7.3 In which matter the roof of your house is made? *(1=Thatch 2=Iron sheets 3=Concrete 4=Other (specify…………….))* | \|___\| | 7.7 What is the distance to the main source of water? (Km) | \|___\| |
| 7.4 What is the main source of lighting? *(1=Parafin/Kerosenel, 2=Solar panel, 3=Candle, 4=Electricity, 5=Power generator, 6=Other (specify…………….))* | \|___\| | 7.8 What is the main source of domestic cooking fuel? | |

| | | | |
|---|---|---|---|
| | | 1=Fire wood, 2=Gas, 3=Electricity, 4=Charcoal, 5=Parafine/Kerosene, 6=Biogas, 7=Other (Specify……………) | |

7.10 Does the household have the following assets?

| Type of Asset (Owned by the Household) | | Ownership : 1=Yes; 0=No | Number | Who owns these assets in the household (Code1) | Current state (Code2) |
|---|---|---|---|---|---|
| 1 | Houses/shops for renting | | | | |
| 2 | Couch/Armchair | | | | |
| 3 | Chairs | | | | |
| 4 | Car/lorry | | | | |
| 5 | Motorcycle | | | | |
| 6 | Bicycle | | | | |
| 7 | Refrigerator | | | | |
| 8 | Television | | | | |
| 9 | Radio | | | | |
| 10 | Cell phone | | | | |
| 11 | Computer | | | | |
| 12 | Hand Cart | | | | |
| 13 | Tractor | | | | |
| 14 | Other (Specify) | | | | |
| 15 | | | | | |
| 16 | | | | | |
| 17 | | | | | |
| 18 | | | | | |

**Code1**: 1=head of the family, 2=husband/wife of the head of the household, 3=son/daughter of the head of the family, 4=nephew/niece, 5=father/mother of the head of the household, 6=brother, sister, brother in-law, sister in-law, 7=in-laws, 8=laborers, 9=other (specify) **Code 2:** 1=In very good condition, 2=in good condition, 3=in bad condition, 4=in very bad condition

7.11 Does the household own these agricultural farming equipments?

| N | Names | Num ber | Unit price | Total current value | N | Names | Numbe r | Unit price | Total current value |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Sickle | | | | 13 | Shovel/pade | | | |
| 2 | Rake | | | | 14 | Wheelbarrow | | | |
| 3 | Irrigation equipment | | | | 15 | Pick axe | | | |
| 4 | Watering can | | | | 16 | Shears | | | |
| 5 | Carts | | | | 17 | Sprayer/Harrow | | | |
| 6 | Donkeys cart | | | | 18 | Machete/cutlass | | | |
| 7 | Horse/mule ox cart | | | | 19 | Hoes | | | |
| 8 | Stores | | | | 20 | Knife | | | |
| 9 | Tractors | | | | 21 | Plough | | | |
| 10 | Sprayers | | | | 22 | | | | |
| 11 | Axe | | | | 23 | | | | |
| 12 | Earth breaking hoe | | | | 24 | | | | |

## Section 8: Household consumption characteristics

8.1 Can you please tell us about the quantity of consumed food in the household this last seven days?

| Food | Consumed (1=yes, 0=No) | Quantity (Kg) | | Food | Consumed (1=yes, 0=No) | Quantity (Kg) |
|---|---|---|---|---|---|---|
| Maize | \|___\| | | | Cow pea | \|___\| | |
| Sorghum | \|___\| | | | French bean | \|___\| | |
| Rice | \|___\| | | | Cassava | \|___\| | |
| Millet | \|___\| | | | Potato | \|___\| | |
| Wheat | \|___\| | | | Cocoyam | \|___\| | |
| Beans | \|___\| | | | Sweet potato | \|___\| | |
| Grim gram | \|___\| | | | Banana | \|___\| | |
| | \|___\| | | | | \|___\| | |

8.2 Could you please tell us about all the different foods that you have eaten in the last 24 hours (1=yes; 0=No) and in the last 30 days (On how many days you eat these different food during the 30 last days: 4= for 16 to 30 days; **3**= for 4 to 15 days; **2**= for 1 to 3 days; **1**= for 0 days (or not at all))

| Items | 24h | 30d | Items | 24h | 30d | Items | 24h | 30d |
|---|---|---|---|---|---|---|---|---|
| **Cereals** | | | **Fruits** | | | **Vegetables** | | |
| Maize | \|___\| | \|___\| | Banana | \|___\| | \|___\| | Carrot | \|___\| | \|___\| |
| Sorghum | \|___\| | \|___\| | Orange | \|___\| | \|___\| | Tomato | \|___\| | \|___\| |
| Millet | \|___\| | \|___\| | Pineapple | \|___\| | \|___\| | Onion | \|___\| | \|___\| |
| Wheat | \|___\| | \|___\| | Pawpaw | \|___\| | \|___\| | Leaves | \|___\| | \|___\| |
| Rice | \|___\| | \|___\| | Mango | \|___\| | \|___\| | Lettuce | \|___\| | \|___\| |
| Other cereals | \|___\| | \|___\| | Other fruits | \|___\| | \|___\| | Other vegetables | \|___\| | \|___\| |
| **Roots & tubers** | | | **Beans** | | | **Meat/fish** | | |
| Cocoyam | \|___\| | \|___\| | French bean | \|___\| | \|___\| | Goat | \|___\| | \|___\| |
| Cassava | \|___\| | \|___\| | Yellow bean | \|___\| | \|___\| | Beef | \|___\| | \|___\| |
| Potato | \|___\| | \|___\| | Rosecoco bean | \|___\| | \|___\| | Poultry | \|___\| | \|___\| |
| Sweet potato | \|___\| | \|___\| | Nyayo bean | \|___\| | \|___\| | Goat /Sheep | \|___\| | \|___\| |
| Groundnut | \|___\| | \|___\| | Red bean | \|___\| | \|___\| | Fish | \|___\| | \|___\| |
| Other roots/tubers | \|___\| | \|___\| | Other beans | \|___\| | \|___\| | Other meat/fish | \|___\| | \|___\| |
| **Peas** | | | **Milk products/Eggs** | | | **Other items** | | |
| Chicken pea | \|___\| | \|___\| | Cow milk | \|___\| | \|___\| | Salt | \|___\| | \|___\| |
| Cowpea | \|___\| | \|___\| | Goat milk | \|___\| | \|___\| | Tea | \|___\| | \|___\| |
| Green pea | \|___\| | \|___\| | Milk product | \|___\| | \|___\| | pepper | \|___\| | \|___\| |
| Other peas | \|___\| | \|___\| | Other milk product | \|___\| | \|___\| | Oil | \|___\| | \|___\| |
| | \|___\| | \|___\| | Eggs | \|___\| | \|___\| | Fat/butter | \|___\| | \|___\| |
| | | | Egg product | \|___\| | \|___\| | Sugar/honey | \|___\| | \|___\| |

8.3 Could you please help tell us on these strategies in food distribution within the household in the last seven days? *(1=Never; 2=Rarely (once); 3= From time to time (2 or 3 times); 4= Often (5 or more times))*

| Questions | Answers |
|---|---|
| 1. Has the household consumed less preferred foods? | \|___\| |

| | |
|---|---|
| 2. Have you reduced the quantity of food served to men in this household? | \|___\| |
| 3. Have you reduced your own consumption of food? | \|___\| |
| 4. Have you reduced the quantity of food served to children in this household? | \|___\| |
| 5. Have members of the household skipped meals in the last seven days? | \|___\| |
| 6. Have members of the household skipped meals for a whole day? | \|___\| |

8.4 Could you please help tell us on these concerns about the household in the past 4 weeks (30 days)? (**Answer1**: *1=Yes, 0= No*); If Yes, how often has it happened (**Answer2**: *1 = Rarely (1–2 times) 2 = Sometimes (3–10 times) , 3 = Often (more than 10 times))*

| **Questions** | **Answer1** (1=Yes, 0=No) | **Answer2** If Yes, how often did this happen |
|---|---|---|
| 7. Did you worry that your household would not have enough food? | \|___\| | \|___\| |
| 8. Were you or any household member not able to eat the kinds of foods you preferred because of a lack of resources? | \|___\| | \|___\| |
| 9. Did you or any household member have to eat a limited variety of foods due to a lack of resources? | \|___\| | \|___\| |
| 10. Did you or any household member have to eat some foods that you really did not want to eat because of a lack of resources to obtain other types of food? | \|___\| | \|___\| |
| 11.Did you or any household member have to eat a smaller meal than you felt you needed because there was not enough food? | \|___\| | \|___\| |
| 12.Did you or any household member have to eat fewer meals in a day because there was not enough food? | \|___\| | \|___\| |
| 13. Was there ever no food to eat of any kind in your household because of lack of resources to get food? (*1 = Yes, 0 = No)* | \|___\| | \|___\| |
| 14. Did you or any household member go to sleep at night hungry because there was not enough food? | \|___\| | \|___\| |
| 15.Did you or any household member go a whole day and night without eating anything because there was not enough food? | \|___\| | \|___\| |

Thank you for your frank and kind collaboration