THE ECONOMICS OF BIOLOGICAL CONTROL OF CEREAL STEMBORERS IN MAIZE FIELDS OF KENYA

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DEDICATION

To my beloved wife Mary.

"When we kill off the natural enemies of a pest we inherit their work."
Carl B. Huffaker (retired Prof. of Entomology, U.C. Berkeley)

LIST OF ACRONYMS

AE	Allocative efficiency
AIDS	Acquired Immune Deficiency Syndrome
B. fusca	*Buseola fusca*
B/C ratio	Benefit-Cost ratio
BC	Biological control
C. flavipes	*Cotesia flavipes*
C. sesamia	*Cotesia sesamia*
Ca. $	Canadian Dollars
Ch. partellus	*Chilo partellus*
HIV	Human Immuno-Deficiency Virus
ICIPE	International Center of Insect Physiology and Ecology
IRR	Internal rate of return
MFC	Marginal factor cost
MVP	Marginal value product
NPV	Net present value
OLS	Ordinary least squares
PRA	Participatory Rural Appraisal
TE	Technical efficiency
USDA	United States Department of Agriculture

ABSTRACT

The invasive crambid *Chilo partellus* and the nuctuid *Buseola fusca* are important stemborer species in the low potential (low-land tropics, dry mid-altitude, dry transitional and the moist mid-altitude agro-ecological zones of Kenya) and the high potential (moist transition and the highlands agro-ecological zones) maize growing areas of Kenya, respectively. The maize yield lost to stemborers in Kenya has been estimated to be up to 73%. The International Centre of Insect Physiology and Ecology (ICIPE) started a biological control (BC) program in 1991 to control stemborers with emphasis on classical BC of *Ch. partellus*. The project released the braconid larval parasitoid *Cotesia flavipes* in 1993 in coastal Kenya, where it got established and spread to other regions. The success of the introduced parasitoid motivated ICIPE to explore the potential of extending a program for the biological control of the indigenous *B. fusca* in the high potential maize growing areas of Kenya. Economic impact of the project was estimated for the low potential areas and later an *ex ante* economic impact assessment of release of two parasitoids, the larval parasitoid *Cotesia sesamia* and egg parasitoid *Telenomus isis* for biological control of *B. fusca* in the high potential areas, was made. Temporal data on percentage parasitism by the introduced parasitoid and on stemborer density collected between 1995 and 2004 was obtained from the ICIPE data bank. Socio-economic data was collected through administration of questionnaires to 300 and 163 farmers in the low and high potential maize growing areas of Kenya, respectively. The transcendental production function and technical inefficiency models were estimated in a one-stage procedure using the FRONTIER4.1 computer software in assessing technical and allocative efficiencies. The net reduction in total stemborer density within the first ten years since introduction was 33.7%, thus abating 47.3% of yield loss. The low potential zones will accumulate a net present value of US $ 183 million in economic benefits in 20 years since release of the parasitoid. The benefit-cost ratio is estimated at 19:1 with an internal rate of return of 41%. The average yields and technical efficiency of maize producers ranged from 1-1.2 tons/ha and 57.9-67.9%, respectively. Farmers who relied on BC were technically significantly more efficient compared to farmers who applied pesticides. The losses to stemborers could fall to less than 5% in ten years in the high potential areas, if pest reduction by each parasitoid grows to at least 20% on the reducing pest density by the 10th year. The internal rate of return (IRR) of the project in the high potential maize growing areas in Kenya ranges between 58.7 and122.9%. Because of low average yields in the low potential areas, marginal productivity of pest control was low. Future yield improvement efforts should therefore, promote biological control as part of a whole strategy package to improve maize yields. Introduction of more parasitoid species targeting other stemborer life cycle stages would be required for biological control to push yield loss by stemborers to an insignificant level in a shorter period of time. Because the benefits of biological control are positively scale-dependent while the costs are generally scale irresponsive, biological control programs would accrue more benefits when parasitoids are released to a wider area.

CHAPTER ONE

BACKGROUND OF THE STUDY

1.1 The nature of biodiversity in agroecosystems

Increasingly research suggests that the level of internal regulation of functions in agroecosystems is largely dependent on the level of plant and animal biodiversity present (Altieri 1999). However, modern agriculture implies the simplification of the structure of the environment over vast areas, replacing nature's diversity with a small number of cultivated plants and domesticated animals. The world's agricultural landscapes are planted mostly with some 12 species of grain crops, 23 vegetable crop species, and about 35 fruit and nut crop species (Fowler and Mooney 1990); i.e., no more than 70 plant species spread over approximately 1440 million ha of presently cultivated land in the world, a sharp contrast with the diversity of plant species found within 1 ha of a tropical rain forest, which typically contains over 100 species of trees (Perry and Reid 1994). The use of chemicals in agriculture is continuously decreasing the population of delicately living flora and fauna.

All living things interact and support one another in some way. Loss of biodiversity or introduction of new species into an ecosystem makes the ecosystems less stable, more vulnerable to extreme events, and weakens its natural cycles. For example, because the natural enemies of the *Chilo partellus* stemborer species were absent in Kenya, the pest that was introduced to coastal Kenya in the 1930s from Asia grew in population to become a major crop pest in 1960s (La Croix 1967).

Biological control attempts to improve biodiversity by uniting parasitoids with their hosts in order to enhance the natural processes of which living things play a part. The modern classical biological control involves importation and release of organism outside its natural range for the purpose of controlling pests. However, with the increase in technological advancements, biodiversity has been considered to play a lesser role in determining the quality of life and in access to resources and the impact of its change may be going on unnoticed (Altieri 1999). There is also a rapid development of biotechnology that creates the specter of new risks from the purposeful release into the environment of an increasing number of artificially engineered organisms (Howarth 1991).

Determining the value of biodiversity is complex and often a cause for debate. This is largely due to the fact that the worth placed on biodiversity is a reflection of underlying human values, and these values vary dramatically both among societies and individuals (Perlman and Adelson 1997). A major difficulty for evaluating a complex environmental system is insufficient information about important ecological processes underpinning the various values generated by the system. Interspecific resource competition, especially for food, is notorious hard to document in the field even when it occurs sparking debate in ecological concerns (Simberloff & Stiling 2007). Many preditors release for BC have preyed on non-target species (Simberloff 1992). For example, the small Indian Mongoose (*Herpestes auropunctatus*), introduced to West Indies, Hawaii island, Mauritius and Fiji to control rats in agricultural fields, has contributed to the decline of native birds in all those areas (Cheke 1987). Herbivores introduced for biological control of weeds have similarly had unintended effects on native species. For example, the introduction of freshwater fish reduced the native vegetation and changed the composition of the native fish communities (Moyle *et al* 1986). Gagne and Howarth (1985) argued that parasitoids introduced to Hawaii for biological control might have been agents for extinction for several lepidopterans.

Economic valuation of biodiversity provides a means for measuring and comparing the various benefits and costs associated with activities that alter the natural occurrence of the living things. This includes their genetic make-up, dispersion in the earth surface, abundance and the interrelationships between the species and their ecosystems. Loss of biodiversity is an economic problem because the important values of the biodiversity disappears, which sometimes irreversibly. Valuation is a powerful tool to aid and improve wise use and management. It attempts to assign quantitative values to the goods and services provided by environmental resources, whether or not market prices are available.

1.2 Maize production in Kenya

Maize is by far the most important crop grown in Kenya in terms of its share in total production and consumption (Karanja *et al* 2003). Over 85 percent of the rural population derives its livelihood from agriculture, most of who engage in maize production. Maize is important in Kenya's crop production patterns, accounting for roughly 20 percent of gross farm output from the small-scale farming sector (Jayne *et al* 2001). In the recent years, the maize sub-sector has received increasing attention including increase in government allocation to the development of maize through breeding and research programs particularly in the marginal regions.

Kenya is divided into six agro-ecological zones: lowlands, dry mid-altitude, moist mid-altitude, dry transition, moist transition and the highlands (Hassan 1998). The agricultural potential of the land increases in that order from the lowlands to the highlands. The first four agro-ecological zones are considered low potential areas for maize production and account for one third of maize production in Kenya (Karanja *et al* 2003).

Table 1.1 Demographic and maize production characteristics in Kenya

Variable	Marginal regions				High potential regions	
	Lowlands	Dry mid-altitude	Moist mid-altitude	Dry transition	Moist transition	Highlands
Total number of agricultural households						
Small farms '000	112	469	639	153	992	628
Large farms '000	24	107	62	30	107	88
Maize production (1992-1998)						
Output (t) '000	39.7	245.1	377	136.4	1076	686.1
Area (ha) '000	44.8	331.4	190	121.7	441	331.3
Yield (t/ha)	0.89	0.74	1.08	1.12	2.44	2.2

Source: Karanja *et al* (2003)

There has been a debate on whether to allocate more resources to the marginal areas where productivity is low, and thus, obtain the greatest potential benefits or in the high potential areas. The regional maize production share (Table 1.1) indicates farmers in the low potential areas obtain about half of the yields obtained in the high potential areas although even in the high potential areas, maize yields are still lower that the potential yields of up to 5 tons/ha. The large farms account for a larger share of the total maize output.

Recent trends indicate that maize productivity growth is declining and that there is a wide yield gap between experiment station and farmers' yields which can be exploited for productivity gains (Hassan and Karanja 1997). Some of the factors that have been held responsible for the low maize yields include bad weather, inadequate use of recommended technologies, high costs of inputs, lack of agricultural extension services, poor flow of information from the research stations to farmers, limitations in the development of infrastructure, low prices from the maize market reforms resulting in lower input use, a general decline in performance of the economy, dislocations associated with adjustment of market reforms, collapse of credit institutions for farmers and crop pests and diseases (Omamo 1998).

Data in Table 1.2 shows that an increase in maize profitability will affect more strongly households for whom the maize profit share represents a large proportion of household income. Profits from maize production range from being highly important for all households in the high potential areas and moist mid-altitude zones to being relatively insignificant for some households in marginal areas. Maize dominance as a staple food is reflected in the data on expenditure shares. Change in a technology that cause a shift in maize supply curve will cause a change in price only if the share of family expenditure in maze is high, in this case in the marginal areas. It is imperative therefore that a change in technology in the marginal areas will cause a higher variability in maize prices.

Table 1.2: The maize production statistics in Kenya

Variable	Marginal regions				High potential regions	
	Lowlands	Dry mid-altitude	Moist mid-altitude	Dry transition	Moist transition	Highlands
Maize production share (% of national total)						
Small farms	0.5	3.3	9.1	3.9	13.6	16.8
Large farms	0.7	4.4	5.8	0.5	27.1	11.2
Farming income share (% of household income from farm profit)						
Small farms	42.1	68.8	40.7	57.8	53.1	74.8
Large farms	41.4	64.5	82.3	51.4	95.3	93.8
Labor profit share (% of farm profit from maize)						
Small farms	6.9	16.0	39.6	22.9	34.2	33.5
Large farms	34.7	16.0	37.7	9.3	38.5	24.2
Maize expenditure share (% of household expenditure on maize)						
Small farms	29.0	15.7	24.1	11.7	11.2	12.8
Large farms	47.2	2.6	19.7	49.8	16.5	19.5

Source: Karanja *et al* (2003)

To increase agricultural productivity that mitigates rural poverty requires development of technologies that maximize yields. Several technologies have been developed that increase the share of land on agricultural production while others enhanced resource productivity. Attempts to increase production by opening up new land areas could not be stretched beyond the limit. Intensification of land production increased household incomes in the short-run but intensification create ideal conditions for the development of pests and diseases that reduced the production and profitability of agricultural enterprises in the long-run. Monoculture depleted soil fertility and provided conducive environments for pest and diseases to thrive. Development of high yielding varieties, soil fertility replenishment technologies, intensification of farming systems, disease and pest control technologies helped to mitigate the decrease in land per capita. However, chemicals to control pests and diseases and use of inorganic fertilizers led to build up of chemical toxins in the soil.

1.3 Maize stemborers in Kenya

Five stemborers species; the noctuids *Busseola fusca* (Fuller) and *Sesamia calamistis* (Hampson), the crambids *Chilo partellus* (Swinhoe) and *Chilo orichalcociliellus* (Strand) and the pyralid *Eldana saccharina* (Walker) attack maize in Kenya. The invasive *Chilo partellus* and the indigenous *Busseola fusca* are the economically most important species of maize accounting for 85% of all the species (De Groote 2003a). The geographic distribution of these two species are generally thought to be dependent on elevation with *Chilo partellus* being a lowland pest (below 1500m above sea level) and *B. fusca* being a mid-altitude to highland pest (above 600m above sea level) species (Seshu Reddy 1983; Harris and Nwanze 1992). These stemborers cause losses of up to 73% (Seshu Reddy and Walker 1990; Overholt *et al* 1997; De Groote *et al* 2003a).

1.4 Options for the control of maize pests

In a free market economy, individual farmers make decisions on managing their farms including the kind of pest control measure to be adopted. Under such circumstances, the control measure of one farmer may have direct effect to the efficiency of the neighbors control measure especially when biological control is one of the alternatives. There are several options for the control of maize pests that include; cultural control, biological control, chemical control and integrated pest control methods.

Cultural methods are non-chemical strategies that give an advantage to the crop rather than the pest. Various tillage methods, crop rotations, sanitation, exclusion (of pests from a field), altered planting dates for pest avoidance, increased row spacing, and bed shaping are examples of techniques that modify the cropping environment and help control pests (Ndema *et al* 2001). Resistant varieties (a product of biological engineering) give the crop an advantage over the pest, so their use is often considered a cultural control. Mechanical and physical control options are often grouped with cultural controls.

Naturally occurring biological control is the cheapest and most efficient form of pest management available. Biological control occurs when predators, parasites, or diseases of pests keep their hosts' populations from building to economically damaging levels. The natural enemy complex can be protected to a certain extent by using insecticides which are more environmentally friendly, and which are not very toxic to non-target organisms. The use of habitat enhancement to increase beneficial organisms and continous increase of new parasitoids improves efficacy of the strategy to reduce yield losses to crop pests.

Pesticides (synthetic pesticides, insecticide soaps, oils, and plant-derived botanical pesticides) are used as the last resort after all other pest control methods have failed. Pesticides have been considered an external disturbance to the ecosystem by altering the natural interactive association between the host and the parasitoids. The society experience direct and indirect damages from using pesticides, which are saved after the parasitoids, reduce the impact of stemborers on maize yield to insignificant levels. Often less than 0.1 % of pesticides applied reach the target (World Resource Institute 1994) while the rest becomes environmental contaminant. The health costs of pesticides use include carcinogenic, reproductive and immune-system damages, skin and eye damages and acute toxicity (Pingali and Roger 1995).

Integrated pest management is a system whereby various strategies are used to protect crops by suppressing the insect population and limiting damage. Maize farmers implementing IPM consider all available control options for maize stemborers and make informed decisions about how best to control them while also considering crop development stage, market demands, pest levels, and weather conditions.

1.5 Biological control of maize stemborers in Kenya

The first attempt to control cereal stemborers using the classical biological control approach involved the importation of nine species of *C. partellus* parasitoids from Asia by the Commonwealth Institute of Biological Control (CIBC). The parasitoids were released in Uganda, Kenya and Tanzania between 1968 – 1972 (CIBC 1968-72). Later, 13 exotic parasitoids targeting cereal stemborers were released in South Africa in 1977 (Kfir 1994). None of the projects reported establishment of the parasitoids.

A project on biological control of stemborers in subsistence agriculture in Africa was launched by the International Center for Insect Physiology and Ecology (ICIPE) in 1991. The project imported *Cotesia flavipes,* Cameron (Hymenoptera: Braconidae), an endo-parasitoid of larvae of cereal stemborers from Asia, in 1991 for host range studies. The parasitoid was released in coastal Kenya 1993 and got fully established (Omwega *et al* 1995; Omwega *et al* 1997; Overholt *et al* 1997). The success of the introduced parasitoid in the control was demonstrated in the establishment and spread from the release points (Omwega *et al* 1997), increasing parasitism by *C. flavipes* and control of stemborers (Zhou *et al* 2001a) and the positive economic impact (Kipkoech *et al* 2006) that motivated the institution to exploit the potential of biological control of indigenous stemborers in the highlands.

This motivated ICIPE to explore the potential of extending biological control of the indigenous *B. fusca* to the high potential (moist transition and the highlands agro-ecological zones) maize growing areas of the Kenya Hassan 1998. ICIPE introduced to Taita Hills, the West African scelionid egg parasitoid *Telenomus isis*, Polaszek (Hymenoptera: Scelionidae) and a virulent strain of the indigenous larval parasitoid *Cotesia sesamiae* Cameron, in June 2005. *Telenomus isis* together with *T. busseolae* (Gahan) are the most important natural control agents of noctuid stemborers in West Africa where they cause egg mortality of up to 95% (Schulthess *et al.* 2001). It has never been reported from East and Southern Africa. In Kenya, *Cotesia sesamiae* exists as a virulent and avirulent strain. The former strain occurs in the highlands where it successfully develops in *B. fusca* and noctuid *Sesamia calamistis* Hampson, a minor borer species, while the latter occurs in the lowland and it only develops in *S calamistis* while is encapsulated in *B. fusca* (Ngi-Song *et al* 1998; Mochiah *et al* 2002). There is need to assess the economic impact of biological control of maize stemborers in Kenya.

The discipline of impact assessment attempts to estimate quantitatively the counterfactual situation of a project by comparing the results of the project with what would be the situation without the project (Baker 2000). In this study, economic impact of the BC project is measured as the net value of the yield loss abated by comparing the actual yield loss achieved with what the yield loss could have been if the parasitoid was not released. The differences in yields, allocative (AE) and technical (TE) efficiencies between maize farmers in the low potential areas who apply pesticides for the control of stemborers and those who do not (rely on biological control) is also compared. In the last section of this study, an *ex ante* evaluation of biological control in the high potential maize production areas of Kenya is carried out. This study is the first attempt to measure economic benefits of biological control of cereal stemborers in Kenya.

1.6 The problem statement

During the green revolution in the 1960s, the focus was to increase crop production to meet the increasing demand for food from the expanding population. The strategies employed were that of expansion of land under production, adoption of high yielding crop varieties, chemicals control of pests and disease and adoption of other technologies. Biological control was thought to be outmoded and not effective as compared to synthetic insecticides such as pheromones, chemosterilants, attractants and hormones in reducing the threat caused by pests to the desired crops. The commercial potential of bioengineering solution for crop protection by the technology developing institutions and governments and the inability to exclude others or sell biological control agents after it has established, except for augmentative releases, made the classical biological control not to be strongly supported.

Over time, plants have been evolving chemical defenses against herbivores and herbivores have respondent by evolving ways of detoxifying the plant poison creating a herbivore fauna not easily conquered by the broadcast use of chemicals (Ehrlich 1970). On the other hand, predatory insects have not had the same level of evolutionary experience with poison and have generally a lower population. The spraying of pesticides therefore, affect more the natural enemies that led to resurgence of the pest that cause considerable damage before control measures are re-established.

In a free market economy individual farmers make their own pest control decisions and producers of alternatives such as pesticides have a right to promote and sell them. The perception of the pest problem by farmers and the marketing skills of those proposing the alternative solutions influence how well biological control are adopted. Introduction in biological control is expected to cause a shift in the production function. Positive and negative externalities may also be experienced that affect the quantity, quality and productivity of human and the ecological resources. Due to the market failure, farmers do not pay for the cost caused to the environment by using the several alternatives for pest control. When decisions are made without adequate information, conversion to inferior alternatives may be permitted that may have adverse effects to the productivity of resources and sustainability of the biodiversity. Economic evaluation of biological control provides a basis for justifying investments in biological control programs and in assessing the impact of adoption of biological control on farm resource use efficiency. The study also needs to determine whether to advocate for sole reliance of BC or to develop other technologies to augment BC.

1.7 Objectives of the study

The overall objective of the study is to assess the economic impact of introducing biological agents for the control of stemborer in maize fields in Kenya. The specific objectives are to:

a) Quantify benefits and costs resulting from the introduction of *C. flavipes* for the control of cereal stemborers.
b) Compare yield, technical and allocative efficiency between user and non-user of pesticides for the control of maize stemborers.
c) Quantify *ex-ante* benefits and costs of biological control of cereal stemborers in the Kenyan highlands.
d) Draw conclusion on impacts of adoption of biological control among resource poor farmers.

CHAPTER TWO

LITERATURE REVIEW

2.1 Biological Control of Pest

The biological control of pests can be categorized as; the classical control measure where pests are predated by their natural enemies and biopesticides. Biopesticides are the pesticides derived from naturally occurring biological organisms like the *Bacillus thuringiensis*, toxins, pyrethrum, use of sterile males obtained either through conventional breeding and selection or through genetic engineering and the periodic colonization of natural enemies. In the classical approach, the natural enemies already existing in an ecosystem is conserved, exotic organisms are introduced either for adaptation and permanent establishment or temporally to control the pest at hand after which they naturally become extinct.

Biological control measures have been implemented in diverse environmental, economic and technological environments. Some of the monumental projects in biological control were the control of cassava mealybug by the introduced *Apoanagyrus Lopezi.*Desautis, over the cassava belt in Africa that allowed for continued production of the staple crop by the subsistence farmers (Zeddies, *at al.* 2001), the biological control strategy of the variegated grasshoppers in the humid tropics of West Africa (Müller, *et al* 2001) and the control of water hyacinth, *Eichhornia crassipes* Martius, in southern Benin and East Africa using two weevils, *Neochetina eichhorniae* Warner and *Neochetina bruchi* Hustache (De Groote, *et al* 2003b).

Because of the high losses to stemborers, in order to increase maize production and alleviate rural poverty require strategies that improve productivity and minimize yield losses. That strategy should include control of stemborer pest where a complete control would imply increase in farmers' yields by the prevailing yield loss level using current technologies. Owing to the fact that small-scale farmers in eastern and southern Africa are resource poor and obtain low yields that do not justify added investments (ICIPE 1994), the appropriate method to meet this end is through development and adoption of simple technologies that require little or no cash expenditure and external inputs. The introduction of natural enemies of stemborers is free of cost once established, unless special procedures are required to augment or reintroduce the populations (Gutierrez *et al* 1999).

Many studies have reported minimal damage of these methods on environment (De Groote, *et al* 2001, Zeddies, *at al.* 2001). However, introduction of exotic natural enemies to Hawaii to control pests adversely affected the natural fauna (Howarth 1983). Where biological control adversely affected natural fauna, restoring the ecological situation is usually nearly impossible (Gutierrez *et al* 1999). The fauna damage is reported to be enormous with the organisms that have polyphagous feeding habits. Some organisms also have been reported to expand their host range. The Eurasian weevil, *Rhinocyllus conicus* Froeh. for control of *musk thistle* in Canada and USA for example, expanded its host range lowering the density of native *Tephritid fier* (Louda *et al* 1997). The risks involved with introduction of BC agents demonstrates the importance of undertaking initial studies to establish any possible non-target impact of a candidate for BC prior to the release of the organism.

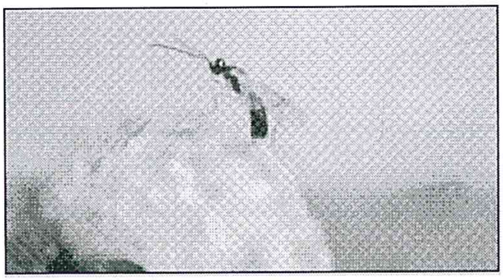

Figure 2.1: ***Cotesia flavipes*** **adult ovipositing in a stem borer larva**

The impact of stemborers on yields depends largely on soil fertility levels (Sétamou *et al.* 1995; Chabi-Olaye *et al.* 2005a,b; Wale *et al.* 2006), farming systems (Schulthess *et al.* 2004; Borgemeister 2005; Chabi-Olaye *et al.* 2005a), maize cultivars (Seshu Reddy & Sum 1991; Ajala *et al.* 2003) and presence of other natural enemies (Schulthess *et al.* 1997; Schulthess *et al.* 2001; Cugala *et al.* 2006), which differ among regions and households.

Infestation by stemborers starts with oviposition on the leaves (Ajala and Saxena 1994). After hatching, the first instar larvae move into the leaf whorls where they feed and develop on the bases of the leaves, causing lesions. The late third or early fourth instars bore into the stem, feeding on the tissue and making tunnels. When the infestation is severe, the larvae, either in the leaf whorl or in the stem can cut through the meristematic tissue when the central leaves dry up, resulting in death of the plant. The pest therefore, lead to yield losses through decrease in photosynthesis, disruption of translocation of water and nutrients, secondary infections with plant pathogens and lodging due to weakened stems.

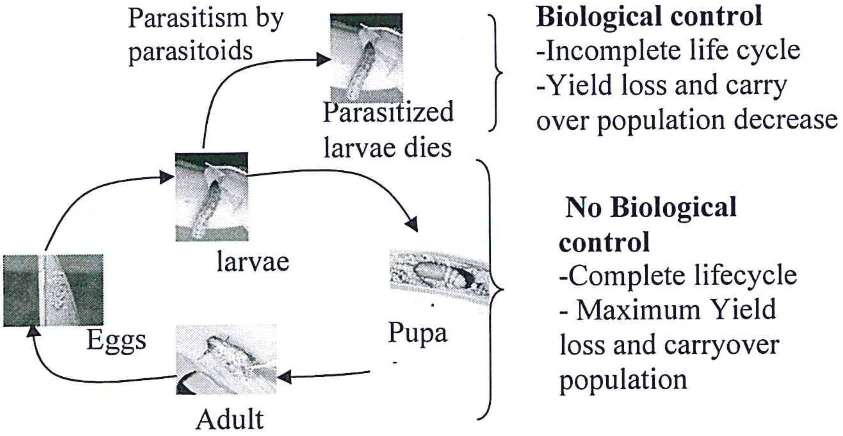

Figure 2.2: Parasitism cause incomplete stemborer lifecycle

The most important step in ensuring sustainability of biological control agents is the maintenance of a favorable environment that allows for pest-parasitoid interaction. This includes the conservation of natural enemies and the refuge vegetations and non-use of toxic chemicals. There is some synergism in classical biological control and habitat management for host and parasitoids. Schulthess *et al* (2004) reported a 67% and 83% reduction in egg and immature numbers of *S. calamistis* respectively in maize-cassava intercrop. They attributed this to the reduced host allocation by adult moth and the increase in parasitism by *Telenomus spp*. In the same study, the insecticide-treated maize, intercropped with cassava led to a yield loss reduction of 9-16%, while on untreated maize, the net effect of reduced pest density and increased plant competition resulted in zero yield differences. Higher yield were obtained from intercropped compared to mono-cropped maize. The use of chemical pesticides is critical because about one quarter of the dose required to control pests is enough to wipe out natural enemies (Kfir 2002; Cugala *et al.* 2006). The eventual impact of the establishment of the parasitoids will not only depend on the intrinsic growth rate of the parasitoid and the prevailing quantity of maize output lost to stemborers but also on its interaction with input use levels.

2.2 Assessing the risks of releasing biological control agents in Kenya

The most important risks of release of BC agents relate to changes in target and non-taget organisms, impacts on human health, environment and the economy. While the non-target impacts on organisms can either be positive or negative depending on the role of the secondary organism that was initially non-targeted, the impact of BC agents on human health is not known except for cases of allergy in the mass production of predatory mites or nematodes (Ehlers 2003). Sometimes the natural enemies vector pathogens such as *Wolbachia sp* have negative effects on the reproductive fitness of BC agents (Ngi-song *et al* 1998). Economic impacts are associated with the introduced parasitoids extending their attack to the non-target species, which are directly useful or indirectly aid in production of goods and services humans consume. As reported by Van Lenteren *et al* (2006) the true risk of introduction of BC agents include possible extinction of a native species (target or non-target), reduction in abundance and redistribution of native organisms, interference in the efficacy of native natural enemies or competitive displacement, vectoring of pathogens harmful to native organisms, loss of biodiversity and identity of native species via hybridization and a major shift in the balance of native species via direct or indirect mechanisms. Because of the absence of a market in most biodiversity resources, attaching a value on the non-target effects is usually difficult.

The potential risks of the released BC agents have been studied in pre-release evaluations (Gitau *et al* 2006; Bruce *et al* 2006). The two parasitoids have been found to be highly specific to stemborer. Bruce (2006, unpublished data) found out that *T. isis* can only reproduce in temperatures ranging from 12 to 30 degrees which show that the parasitoid is not likely to spread beyond its niche. Chabi-Olaye *et al* (2001) found out that *T. isis* distinguished between host plant species and recognized markings by females of other species and tried to avoid super parasitism. This behavior helps to ensure the continuous proliferation of indigenous parasitoids while pest reduction is perpetually achieved in the maize fields.

Although administrative boundaries can form barriers to legislations that influence purposive introduction of organisms, exchange of biodiversities between adjacent ecosystems occurs throughout. Because large seas and oceans present barriers for the spread of biological organisms, it is more realistic to consider parasitoids from overseas exotic. Overholt *et al* (2001) found out that the *C. flavipes* parasitoid would move an average of 64 meters within its lifetime. With such a spread, it is expected that over time, introduced insects spread to cover their entire niche. The introduction of the two parasitoids played the role of speeding the process of spread and perhaps to by-pass physical barriers such as the lowlands surrounding the Taita Hills.

2.3 Review of Methodologies

2.3.1 Modeling of pest and parasitoid interactions

The host-parasitoid interaction in nature represents a complex phenomenon which is difficult to capture through mathematical modeling (Pielou 1977). The biotic and a biotic factors influence how the organisms relate in nature. Most studies confine factors for inclusion in modeling the insect population dynamics to a few, which often include pest and parasitoid population growth rates, dispersion rates and the impact of parasitism on host population captured as negative growth rate of the host over time.

Lotka and Volterra (1925) independently developed the Lotka-Volterra model of predator-prey interactions. In the model, the change in the host and parasitoid populations is estimated as: $\frac{\delta H}{\delta T} = rH - aHP$ and $\frac{\delta P}{\delta T} = bHP - mP$

The model has two variables (P and H). Where: H = density of prey, P = density of predators, r = intrinsic rate of prey population increase, a = predation rate coefficient, b = reproduction rate of predators per one prey eaten, m = predator mortality rate.

The parameters of the model could be measured by carrying out experiments to determine r, a, b and m. In estimation of parameters b and m, linear regression of the intrinsic rate of predator population increase against prey density of the form $r_p = bH - m$ was used.

In determining the change in population over time, analytical and numerical methods can be used. The Euler's method is mostly used. The main source of error in the Euler's method is estimation of derivative at the start of time interval. The direction of actual solution may change drastically during this time interval and numerically predicted point could be far from the actual solution. Euler's method can be improved, if the derivative (slope) is estimated at the center of time interval Δt.

Using the model, the prey and predator densities (H and P, respectively) are first estimated at the center of time interval and then estimated at the end of the time. The initial density of the prey and host will determine the population dynamics. The model has no asymptotic stability, therefore, it does not converge to an attractor.

The disadvantage with this model is that predators have no saturation and their consumption rate is unlimited. As a result, prey population may grow infinitely without any resource limits. The rate of prey consumption is proportional to prey density. Thus, it is not surprising that model behavior is unnatural showing no asymptotic stability. The model also does to consider spatial distribution of the parasitoids.

The importance of spatial models is based on the fact that many insects disperse hundreds of miles during one season (Westbrook *et al.* 1992). It is therefore difficult to predict insect population based on its past population in isolation from neighboring stands (Campbell and Sloan 1978, Gould *et al.* 1990). For introduced species such as the *C. flavipes* and *T. isis* several important phenomena like spatial pattern of population change, synchronization of pest outbreaks and spread of the species can be studied only using spatial models. DeAngelis and Waterhouse, (1987) also noted that the local population dynamics are often unstable, and therefore, it is hardly predictable (e.g., population may get extinct) but ensembles of spatially distributed local populations have stable patterns and can be simulated.

Celini and Vaillant (2004) studied the spatio-temporal distribution of *Aphis gossypii* (Glover) for a 4-year period in a plot of *Gossypium hirsutum* located in Bangui, Central African Republic. The temporal evolution of aphids was studied by means of polynomial regression using the logarithm of the sample mean as dependent variable and the time t as explicative variable. The regression model was of the form:

$$Lm(m_t) = a_0 + a_1 t + a_1 t^2 + ... + a_k t^k$$

a_i are the estimated coefficients and t is the time period elapsed since the introduction. The goodness-of-fit of this model was tested over the whole period of observations, using multiple regression techniques (Tomassone *et al* 1989).

In the study three laws were tested. The Iwao's relation states that the relationship between the mean m and the variance σ^2, is based on the mean crowding index m^* (Lloyd 1967). Mathematically, this can be expressed as:

$$\delta^2 = (a+1)m + (b-1)m^2$$

Where a and b are the regression parameters between m^* and m.

For populations distributed in colonies, a corresponds to the mean number of co-settlers per colony per individual, and b is a dispersion index characterizing the distribution of the colonies. $a + 1$ and $b - 1$ can be estimated by simple linear regression. The Taylor's (Taylor 1961) law connects the mean m and the variance of insect populations in the following way: $\delta^2 = cm^d$

The Taylor's relationship could be estimated using linear regression by obtaining natural logarithms of the parameters.

The third relationship tested was the Nachman's relationship (Nachman 1981) stated mathematically *as:* $p = 1 - \exp(-fm^2)$

f is a positive scale parameter and g is a dispersion parameter. Where $f = g = 1$, a classical relationship which corresponds to a completely random distribution of individuals is obtained. The higher the value of f, the higher the proportion p was for a given value m.

The polynomial regression curves generated were almost of the same appearance and consisted of three parts: (i) the ascending phase described the progressive increase of the population levels on the cotton plants which are in full vegetative development and corresponded to the exponential evolution curve $m_t = \exp(0{,}35t + 3{,}24)$; (ii) the second part shows the population level variations when the cotton plants were in the final phase of vegetative development; the blooming stages at the beginning of fructification. This part corresponded to the evolution curve m_t = exp (-0.08t+6.51); (iii) the rapid decline of the aphid populations on the cotton plants in the final phase of fructification, and the beginning of senescence corresponded to the curve equation m_t = exp ($-0.15t^2+6.25t-60.26$). However, the spatial model could not be adopted to our model because spatial data was missing.

Zhou *et al* (2001) found linear models of first order autoregression form to be adequate for description of the reduction in stemborer density resulting from parasitism by *C. flavipes*. Other model specifications that could be used to predict the stemborer densities and parasitism were the modifications of Nicholson-Bailey and the Lotka-Volterra models (Pielou 1977). Estimating parameters of these models would have been difficult because of the limitation of our data and complexity of the models. The field data used in this study had initial parasitism of zero before the introduction of *C. flavipes*, a condition that could not be accommodated by these models. The parameters of model used in the present study are easy to compute and the model meets our objective of capturing the impact of the introduced parasitoid on pest densities.

The Zhou model (Zhou *et al* 2001) was adapted for this study. Zhou *et al* predicted stem borer population dynamics in two locations of North and South coastal Kenya using a modified host-parasite interaction model of the form:

$$D_t = a_o + b_1 D_{t-1} + .. b_k D_{t-k} + C_{0t} + f_1 C_{1(t-1)} + ... + f_r C_{r(t-r)}$$

where D_t is the mean density of the stem borer complex (all species) at growing season *t, k* is the time lag of the stemborers, *r* is the time lag of parasitoid (*C. flavipes*) to stemborers, C_{lt} is the parasitism of stemborers by *C. flavipes* at time t and specific to stemborer complex or to *C. partellus*, a_0, b_j $(j=1,2,...,k)$, f_j $(j=1,2,....,r)$ and C_0 are parameters specific to stemborer complex. Parameter b_j represented the time dependence of stemborer population dynamics, and f_i represented the time-delayed parasitoid impact.

In constructing this model, they assumed that the stem population density depended on both the previous occurrence of the stemborers and the distribution of the parasitoid.

The Zhou model is a ratio-dependent host-parasite interaction model (Gutieerez *et al* 1993). In this case, if the density of *C. flavipes* ($D_{cf(t-1)}$) was used instead of parasitism by *C. flavipes,* in this case, $k=r=1$, then the model would have been:

$$D_t = a_o + b_1 D_{t-1} + C_{0t} + f_1 \left(\frac{D_{cf(t-1)}}{D_{t-1}} \right)$$

In this model, the ratio of demand $D_{cf(t-1)}$, over supply, $D_{(t-1)}$, rather that the reverse was used because the demand for the first several seasons was zero (parasitoid was released in 1993). The time lag *r,* was identified using the autocorrelation and the partial autocorrelation functions while the time lag *k,* was identified using the cross correlation function (Box *et al* 1994). The means values of the stemborers were used at every time. The least square method was used to estimate the parameters of the model. A linear trend was used in the model because a linear trend had been reported in the first eleven seasons.

The results of their analysis showed that there was an exponential decay along with the increase of time lags. The partial autocorrelation factor (PACF) was found to spike at time lag 1, with no correlation for other lags for all of the cases. This implied therefore that the series fitted the first order autoregresion model. The cross correlation analysis showed significant lagged correlation between *C. flavipes* and stemborers. This implied that the impact of C. *flavipes* on stem borer density appears on the succeeding season and continues for the subsequent seasons.

The regression results showed that the lagged density of the stemborer contributed little to the current density. The regression coefficients of the trend term were significant which showed that the stemborer density depended more on the long-tern trend and that the stem borer density was more time dependant. The model predicted suppression of stem borer density by *C. flavipes* but more on the North than in the southern coast.

This model ignored the effect of climatic and physical features on the host and parasitoid density. Changes in weather affect plant vigor and consequently the ability of the plant to support the stemborers. Fertile soils influence the plant vigor and size and stem borer population is expected to vary linearly with the size of the maize stalk.

The model also focused on local populations and considered it isolated from the rest of the world by failing to consider the impact of host and parasitoid migration on their densities.

2.3.2 Yield loss assessment

Since the early 1970s, the stemborer density in the study area increased up to 1998 (Zhou *et al.* 2001). During this time, *C. partellus* was found to be displacing indigenous stemborers to become the most important species (Zhou *et al.* 2001). Seshu Reddy & Walker (1990) reported yield losses due to *C. partellus* ranging from 4 to 73%. The magnitude of the damage is influenced by soil fertility levels (Sétamou *et al* 1995; Chabi-Olaye *et al* 2005a), farming systems (Schulthess *et al* 2004; Borgemeister 2005; Chabi-Olaye *et al* 2005b) and maize cultivars (Seshu Reddy & Sum 1991; Ajala *et al* 2003). Several studies have shown that grain weight loss caused by stemborers is linearly related to borer numbers (Usua 1968; Bosque-Pérez & Marek 1991; Seshu Reddy & Sum 1991; Gounou *et al* 1994; Ajala & Saxena 1994; Sétamou *et al* 1995; Ndemah & Schulthess 2002).

Although studies on the impact of stemborers on yields have been carried out (Songa *et al* 2001; Songa 1999; Seshu Reddy and Sum 1991), few studied the link between parasitism, pest reduction and the resultant yield loss abatement. Van Rensburg *et al* (1988) and Gounou *et al* (1994) showed that stem tunneling and cob damage were more meaningful and reliable variables in assessing output losses than stemborer numbers as many of the borers are no longer present at harvest. However, estimation of output losses using tunneling length is limited when data on yields and corresponding tunneling length are missing like in the present study.

Several studies have shown that grain weight loss caused by stemborers is linearly related to borer numbers (Usua 1968; Bosque-Pérez & Marek 1991; Seshu Reddy & Sum 1991; Gounou *et al* 1994; Ajala & Saxena 1994; Sétamou *et al* 1995; Ndemah & Schulthess 2002). Because stemborers experience high mortality from natural causes (Bonhof 2000), the important stemborer density is that of the surviving larvae that cause economic damage to maize plants, which the introduced parasitoid contribute to their reduction. Holding other factors constant, reduction in stemborer density resulting from parasitism by the two parasitoids will lead to a linear reduction in the quantity of maize lost to stemborers.

The two parasitoids act in two different stages of the stemborer lifecycle that creates a complex synergistic pest control environment. Young larval stages of *B. fusca* disperse from the oviposition site to the whorl of the plant and then to other plants (Kaufmann 1983). As dispersal is positively density dependent, reducing the number of young larvae before they disperse would also reduce the numbers of plants infested. *Cotesia sesamiae* will attack the pest population that will manage to escape into the larval stage. The egg parasitoid, *T. isis* causes yield loss to pest abatement by reducing the number of plants infested, thus allowing more plants to achieve their potential output. The egg parasitoid is important given that the pest is controlled before it can cause any damage (Temerak 1981). The larval parasitoids are important in the long-term reduction in stemborer density by reducing the carry over population from one season to the following season.

2.3.3 Economic impact assessment

The impact of the biological control agents on target pests is difficult to asses particularly when attempts are made to attach monetary values on both positive and negative externalities resulting from successful introduction of effective natural enemies (Cullen and Whitten 1995). The methods often used in economic impact assessment are: econometric approaches that aim at estimating the marginal productivity of every dollar spent on the program, programming methods that identify optimal technological packages from a basket of options and the benefits and costs techniques that measure the benefits and costs of a particular research project.

For the econometric approaches, the production function is often estimated. A common practice for assessing impact is to divide the sample into groups such as 'with' and 'without' a technology and estimate separate production functions for each group (see Howard 1985, Yotopolous and Lau 1976) or use dummies that are interpreted to give the implications for 'with' and 'without' the program. Since it is difficult to distinguish the impact of research from other factors such as input prices, change in managerial skills, rainfall and other climatic factors, the econometric studies are undertaken only where large amount of data is available. The estimated impact is also sensitive to the specification of the functions used to estimate the impact parameters. This makes this tool more appropriate to academic studies and only to context where data is not limiting (Masters *et al.* 1996).

Programming models are often used to represent farm-level decisions and show change in farm operations when new technologies are introduced. The model specifies farmers' objectives and constraints and analyzes both 'with' and 'without' the technology showing changes in activity and factor level. The programming models are useful when the researcher wishes to study the farming system as a whole. The mathematical programming techniques have been widely advocated in modeling management decisions. The strength of programming lies in its ability to handle multiple goals and complex resource allocation scenarios in a more comprehensive and realistic manner (Getachew 1980). The programming models can be constructed in such a way that the household objectives and constraints that affect decision-making are captured. One of the most successful agricultural sector models that used mathematical programming was the CHAC model for Mexico (Norton 1974; Norton and Solis 1981). The model describes 29 different producing locations, 31 different crops, and has over 2500 different production technologies vectors. However, just like the econometric models, this method requires a lot of data, custom-made models for specific data analysis and very intensive research effort. Programming models also provide little guidance as to what technologies would be actually desirable.

In benefit-cost analysis, estimates of the benefits of the project are balanced against the project cost and any implied cost (CIMMYT 1993). Benefit-cost analysis seeks to ascertain in monetary terms the gain or loss under the pest control strategy. The net benefits approach adds up the gains and subtracts the loss of value or satisfaction that can be compared across options. While it is possible that in attempting to uphold ones person's satisfaction, the satisfaction to others may be affected, benefit-cost analysis assumes that satisfaction to the society is the summation of individual valuation in the society and does not cast judgment on the differences between peoples' valuation. Measurement of benefits over costs can be supplemented by computation of returns to scarce resources valued at their shadow prices to reflect their scarcity.

The benefits-cost approach requires least data compared to the other techniques and ignores major overhead costs such as costs of land and sunken capital in computing the social gains (SG) to the society. However, it gives a general indication of the attractiveness of the technology to the farmers and the funding agency. Since some of the benefits and costs of projects may not be relevant to the farmers (Rudat *et al* 1995) economic surplus criterion may be adopted when the benefits and costs that are significant to the farmers need to be assessed. A complete benefit-cost analysis provides a criterion for deciding whether the technology provides net positive benefits, taking into consideration all the facets of the economy.

The approach however, does not tell which particular technology is feasible and desirable. It also does not examine the performance of the required changes in the resource use. Benefit-cost criterion is dimensionless and tells nothing about the total gain, rather it is a useful measure of the rate of return per dollar invested. In spite of these setbacks the method is very useful in analyzing the economic impact of a technology change and is the most common method used to determine the impact of a new technology (Gittinger 1989).

2.3.4 Benefits and costs of biological control

Benefits and costs of biological control programs stream infinitely or over a long period of time to the economy. The benefits of biological control are diverse and include increase in resource productivity, reduction in cost of production and positive contribution to environmental and health. The stream of benefits needs to be corrected for time once computed. The benefits of biological control can be estimated as:

$$NB = \sum (B_i - C_i) / (1 + r)^i$$

Where $(1 + r)^i$ is the discounting factor, B_i and C_i are benefits and costs resulting from release of the BC agent in the i^{th} year respectively.

The costs of a classical biological control project may be calculated by summing the cost of the base line research, the cost of foreign exploration, shipping, quarantine processing, mass rearing, field releases and post release evaluation. Often, pursuing academic interest may push the costs higher and should be astutely evaluated (Gutierrez *et al* 1999). Harris (1979) proposed that costs be measured in scientist years (SY), with one SY being the administrative and technical support costs for one scientist for one year.

In evaluating the costs of the project, all cost need to be included, regardless of whether the activity was successful or not (Ehler & Andrés 1983). Costs of a biological program should also include any perceived risks of the project. For example, an economic analysis of the proposed eradication of the boll weevil from the southern United States predicted that the eradication of the pest would cause the displacement of cotton from the area (Taylor & Lacewell 1977). In this scenario increased cotton production due to eradication of the pest would cause prices to fall forcing production to move to the west where it was more efficiently produced.

The environmental costs of biological control derived from the possible suppression or eradication of native species by introduced exotic natural enemies could be included in a benefit/cost analysis if some monetary value could be placed on them. However, such factors cannot be accurately priced in much the same way that increased cancer risks due to the use of some pesticides that cannot be priced (Howarth 1983, Turner 1985).

Economic benefits of naturally occurring biological control have been repeatedly demonstrated in cases where secondary pests become unmanageable as a result of overuse of chemical pesticides to control primary pests (Gutierrez *et al* 1999), for instance, most of the pests in cotton in San Joaquin valley of California (Burrows *et al* 1982), Australia (Room *et al* 1981) and Sudan (Von Arx *et al* 1983) were pesticide-induced. The cost of such control measures is the loss in cotton production as a result of population explosion by the pests.

Classical biological control has been found to give a higher benefit cost ratio compared to the other forms of biological control. Gutierrez *et al* (1999) compare the economic benefits of several successful classical biological control projects with the use of inundative releases of natural enemies in soybean for control of Mexican bean beetle and for greenhouse pests, and the sterile male eradication program. The release of resistant predatory mites in almonds gave a benefit-cost ratio of 100, and the screwworm eradication project was estimated to have given a benefit-cost ratio of 10

(Headley & Hoy 1987). Although impressive, these benefit-cost ratios on average are still not as high as those achieved using classical biological control.

Gutierrez (1999) summarized several classical biological control projects worldwide and noted their benefit/cost ratios. These estimates were overwhelming with the benefit-cost ratios ranging from close to zero to several thousands. For example, the BC ratio of the BC of the Citrophilus mealybug was 12,698 while that of the control of *Hypericum perforatum* in the USA was 11,464 (Huffaker *et al* 1976).

In the following section, some of the biological control programs whose benefits and costs have been analyzed are described. Tassan *et al* (1982) showed that the introduced natural enemies to control the scales on the ornamental ice plants that were used to landscape freeways potentially saved the California Department of Transportation ca. $ 20 million dollars in replanting costs on 2,428 ha. and ca. $ 450,000 annually saved for not using chemical control. The total cost of the project was $190,000 per year giving a benefit-cost ratio of 105. This was certainly a cost effective biological control project though the benefits were felt to be unsatisfactory. The study concluded that if suitable biological control agents did not exist, then the minimum long-term benefit would appear to be the replacement cost.

Bokonom-Ganta, *et al* (2002) carried out a socio-economic impact of biological control the exotic mango mealybug that was first observed in Benin in 1986. Natural enemies of the pest were released in subsequent years. Data was collected from the individual farmers and the response judged by their coherence and veracity to the questions asked and a degree of confidence ranking from 1 to5 attributed to all responses. Since the yield per mango tree depended on the age of the tree, the study considered only the mangoes at the normal full production periods. Under these conditions, the change in mango production was considered to be caused by the change in the density of the mango mealybug. The study noted that there were no changes on crop density, fertilizer use and mango varieties and thus their influence on yield had not changed. Based on the production estimates by the producers, the study demonstrated the negative impact of the pest on the plant production and the positive impact of the introduction of the natural enemies. The impact of the introduced insect pest was estimated by comparing the mean production by the same farmers at the height of the infestation with the average production of the last few years after the introduction and full establishment of the natural enemies. The benefits on the introduction of the natural enemies were considered to be the increase in mango yields while the costs were the cost of introduction, rearing and release of the natural enemies. The benefits and costs of the project was discounted at the rate of 10% per annum and accumulated over a period of 20 years.

The results of the study showed that the successful biological control of the mango mealybug had significant impact on fruit production, nutrition, health and social activities. It was estimated that the farmers gained an average of US$ 328 per year from the biological control program and US$ 50 million for the entire country. The present value of accrued benefits was estimated at US$ 531 million over a period of 20 years and cost estimated at US$ 3.66 million, which resulted in a benefit-cost ratio of 145:1.

The model gave a good estimate of the benefits and cost associated with the project. It however, never considered the temporal and spatial changes in host and natural enemy population that affected the magnitude of cost and benefits of the project. They assumed that the benefits could be averaged overtime and space is not valid since the natural enemies' population grew over time while that of the mealybug decreased.

Phytoseiulus persimilis Athias-Henriot was imported from Chile and Italy and were introduced on strawberry in 1960 in integration with pesticides (Trumble and Morse 1993). The need for biological control was aroused after the pests developed resistance to a variety of pesticides. Although the predaceous mites became established, the control levels were not economically significant. Researchers then attempted an inundative release programs. The release achieved increase in yields through substantial suppression of *T. urticae*, but the cost of releasing over 553,500 predaceous mites per hectare was not economically feasible. Attempts were then made to integrate chemicals and biological control. Economic evaluation of the pest control strategies was conducted using partial budgeting. Since the prices of strawberries varied on a weekly basis, 'Free on Board' values for weekly harvest were compiled from the Federal state market news reports. Costs of various control measures were also calculated and standardized to 1990 dollars at 4% inflation rate.

The results of the study indicated that the both chemical and biological control provided economically viable return for cost invested. The return from biological control was higher in 1990-1991 because of the early season buildup and higher population densities of the pest. Use of fenbutatin-oxide was found to be consistently incompatible with *P. persimilis.* In 1988-1989, the net benefits of using fenbutatin-oxide and *P. persimilis* was $2222, which was $4000 less than using fenbutatin-oxide only. The interaction was found to be antagonistic arising from the toxicity of fenbutatin-oxide to *P. persimilis.* In the following year, the combination treatment produced benefits about $1000 less than accumulation of individual treatments. However, another chemical for pest control, abamectin, was found to be compatible with *P. persimilis*. The accumulative net benefits from abamectin alone and *P. persimilis* alone were equal to the net benefits from the combination. The lack of antagonistic or synergistic effect from abamectin may have been as a result of the activity spectrum of the pesticide. The pesticides remained active in the leaves of strawberry plants only for some few days and do not kill the *P. urticae* eggs hence preserving food for *P. persimilis* (Lasota and Dybas 1991). It was therefore concluded that the efficiency of a biological control program depended on the management strategies and on other pest control measures adopted by farmers.

The water hyacinth had gained attention, as an ornamental plant because of its attractive purple colored flowers in most parts of the world. It was first observed in Benin in late 1970 but soon became a major weed in 1980s that hindered fishing, water transport and exploitation. Biological control was favored for controlling the weed as compared to other control measures; mechanical and chemical because of the less risks and costs that were involved when biological control was used (Cilliers 1991; Julien *et al* 1999). The biological control program started in December 1991 by the introduction of *N. eichhorniae,* a host-specific weevil. In March 1993, the *N. bruchi* was introduced and later in December 1993, the moth *Sameodes albiguttalis* (Warren) were introduced. De Groote *et al* (2000) carried out an economic impact assessment of the control measure in the region. He collected data through field surveys from household living near the Pacific Ocean.

The results indicated that the weed had impacted on agriculture, fishing and trading on fish, which had direct impact on household incomes. The per capita male income had dropped from $ 2,285 to $678 at the peak of infestation but the biological control had managed to restore the incomes to $1,290. In computing the benefit-cost ratio of the project, the study assumed that the effect of the biological control would be the same for all the years. The present value of the future stream of income for 20 years was estimated at $311 million, at a discounting rate of 10%. The present value of total cost that accrued to all institutions that were involved in the program was estimated at $2.07 million and gave a benefit-cost ratio of 149:1. The effect of the assumption was that the benefits were likely to be underestimated because the efficiency of the introduced pests was expected to increase with time.

2.3.5 Valuation of the Environment

Once the two parasitoids are established throughout all possible agro-climatic zones, they become part of the ecosystem. The BC agent may affect provision of services in the ecosystem in two main categories: their influence in survival of plants and animals and the provision of non-use value which include existence and optional values. In valuing the impact to the parasitoids, both direct and indirect effects are considered. Direct effects include all impacts to the production of food for human while indirect impacts will include the effects to plants and animals that are lower in the food chain that help sustain other animals we consume directly, for example, supporting birds we like watching.

In valuing environment, the philosophical, anthropocentric (emerical) and biocentric approaches provide the basis for attaching value to activities. The philosophical event seek to identify the ethics basis of value while empirical element aim at finding techniques for the measurement of value as defined according to a given philosophical notion (Goulder and Donald 2001). According to the anthropocentric approach, elements of nature are valuable insofar as they serve human beings. Within the anthropocentric approach is the utilitarian approach that maintains that natural things have value to the extent that they confer satisfaction to humans. The satisfaction may be directly or indirectly, consumptive and non-consumptive use values. The non-use values (passive use value) such as the satisfaction one enjoys by knowing an entity exists.

Under the Anthropocentric approach, values are generally attached through effects of the introduced parasitoids to animals that are taxonomically proximal to humans, rare, genetically unique or have unique importance in the ecosystem. Market prices are used when goods and services arising from the introduction of the natural enemies are sold in the market. The amount people were willing to pay (marginal value) may be imputed through field surveys and other indirect methods where no goods or services are commercialized.

Another approach, biocentric, appeals to certain intrinsic rights. They view species and other natural things as having intrinsic rights to exist and prosper independent of whether human beings derive satisfaction from them. Singer, (1975) argues that non-human animals have the basic rights to be spared of suffering that is deliberately caused by human beings. The Kautian justice approach argues that human beings should act in ways that can be universalized in the sense that it would seem appropriate for any human being in comparable situation. Under this approach, ones own stake ought to be removed before making a decision on the alternative to adopt for pest control.

2.4 Econometric Models

2.4.1 Production functions

Production functions are mathematical function that the expected output given a set of inputs using a given technology. The mathematical relationships gives the minimum input requirements needed to produce designated quantities of output, given available technology (Henderson and Quandt 1971). The farm is assumed to be making allocative choices concerning how much of each input factor to use, given the price of the factor and the technological determinants represented by the production function. By fitting a production function, an attempt is made to determine the feasible cost minimizing input combination. High cost of production could be a result of poor allocative or technical efficiency (Nyoro *et al* 2004).

In a general mathematical form, a production function can be expressed as:

$$Q = f(X_1,X_2..,X_n)$$

where: Q = quantity of output, $X_1,X_2,,X_n$ are the factor inputs (such as capital, labour, land or raw materials). The production function $Q = f(X_1,X_2)$ is said to be homogeneous of degree n, if given any positive constant k, $f(kX_1,kX_2) = knf(X_1,X_2)$. The function exhibits increasing returns when n > 1, and decreasing returns when n < 1. When it is homogeneous of degree 1, the function exhibits constant returns to scale.

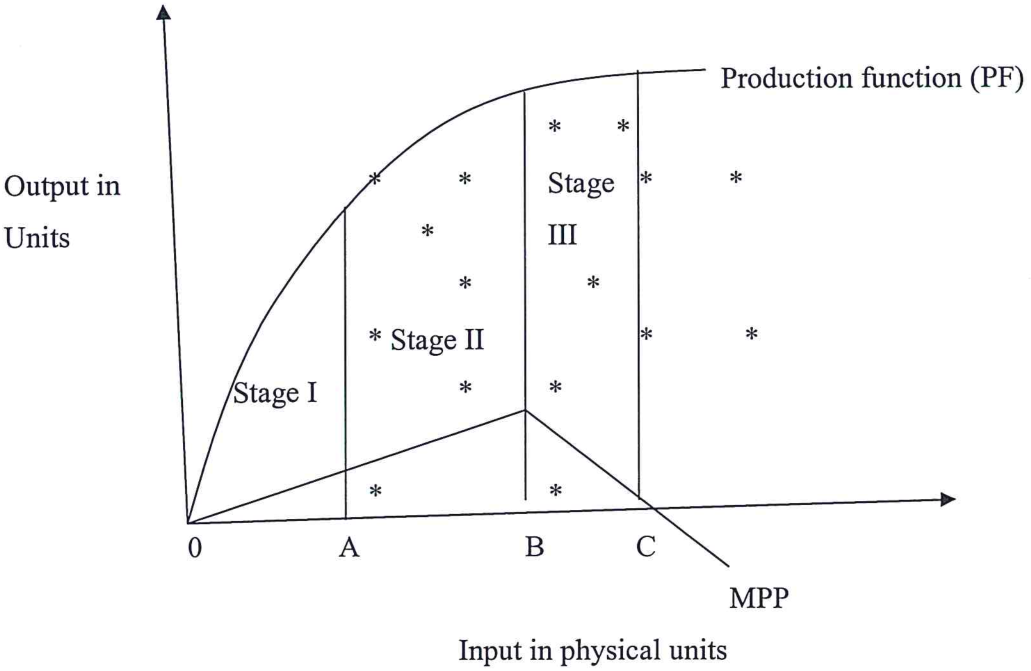

Figure 2.3: The relationship between marginal physical product and the production function

The production function can be divided into three stages. From the origin, 0 to point A (Figure 2.3) farmers use variable input with increasing efficiency, reaching a maximum at point B. As additional inputs are employed, output increases at an increasing rate. Both marginal physical product (MPP) and average physical product (APP) is rising. Farmers will attempt to work beyond this stage because the fixed inputs are underutilized. The inflection point A, defines the point of diminishing marginal returns, as can be seen from the declining MPP curve beyond point B. From point B to point C, the firm is experiencing positive but decreasing returns to variable inputs. In this stage, the employment of additional variable inputs increase the efficiency of fixed inputs but decrease the efficiency of variable inputs. In Stage three (beyond point C), too much variable input is being used relative to the available fixed inputs. The efficiency of variable inputs and that of the fixed inputs decline through out this stage. For products with low demand, the profit maximizing point may be found in stage one. At the boundary between stage 2 and stage 3, fixed input is being utilized most efficiently and short-run output is maximized.

The primary purpose of the production function is to address technical efficiency in production and the allocative efficiency in the use of factor inputs and the resulting distribution of income to those factors. A study carried out by Nyoro *et al* (2004) that compared the cost of maize production in Kenya and Uganda found out that farmers incurred a higher cost to produce maize in Kenya because of production inefficiency.

2.4.2 Efficiency of production

A production process is said to be inefficient when there exists another feasible process that, for any given output, uses less inputs. Some economists use the term X-efficiency to indicate that production processes tend to be inherently inefficient. The modeling and estimation of both technical and allocative efficiency of agricultural production is often motivated by the need for a more complete representation of economic efficiency of farmers implied by the economic theory of production (Alene and Hassan 2005). Increasing farm level production efficiency provides the single best means by which farmers increase maize production without additional conventional inputs and with existing technologies. Determining the efficiency of production in maize production systems and comparing technical and allocative efficiencies between farmers who apply pesticides and those that do not will help in determining whether the introduction of the parasitoid has achieved the desired goal of improving maize production. It will also provide a basis for deciding whether to improve efficiency or to develop new technologies to raise maize productivity. In addition, identifying important factors associated with an efficient production system through assessing potential sources of production inefficiency are essential for developing sustainable maize production systems. However, due to scale biases arising from imposing an input-oriented framework on the output-oriented stochastic production frontier results, the efficiency estimates derived from the conventional efficiency decomposition technique either overestimate or underestimate the true measures and thus may be inconsistent (Singh *et al* 2000).

2.4.3 Technical efficiency

Technical efficiency (TE) is the ability of the farmer to produce the maximum possible output using a set of farm resources and technologies. The technical efficiency of i^{th} farm is the proportion of the expected output when the farmer applies X_{ij} resources to produce maize and experiences technical inefficiency of μ_i to the yield expected when the farmer uses X_{ij} but $\mu_i = 0$. This can be represented as follows: $TE= E(Y_i|\mu_i, X_{ij})/E(Y_i^*|\mu_i=0, X_{ij})$ where μ_i is technical efficiency coefficient, E refers to expected.

Several techniques have been developed for the study of technical efficiency of production that can broadly be divided into non-parametric linear programming technique and parametric stochastic frontier techniques. Farrell (1957) first proposed a non-parametric mathematical programming approach for estimation of a production or cost frontier. Using this technique, the error term *(e)* is assumed to capture the level of technical inefficiency. The frontier production function is obtained by maximizing output subject to the technical inefficiency coefficients (μ_s) being positive. The shortcoming of this procedure is that it does not take into consideration any random process in production and assumes all deviation from the potential output results from inefficiency.

Aigner, Lovell and Schmidt (1977), and Meeused and Van den Broeck (1977) independently proposed a general stochastic production function, which had the error term with two components, one to account for random effects, V_i and another for technical inefficiency, μ_i expressed as $Y=\beta_jX_{ij}+(V_i-\mu_i)$ for $i=1,2,\ldots,n$ farms, β_j is a vector of parameters to be estimated associated with j inputs, V_i is random variable normally distributed with equal variance $N(0,\delta_V^2)$ and $\mu_i = (\mu_i exp(-\eta(t-T)))$, where the μ_i are non-negative random variables which are assumed to account for technical inefficiency in production and are assumed to be iid and truncations at zero of the $N(\mu, \sigma_U^2)$ distribution; η is a parameter to be estimated; and the panel of data need not be complete (i.e. accommodate unbalanced panel data). Using parameterization of

Battese and Corra (1977), $\sigma^2 = \sigma_V^2 + \sigma_U^2$ and $\gamma = \sigma_U^2/(\sigma_V^2 + \sigma_U^2)$, the parameter, γ, must lie between 0 and 1.

Imposition of one or more restrictions will alter the function as follows:

i) Setting η to zero provides the time-invariant model.

ii) Setting μ equal to zero reduces the model to a deterministic model where all the error term is assumed to be equal to the farm technical inefficiency.

iii) Setting $T=1$, the model becomes a cross-sectional data.

The stochastic frontier can be estimated with either a one-step or a two-step process. Using the two-step procedure the production function is first estimated using a set of variables hypothesized to influence farm production and the resultant error term is used as a variable during the second regression. The problem with the two-stage procedure is the inconsistency in the assumptions about the distribution of the inefficiencies. In the first stage, the inefficiencies are assumed to be independently and identically distributed (iid) in order to estimate their values. However, in the second stage, the estimated inefficiencies are assumed to be a function of a number of farm- specific factors, and hence are not identically distributed. This problem is overcome using estimation procedure proposed by Battese and Coelli, (1995) whereby the random factor and an estimate of technical efficiency are estimated through a one-stage estimation procedure.

This problem was addressed by Kumbhakar, Ghosh and McGukin (1991) and Reifschneider and Stevenson (1991) who propose stochastic frontier models in which the inefficiency effects are expressed as an explicit function of a vector of firm-specific variables and a random error. Battese and Coelli (1995) propose a model which is equivalent to the Kumbhakar, Ghosh and McGukin (1991) specification, with the exceptions that allocative efficiency is imposed, the first-order profit maximising conditions removed, and panel data is permitted. The Battese and Coelli (1995) model specification may be expressed as:

$Y_{it} = x_{it}\beta + (V_{it} - \mu_{it}) \quad ,i=1,...,N,\ t=1,...,T,$

where Y_{it}, x_{it}, and β are as defined earlier; the V_{it} are random variables which are assumed to be iid. $N(0, \sigma_V^2)$, and independent of the μ_{it} which are non-negative random variables which are assumed to account for technical inefficiency in production and are assumed to be independently distributed as truncations at zero of the $N(m_{it}, \sigma_{\mu}^{2})$ distribution;

$m_{it} = z_{it}\delta$, where z_{it} is a $p \times 1$ vector of variables which may influence the efficiency of a firm; and δ is an $1 \times p$ vector of parameters to be estimated. We once again use the parameterisation from Battese and Corra (1977), replacing σ_V^2 and σ_μ^2 with $\sigma^2 = \sigma_V^2 + \sigma_\mu^2$ and $\gamma = \sigma_\mu^2/(\sigma_V^2 + \sigma_\mu^2)$.

Before fitting a production inefficiency model, one can also test whether any form of stochastic frontier production function is required at all by testing the significance of the γ parameter. If the null hypothesis, that γ equals zero, is accepted, this would indicate that σ_μ^2 is zero and hence that the μ_{it} term should be removed from the model, leaving a specification with parameters that can be consistently estimated using ordinary least squares (OLS).

The frontier analysis has been used to compare different technologies and practices. Khairo and Battese (2005) used the frontier analysis to compare TE of farmers within and outside a new agricultural extension service in Ethiopia while Sharma and Leung (2000) compared TE between semi-intensive/intensive and extensive carp producers in India. Alene and Hassan (2005) compared TE between farmers planting traditional and hybrid maize in Eastern Ethiopia. Roudaut (2006) compared technical efficiencies and efficiency levels net of business environment influences among the manufacturing firms in Côte d'Ivoire. Audibert (1997) used a stochastic frontier production function to measure technical efficiency of paddy farmers from 29 villages in Mali using data from an economic survey conducted during two consecutive agricultural seasons.

2.4.4 Allocative efficiency

For optimal resource allocation in any production process, the inputs should be applied at the point where the marginal value product (MVP) is equal to its marginal factor cost (MFC). It is a static microeconomic concept that concentrates on identifying disequilibria that might appear in the utilization of existing factors of production given technology and input prices. Given the assumption that the farmers' objective is to maximize net earnings over the cost of X_{ij}, the farmers would increase net revenue by allocating more resource in production if $MVP_{x_{ij}} > MFC_{x_{ij}}$, and will decrease their net revenue if they allocate more resources to maize production when $MVP_{x_{ij}} < MFC_{x_{ij}}$. Therefore, for efficiency in resource allocation to exist, the *MVP* of resource X_{ij}, should equal its *MFC*, which in a competitive market is also equal to its price. At the point where $MVP_{x_{ij}} = MFC_{x_{ij}}$, there is no way farmers can increase or decrease resource use level without reducing the net returns from using the resource. The marginal physical productivity of X_j (MPP_{x_j}) can be obtained by differentiating the production function with respect to X_j, thus, $MPP_{x_j} = \partial Y / \partial X_j$. Production elasticity associated with a resource X_j is given by $\beta_j = \frac{\partial Y}{\partial X_j} \times \frac{\bar{X}_j}{\bar{Y}} = \frac{MPP_{x_j}}{APP_{x_j}}$ where $\bar{Y}$ is the mean Y_i and $\bar{X}_j$ is mean X_j. APP_{x_j} is the average physical productivity. Manipulation of this equation $MPP_{x_j} = \beta_j \times \frac{\bar{Y}}{\bar{X}_j}$. MPP_{x_j} multiplied by the price of output gives the MVP_{x_j}. If farmers allocate resources efficiently then $MVP_{x_j} - MFC_{x_j} = 0$.

2.2.5 Damage control production function

The pesticides have been included in the production function as a conventional 'output increasing' input (Thirtle and Beyers 2003; Qaim *et al* 2003; Qaim and Zilberman 2003) or yield loss abatement input (Huang *et al* 2002; Shankar and Thirtle 2005). The use of chemical pesticides does not increase yields per se but instead its primary role is to abate damage that is likely to be caused by the attack of the stemborers. In contrast, the use of inputs, such as fertilizer and labor, contribute by directly increasing yields and therefore, we examine pesticides as damage abatement input. By including pesticide as a yield increasing output such as in the Cobb-Douglas function one commits specification errors that lead to biased estimates and the marginal product of the damage control agents is overestimated (Lichtenberg and Zilberman 1986).

For a production function where pesticide is used to control pests, $Y = f(X)G(Z)$, the term, $G(Z)$, is a damage abatement function that is a function of the quantity of pesticide used, Z. The abatement function possesses the properties of a cumulative probability distribution, defined on the interval of [0 1]. When $G(Z) = 1$, it means that the pesticides have a complete abatement of crop yield losses due to stemborers and when $G(Z) = 0$ it means that the maize crop was completely destroyed by stemborers. The proportion of the potential yield abated will depend on the efficacy of the pesticide used and the quantity applied. In estimating the yield abatement function, the logistic, Weibull and exponential functional forms are often used. The exponential functional form is chosen because of its ease of interpretation and satisfactorily fit the data and is most appropriate for pesticides (Moffit 1992).

2.2.6 Correcting for endogeniety and selection bias

Farmers often applied stemborer control measures impetuously in response to a high infestation (Kipkoech *et al* 2006). There could be a systematic relationship between stemborer attack, pesticide use and maize output. The covariance of damage variable, pesticide, and the residual of the maize output function is thus, not zero posing the problem of endogeniety. Also, there are some unobserved farmers and farm attributes that are likely to be correlated with both farm productivity and use of farm inputs. Farmers who are more productive when they apply pesticides are also likely to be more productive when they do not control the pest. There could also the problem that many farmers do not apply pesticides but if they apply pesticides, they are also likely to apply more of other inputs and better manage their farms, thus, get better yields. The decision to apply pesticides may be influenced by some intrinsic farmer characteristics that are not obviously observable. Establishing the productivity of pesticides using a production function that does not consider endogeniety and selection bias could result in biased estimates.

The Heckman (1979) two-stage estimation procedure for a continuous decision variable can be used to incorporate the impact of pest control on yields including the decision to use pesticides. This method assumes that the decision to use pesticides and other inputs are made simultaneously. The model will first compute a selection bias control factor, lambda (λ) that reflects the effect of all the unmeasured characteristics.

In the second stage, the program uses the Lambda, in computing the coefficients of the production function. In this way, the coefficients of the inputs used in the analysis are free from the inherent farmer characteristics that influenced his/her decision to use pesticides.

2.4.7 Choosing appropriate functional form

The functional form for the production functions can take several forms; linear, quadratic, exponential, logistic etc. The most common functional forms used in production function are the constant elasticity of substitution production function (CES) which is a generalized form of the Cobb-Douglas function, and the quadratic production function which is a specific type of additive function. No single functional form can be used to characterize agricultural production under all environmental conditions (Heady and Dillon 1969). Whatever functional form chosen automatically imposed certain restrictions with respect to the relationship being studied. The functional form chosen to represent any production situation will depend on the ease with which important economic parameters can be derived and interpreted and whether the functional form considered is considered robust (Yotopoulu 1969; Heady and Dillon 1969; Wambia 1979). The functional form should generally have had acceptance with other users (Heady and Dillon 1969). The production function form chosen should also allow use of few parameters that avoids convergence problems which occur in estimation process when there are large numbers of independent variables (Nigel and Bardsley 1987; Dawson and Lingard 1989).

The Cobb-Douglas and the nested transcendental logarithmic (translog) production functional forms are the common functional forms used to study production efficiency that meets the above criteria. The log of likelihood ratio that approximates the Chi-square distribution with a degrees of freedom equal to number of parameter restrictions is used to choose among nested models (Norsworthy and Malmquist 1983). This ratio is the maximum value of the likelihood function for restricted production function to the maximum value of the likelihood function for the unrestricted one. The hypotheses tested are: $H0 : P1's = P2's$ and $H1 : P1's \neq P2's$. Where, $H0$ and $H1$ represent the null and the alternative hypothesis respectively. $P1's$ and $P2's$ represent parameter estimates from unrestricted and restricted model respectively. The test statistic is based on minus twice the logarithm of the likelihood ratio, *-2Ln (R-U),* where, *Ln R* and *Ln U* represent restricted and unrestricted log of likelihood production function respectively. To choose among nested model we calculate Chi-square. Then, if the computed Chi-square is less than tabulated one, we do not reject the null hypothesis and we conclude that restricted model is appropriate to our data.

2.5 Computer software for estimating production efficiency

The computer program, FRONTIER Version 4.1, can be used to obtain maximum likelihood estimates of a subset of the stochastic frontier production (Battese and Coelli 1996). The program can accommodate panel data; time-varying and invariant efficiencies; cost and production functions; half-normal and truncated normal distributions; and functional forms which have a dependent variable in logged or original units. However, the program cannot accommodate exponential or gamma distributions, nor can it estimate systems of equations.

2.6 Remote Sensing

Advance in the Geographical Information System (GIS) and Global Positioning System (GPS) provides tools for the application of information from the multi-spectral images in management problems. Remote sensing is the ability to measure properties of an object without touching it. Brown and Steckler (1995) developed a method to use digitized color-infrared photographs to classify weeds in a no-till cornfield. The classified data were placed in a GIS, and a decision support system was then used to determine the appropriate herbicide and amount to apply. Penuelas *et al* (1995) used reflectance measurements to assess mite effects on apple trees. Powdery mildew has also shown to be detectable with reflectance measurements in the visible portion of the spectrum (Lorenzen and Jensen 1989). The ability to detect and map insect damage with remotely sensed imagery implies that methods can be developed to determine the distribution of stemborers. Remote sensing can utilize multispectral images of vegetated fields to determine within-field management system (Yang and Anderson 1996) that can be explored for used in studying stemborers-parasitoids-environmental interaction. Unlike in the countries where remote sensing has been used, maize growing areas along the coast are small and scattered, which require the development of highly specific spectrum that is expensive. Such spectra have not been developed for such production systems as in Kenya and therefore remote sensing could not be used in the present study.

CHAPTER THREE

3.0 METHODOLOGY

3.1 Study areas, sampling and data collection

3.1.1 Benefits and cost of release of *Chilo partellus* for the control of cereal stemborers in Kenya

The introduced parasitoid, *C. flavipes* spread to 4 agro-ecological zones that fall between the low-land tropics and the dry transitional zones (Zhou & Overholt 2001). These zones experience a bi-modal rainfall pattern, with the long rains from April to June and the short rains from October to December. The area includes 26 administrative districts of Kenya covering 29% of total area under maize production (De Groote *et al* 2003a). Farmers in these areas are essentially subsistence maize producers. All four zones were included in assessing the benefits and costs of release of the parasitoid in Kenya (Figure 3.1).

Primary data was obtained through administration of a questionnaire to randomly selected farmers after the harvest of 2004 long rains. Five districts[1] were selected randomly from the list of districts, where the introduced parasitoid had spread to as: Kwale and Kilifi in coastal Kenya, Machakos and Makueni in Eastern Kenya, and Siaya in western Kenya. In each of the districts 2 locations and then two sub-locations per location were randomly selected. The sub-locations chosen were Mpongwe and Perani in Kwale, Chonyi and Bamba in Kilifi, Masii and Tawa in Machakos, Yeekanka and Kimundu in Makueni, and Sega and Boro in Siaya. A list of farmers in each sub-location was then compiled and 15 farmers were selected randomly from the list to give a sample size of 300 farmers.

The primary data collected were input prices, maize yields (90 kg bags), maize price (per 2 kg tin), stemborer infestation scored on a scale of 1-5 (Highest infestation 1 and lowest 5), maize quality indicator (i.e. grain rot on a scale of 1-5; highest rotting 5, lowest rotting 1), causes of low yields, farmers' awareness of the biological control program and their view of the impact of the parasitoid. Grain rot levels were

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[1] The lowest administrative unit in Kenya is the sub-location that are grouped to form locations. A group of locations and division form a divisions and districts, respectively. Districts are grouped to make a province that is the largest administrative unit before the country.

estimated as the proportion of discoloured maize. Stemborer density and parasitization rates over time were obtained from ICIPE's biological control project's data bank at the headquarters in Nairobi. District maize production levels and the area allocated to maize production were obtained from districts' annual reports.

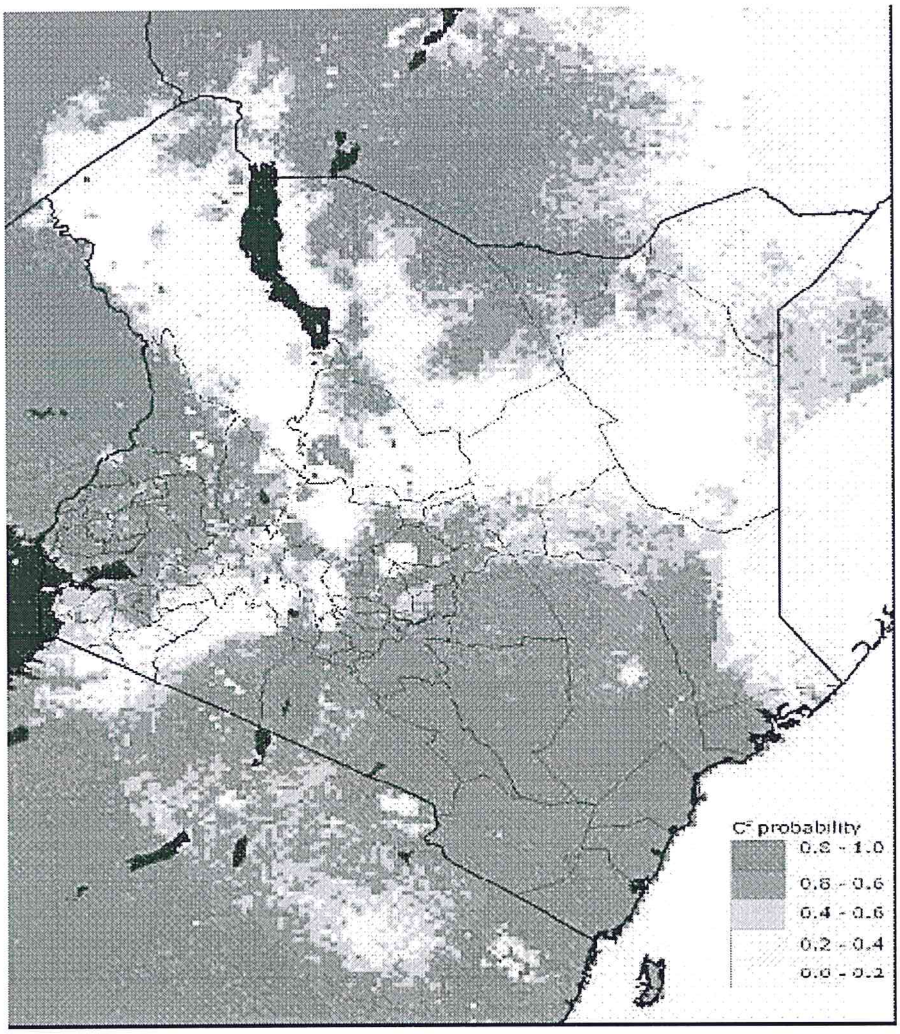

Figure 3.1: Spread of *C.flavipes* in Kenya by 2005

3.1.2 Assessing yield and production efficiency implications of relying on parasitoids for the control of stemborers

This study was carried out in two districts in the low potential areas of coastal Kenya (Kwale and Kilifi) that were purposely selected because the parasitoid was first released in the districts. A survey was conducted in 2006 and covered the long rains maize production seasons (April-September) of 2004 and 2005, 12 and 13 years after release of the introduced parasitoid, in the two district. Using a multi-stage stratified random sampling procedure, five administrative locations were chosen in each of two districts namely Maluvaga, Mpongwe, Msambweni, Ramisi and Tiwi in Kwale (south coast) and Bahari, Gandini, Kaloleni, Mazeras and Vipingo in Kilifi (north coast).

Data on inputs used in maize production, varieties grown and the demographic characteristics of the respondent were collected. Because of the hypotheses that farmers with the same characteristics and operating with the same resource base operate at the same efficiency level and obtain identical yields, only farmers who planted less that two ha of maize and had no farm machinery formed the sampling frame for each of the two categories. The pest control methods farmers employed in the area were use of pesticides and the sprinkling of soil or ash in the whorl. Some farmers never made any effort to control stemborers and were interchangeable referred in this thesis as the category not applying pesticides or relying on biological control. Data was collected from 264 respondents grouped into four categories, two groups from those applying pesticides each for 2004 and 2005 long rains, and another two categories from those who never made an effort to control stemborers thereby unconsciously relying on BC for the two years.

Out of the 264 respondents, 56 and 54 of the respondents applied pesticides while 76 and 78 respondents did not apply pesticides in 2004 and 2005, respectively. The distribution does not represent the proportion of farmers using either of the strategy since two sampling frames, one for farmers using pesticides and the other for farmers relying on BC was first made from where the sample units where randomly selected. The construction of separate sampling frames for the two categories was appropriate because of the *a priori* knowledge concerning the low adoption of pesticides of about 13% (Kipkoech *et al* 2006). Complete random sampling would obtain a sufficient number of respondents only if the sample size was very high while in our case it was not possible to obtain such huge sample size because of the constraints of funds and time.

Data for the two years were pooled together in calculating the overall farm efficiency. The mean maize yield of farmers who applied pesticides and those who did not, and the maize yield difference among farmers categorized according to their age, years of experience, input used in maize production and the difference between the marginal value products (*MVPs)* and marginal factor costs (*MFCs),* was compared using t-test. Pearson correlation coefficient was computed to determine the relationship between variables. Although farmers reported to use hybrid seed, it was discovered that whenever the seed bought was not enough, farmers would mix the certified seed with grains preserved from the previous season. Farmers who used more than half of hybrid seed were taken to be hybrid users. Inspection of farmers' fields also revealed that most of the pesticides used by farmers were not always effective. To ensure that we got representation of farmers who applied adequate quantities of pesticides, farmers who applied pesticides at less than the manufacturers' recommended rates were excluded from the study. These farmers could not be included in the biological control group either because of the toxicity of chemicals to natural enemies (Cugala *et al* 2006; Kfir 2002), which might have lead to an increase in pest densities.

3.1.3 *Ex ante* economic evaluation of biological control in the Kenyan highlands

This study was carried out in the the Kenyan highlands (Figure 3.2). In order to determine the initial stemborer density, plants were randomly sampled in July and December 2004, and July 2005 referred in this thesis as season 1, 2 and 3 respectively to establish the initial stemborer density in the area. During the surveys 10-15 plants at the grain filling stage were chosen at random from farms 1 km away from each other in all the four directions of the compass from Wundanyi urban center.

The high potential maize growing areas experience a bi-modal rainfall pattern of over 2000 mm per annum. Fertile volcanic soils make the area highly productive. Both small-scale and large-scale intensive and extensive farmer are found in the area.

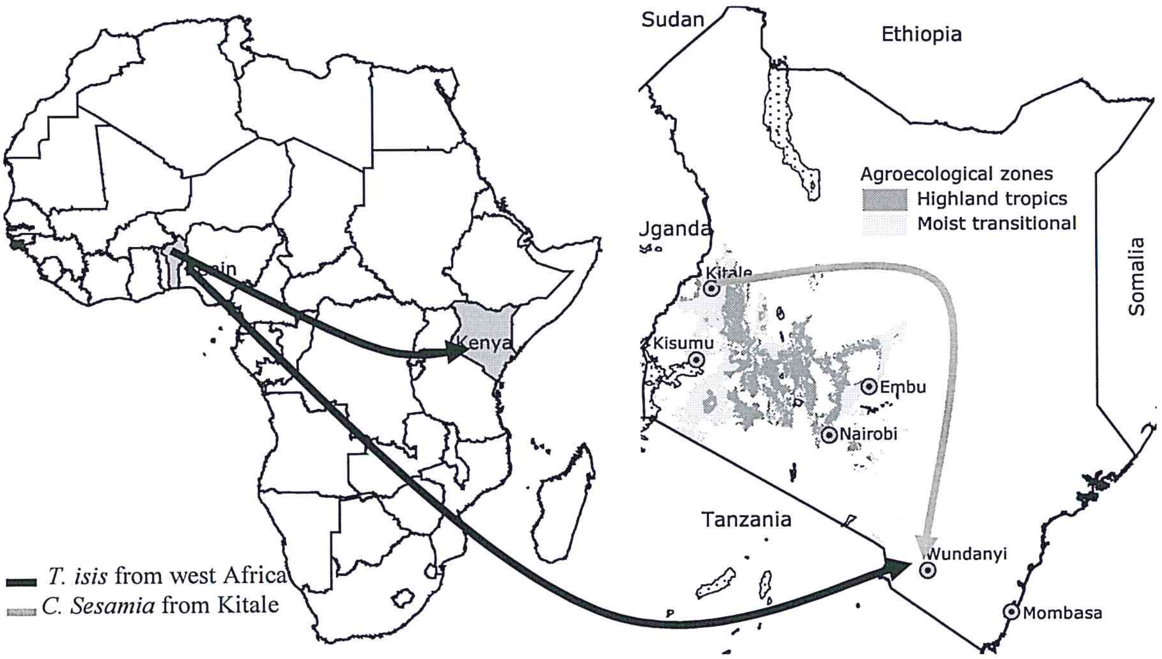

Figure 3.2: Introduction of *Telenomus isis* and *Cotesia sesamia* to Taita Hills

The socio-economic data were collected from the Taita hills (Latitude 3°25 and 38°20 longitude), part of Taita-Taveta district. The area is surrounded by dry savannah grassland lowlands of an elevation of about 700 m above sea level (asl) in all directions with its highest peak being 2230 m asl. The area receives annual rainfall of about 1500 mm and has good soils and an extensive network of rivers originating from the numerous hills. Farmers whose farms extend to the river valleys grew maize throughout the year and practiced semi-intensive agriculture.

The Taita-Taveta district is divided into six administrative divisions, i.e., Wundanyi, Mwatate, Voi, Tausa, Taveta and Mwambiri. Voi, Tausa and parts of Mwatate are in the low altitude zones where *B. fusca* does not occur and were therefore excluded from this study. From the remaining three divisions, a list of all locations was made, and two locations randomly selected per division. Two sub-locations were randomly selected per location. From the chosen sub-locations a list of all farmers was made and a sample of 25 farmers was randomly selected using the systematic random sampling procedure to give a sample size of 300 farmers. The data was collected through administration of questionnaire to assess the maize output, input use, farm and farmer characteristics and the farming system.

3.2 Analytical framework for assessing benefits and costs of biological control program

Technological change accounts for growth in output that is not accounted for by growth in physical input use, reflected as a shift of the production function. The diagrammatic representation in Figure 3.3 shows the theoretical maize production system in the Kenyan Highlands. Y is the maize output while X represents a basket of inputs used to produce maize. TPP is the total physical product. The curve TPP_1 shows the maximum total physical product of an average farm in absence of the stemborer problem, given an input level X, using the available technology and the prevailing weather conditions. However, farmers are only able to achieve Y_3 maize in any production year and operate at the production function TPP_3. The difference in yield ($Y_1 - Y_3$) denoted by w is lost to stemborers and will vary with stemborer density during any production season. Unless farming technologies change, farmers will always operate on Y_3 production function producing varying quantities of maize depending on the level of inputs used. The introduction of the parasitoid *C. flavipes* would reduce a proportion of the pest and thereby of the yield loss caused by it. This is a change in technology that causes a shift in the production function to TPP_2.

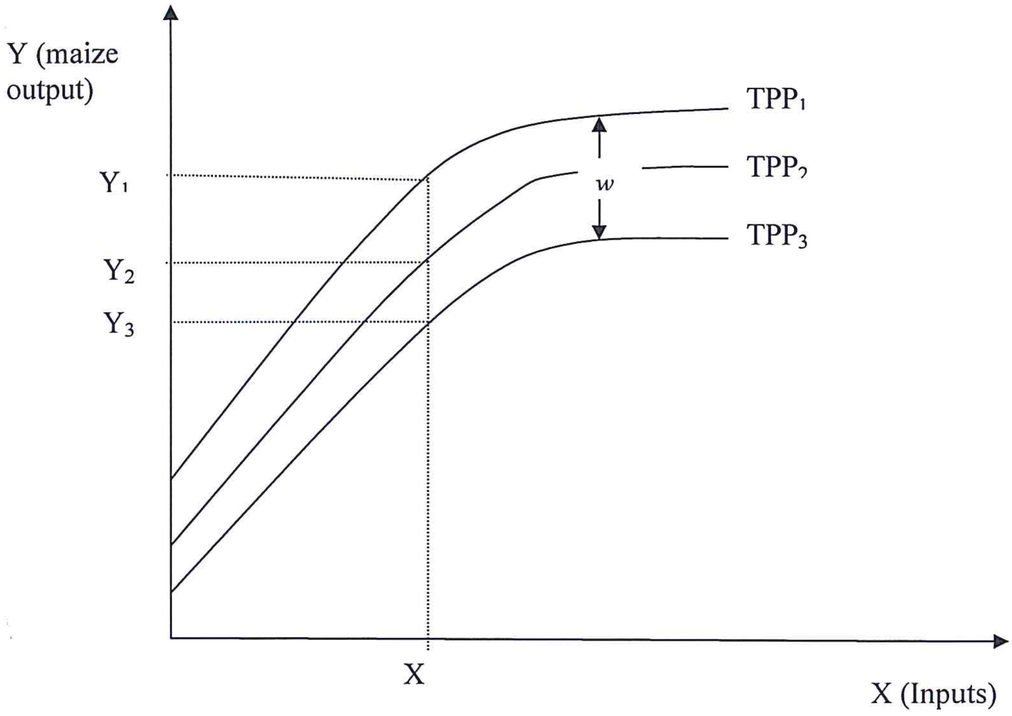

Figure 3.3: Impact of biological control on maize production

The reduction of pest densities as a result of introduction of the BC agent and thus, the maize yield loss abated, can be assessed directly through yield loss assessments in experimental fields (FAO 1995) and via farmers' interviews (Macharia *et al* 2005). In this study, it was not possible to categorize farmers into users and non-users of BC in order to determine the impact of the parasitoid on maize yield amongst the farmers because the BC agent spread to all maize fields. Farmers also could not recall pest densities and maize yields in the past 13 years and the baseline data in terms of yield loss attributed to stemborers at the start of the project and corresponding temporal changes were not available. This study therefore had to determine how the pest situation would have been without the parasitoid using pest and parasitoid models based on long-term data from the release areas and compare the associated density dependant yield losses with actual yield losses. Yield loss abated was assessed using established pest density-yield loss functions. Determining benefits (yield loss abated) of the project gives a general indication of the attractiveness of the technology to the farmers while evaluation of benefits and costs incurred by the project would help to establish the returns to investment by ICIPE and the funding agency.

In order to carry out the economic analysis based on this framework, several assumptions were made. It was assumed that technological changes do not occur during the period under analysis. The high poverty level was assumed to continue limiting farmers' ability to adopt purchased inputs. This was because resource constraints play an important role in explaining non-participation in markets for inputs by farmers (Omamo 1998). Because the ability of poor farmers to invest in soil nutrient amendments is limited (Freeman & Coe 2002), the low rate of fertilizer inputs use in the region (Wekesa *et al* 2003) was assumed to maintain and not to improve fertility levels during the period after introduction of the biological control. Other factors outside this model such as improvement of farming skills arising from increasing farming experience were assumed to improve yield by 10 % every 10 years.

Under these assumptions, it was possible to compute the change in maize yield resulting from change in stemborer density. Increases in the investment in the agricultural sector that influence the efficacy of farmer education, access to credit, inputs and markets may affect the validity of these assumptions. However, with the continued reduction in investment in agriculture by the government, who is a regulator of the agricultural sector in Kenya, the assumptions were expected to hold over the study period. Given that soil fertility remains constant, the biological control program will therefore lead to a linear proportion of yield loss abatement, thus, farmers will move to a higher production function TPP_2 from their original production function TPP_3. The magnitude of the shift in the production function will depend on the percentage pest control achieved by the parasitoid.

It was hypothesized that the density of total stemborers at time t depended on the density during the previous period ($t-1$), parasitism during the current period (t) and the impact of time on stemborer-parasitoid association captured by T starting with the long rains of 1995 ($T = 1$), when the parasitoid showed to have a significant impact on stemborer density. For the parasitoid model, the regressants were the number of seasons elapsed since introduction of *C. flavipes* (T), stemborer density (D_{t-1}) and parasitism during the previous season (P_{t-1}). The general host-parasitoid interaction models used to predict density of stemborers (D_t)= $\alpha + aD_{(t-1)} + bP_t + cT$ while parasitism by *C. flavipes* (P_t) $= \beta + dP_{(t-1)} + eD_{(t-1)} + fT$, where D_t is the mean density of the stemborer complex during season t; P_t is the percentage parasitism of stemborers by *C. flavipes* at t; a, b and c, are slopes of the stemborer model while d, e and f are the slopes of the parasitism model estimated using the step-wise regression procedure; α and β are the intercept of stemborer and parasitism models; parameter c and f represented the time dependence of stemborer population dynamics and parasitoid impact, while a, d and e represented the time-delayed stemborer and parasitoid impacts. Stemborer density without parasitism (D_{nt}) was obtained by setting parasitism at zero in the pest model.

The linear models were used to predict P_t, D_t and D_{nt} within the data range of 10 years starting in 1995 and results extrapolated to 20 years. The density and parasitism levels for each year were the projected average for the short (April-June) and long (October-December) seasons of that year. The yield loss abated attributed to stemborer control was computed based on the borer density reduction attributed to parasitism. A larval density of 2 per plant lead to a grain yield loss of about 35% while 6 stemborers cause about 90% loss (Usua 1968; Mailu 1997). The level of yield loss was obtained by constructing a curve for the percentage yield loss against stemborer densities. With predicted D_t and D_{nt}, the actual and expected output loss were obtained from the curve as $f(D_t)$ and $f(D_{nt})$ respectively. The maize output loss abated attributed to the parasitoid was therefore $f(D_{nt})-f(D_t)$ denoted by w.

3.2.1 Other benefits of the project

Apart from the yield loss abated, there were several other benefits of the project. Yield loss abatement improved food security and led to increase in caloric intake by households as a results of increased maize output in the regions and the reduction in food poisoning resulting from reduced aflatoxins contamination of ears damaged by stemborers (Sétamou *et al* 1998; Tuner *et al* 2005). Increase in farm income was also expected to result in possible resource reallocation to farming enterprises to reflect the change in relative profitability of maize in farming households. However, at this stage, the information required to price these benefits was missing, thus, in this study, the benefits were confined to yield losses abated.

3.2.2 Project Costs

Total project costs as incurred by ICIPE, were evaluated to determine the actual costs of the biological control programme. Project costs include cost of scientists, administrative and technical costs, baseline research, foreign exploration, shipping, quarantine processing, mass rearing, field releases, post release evaluation and the cost of acquiring equipment and vehicles necessary for project activities. The costs of supporting graduate training programs were excluded.

3.3 Analytical framework for assessing the maize production efficiency

With a given set of productive resources X, farmers allocate the resources to production alternatives in varying quantities to best meet household objectives. In maize production, there is an optimal input combination mix, X^*, that optimizes farmers' maize output, Y^*. Farmers using the same technologies and input levels and who have the same farm size and socio-economic characteristics were expected to obtain identical yields and operate at the same efficiency level. However, farmers may combine X inefficiently such that $Y^* > Y_i$, where Y_i is maize output for farmer i resulting from the farmer's resource combination mix, X_{ij} for all $j = 1, 2, .., J$, farming resources used by farmer i. The deviation of farmer's output from the optimal output level (Y^*) can be decomposed into reduction of output as a result of factors beyond farmers control or reduction in output resulting from production inefficiency. In comparing maize outputs among the categories, care was taken to ensure that farmers sampled had the same resource base by sampling farmers who planted not more than two ha of maize and had no farm machinery. Technical and allocative efficiency of farmers applying pesticides was compared with that of farmers who did not.

3.3.1 Empirical efficiency model

A range of functional forms for the stochastic production function frontier are available, with the most frequently used being a translog function that is a second order log-linear form. This is a relatively flexible functional form, as it does not impose assumptions about constant elasticities of production nor elasticities of substitution between inputs, which allows the data to indicate the actual curvature of the function, rather than imposing *a priori* assumptions.

A following stochastic time variant technical effects transcendental production function was estimated:

(4.1) $$LnY_i = \beta_o + \sum_{j=1}^{10} \beta_j \ln X_{ij} + e_i$$ where all variables are as defined above. The farm inputs ($X_j s$) used in the model were dummy variable for use of hybrid seed (1 = yes, 0 = no), non-harvest labor used in all farm operation to produce maize in man-days, dummy for pesticide use (1=yes, 0=no), land used to produce maize in hectares, quantity of inorganic fertilizer used in kg, quantity of organic fertilizer used in kg, dummy for presence of grasses surrounding maize fields (1= yes, 0=no) and the multiplicative interaction terms between land and labor, land and manure and labor and manure.

The inefficiency model is estimated from the equation

(4.2) $$\mu_i = \delta_0 + \sum_{m=1}^{7} \delta_m Z_{im}$$ μ_i is the i^{th} farm inefficiency coefficient, δ_m are parameters to be estimated. The inefficiency model variables Z_{im} are stemborer incidence, number of companion crops intercropped with maize, age of household head, years in school of the household head, dummy for availability of off-farm income (1=yes, 0=no), farming experience in years and the total household farm size in hectares (Table 1). According to definition of equation (4.2) an independent variable included in the model associated with negative (positive) coefficient will have a positive (negative) impact on technical efficiency.

The stochastic production frontier and technical efficiency model were estimated using the one stage estimation procedure in the FRONTIER version 4.1 computer software, which also estimates the variance parameter of the likelihood function in terms of $\sigma^2 = \sigma^2_u + \sigma^2_v$ and $\gamma = \sigma^2_u/\sigma^2$. It was also important to test the null hypothesis that technical inefficiency is not present i.e. $\gamma = \delta_0 = \delta_1 = \ldots = \delta_{10} = 0$ and whether the model fitted was appropriate using the generalized likelihood-ratio statistic, λ, given by $\lambda = 2\{Ln[L(H_0)]-Ln[L(H_1)]\}$ where Ln is the natural log, $L(H_0)$ and $L(H_1)$ denote the values of likelihood function under the null (H_0) and alternative (H_1) hypotheses respectively. The statistic, λ has approximately Chi-square distribution while γ has a mixed Chi-square distribution (Coelli 1995).

3.4 Damage control production function

Following Lichtenberg and Zilberman (1986), a damage abatement function was incorporated into the traditional models of agricultural production. The nature of crop yield, *Y*, was specified as a function of both standard inputs, *X*, and damage control measure, Z, as:

$$(4.3) \qquad Y_j = \alpha \prod\nolimits_1^n X_{ij}^{\beta_i} . \exp(Z_j^m)$$

Y is output, X the vector of input used, α is the intercept, $\beta_i s$ are slopes of the X inputs, m is the slope of Z (damage variable). j refers to the subscript of j^{th} farm, i is the subscript of i^{th} input, for all inputs $i=1,2,\ldots,n$. $exp(Z^m)$ is the damage abatement function with Z being quantity of pesticide and m being the coefficient of pesticides. Taking natural logarithms on both sides of equation (4.3) gives:

$$(4.4) \qquad Ln\ Y_j = Ln\ \alpha_j + \sum_{i=1}^{n} \beta_j \ln X_{ij} + mZ_j + e$$

e is the random disturbance term.

The instrumental Variable (IV) approach was used to correct for endogeniety by developing an instrument for pesticide application that was correlated with actual pesticide use but did not affect output except through its impact on pesticides. A set of variables that could influence the use of pesticides was used to explain pesticide use. The predicted value of the pesticide use was then used in the estimation of model (4.4). To compute the IV, we hypothesize that a number variables –age of the farmer, education (measured in years of schooling attained), availability of off-farm income and the farmer's perception of the severity of his/her farm's pest infestation problem (measured as the per cent of the crop that the farmer believed would have been lost if he had not applied pesticides).

The empirical model estimated incorporating pesticides as a damage control variable is given in equation (4.4). The farm inputs *(Xs)* used in the model were maize production area in ha, labor in man-days used to produce maize, dummy variable for use of hybrid seed (1= yes, 0= no), organic fertilizer used in kg and inorganic fertilizer used in kg.

The selection model was defined as $P_j = \sum_{k=1}^{5} \delta_k \gamma_{jk} + \mu_j$ where j is as defined above, k refers to the subscript of k^{th} selection variable, P is a dummy dependent variable for use of pesticides (1= use, 0=do not use), μ is the disturbance term for the selection model, γ_s are selection variables that influence use of pesticides by farmers; dummy for availability of off-farm income (1= yes, 0=no), dummy for availability of farm employees (1 = yes, 0 = no), education level of household head (no schooling = 1, primary = 2, secondary = 3, tertiary colleges and above = 4), dummy for availability of grass surrounding maize field (1= available, 0=not available), and total household farm size in ha.

3.5 Pest control scenarios

In order to estimate the *ex ante* impact of introduction of two parasitoids (*T isis* and *C. flacipes)* to the Kenyan Highlands, different linear pest suppression scenarios were constructed based on the probable stemborer suppression levels on a reducing stemborer density reported in related studies (Nagarkatti and Nair 1973; Omwega *et al* 1997; Jiang *et al* 2006), namely, i) only *T. isis* or *C. sesamia* establish and achieve pest suppression of 10% ii) One parasitoids establishes and achieves pest suppression of 20% iii) both parasitoids establish and each achieve a pest suppression of 20% iv) one parasitoid establishes and achieves pest suppression of 40% iv) Both parasitoids establish but *T. isis* cause pest suppression of 20% while *C. sesamiae* cause 10% pest suppression, by the 10th year.

By simulating the stemborer densities using the projected suppression levels, the net reduction in the effective stemborer density per scenario was obtained. The output loss abated by the parasitoids was obtained by constructing a linear relationship of stemborer density with output loss. Using the coefficient of pesticides, the initial output loss to stemborers was obtained by comparing the actual output (when the current pesticide use prevails) with the potential output (based on the recommended rates of standard pesticides). The economic benefits of the biological control per scenario were calculated based on the value of the maize loss abated.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 Socio-economic characteristics of the low potential maize growing farming systems

Maize prices in the region exhibited a cycle with the lowest price of Kshs 20 per 2 kg tin (Kshs 900/90 kg bag) during harvest and an increase to Kshs 40 per 2 kg tin (Kshs 1800/90 kg bag) as maize stocks declined just before the following harvest. The yields obtained by farmers were variable with 80% of the farmers producing an average of 0.6-1.1 ton/ha. All the respondents acknowledged the yield loss as a result of infestation by stemborers. When farmers were asked to rank the major causes of yield loss on a scale of 1-5, stemborers were ranked first and second by 29 and 31% of the respondents, respectively. In lowland tropics of coastal Kenya, drought stress during maize growing seasons and the impact of stemborers were made responsible for crop failure in 1 out of 4 successive seasons and, therefore, the probability of no harvest or low yields during any cropping season was 0.25. Over 90% of the farmers practiced intercropping as insurance to food security. There was generally low usage of pesticide to control crop pests with only 13.7% of farmers using commercial pesticides to control pests on maize; application of soil was the most frequently used method of control of stemborers (Table 4.1). Soil or ash was impetuously applied often during weeding only to plants that showed obvious symptoms of stemborer attack and therefore, labor input for the application did not increase the cost of maize production. Farmers who did not control the stemborers obtained yields that were not significantly different from that obtained by farmers using soil (P=0.63) and ash (P=0.32) to control the pest. Thus, the ‘no control’ group was considered as appropriate baseline for comparison. With exception of the farmers involved in the project none was aware of the introduced parasitoid.

Table 4.1: Farm characteristics and use of farm inputs

Variable	Description	Percentage of farmers
Yields obtained	< 0.6 tons/ha	80.0
	> 0.6 tons/ha	20.0
Use of fertilizers	Inorganic fertilizers at planting	36.2
	Organic fertilizers	63.8
Pest control method	Pesticides	13.7
	Soil	52.3
	Ash	20.4
	No control	13.4
Farming system	Maize mono-crop	9.4
	Maize +1 intercrop	12.8
	Maize +2 intercrops	23.4
	Maize +3 intercrops	38.6
	Maize +4 intercrops	15.8
Major cause of yield loss ranked 1st by farmers	Inadequate and unreliable rainfall	50.0
	Stemborers	29.0
	Low input use	9.8
	Poor seed quality	11.2

Stemborers damage to the husk allows water to enter into the cob creating a conducive environment for fungal growth. Thirty percent of the respondents reported that maize rotting had reduced at the time of data collection. Ear rot was rated at 3 in the 1990s but reduced to 2 after 2000 on a scale of 1 to 5. There was a significant ($P<0.05$) negative correlation between stemborer density and the number of man-days spent on weeding of -0.29 ($P<0.05$) and the number of intercropped food crops, especially non-host plants of stemborers (-0.41). *Chilo partellus* larvae migrate to the whorl from where they disperse to other plants. It was suggested that in weed free fields migration related mortality was higher than in weedy fields, especially if some of the weeds are alternative hosts, e.g. grasses, to the borer. The negative effect of intercropped and pest infestation has also been described by Schulthess *et al.* (2004) and Chabi-Olaye *et al* (2005b) and was attributed to the reduced host finding capacity by the ovipositing female moth because of mix-up of plant volatiles. Correlating the stemborer infestation with yields estimated by farmers gave a significantly negative correlation (-0.61; P<0.01) corroborating results from yield loss trials carried out in the area (De Groote 2001).

4.2 Comparing maize production environment between the north and south coast

The average household farm size and area allocated to maize was significantly higher in the north than the south coast (3.3 ha and 1.2 ha, respectively, in the north, and 1.2 ha and 0.6 ha, respectively in the south; P<0.001). Similarly, yields in the north were higher than in the south coast (1.2 vs. 0.9 tons/ha, respectively; P<0.001). A possible explanation was higher soil fertility and rainfall (850 versus 650 mm) in the north coast. Moreover, parasitism rates by *C. flavipes* and suppression of *C. partellus* was higher in the north than the south coast, which was attributed to a higher proportion of land allocated to maize in the north coast. Maize was the most common and suitable host plant for both the pest and its parasitoid in East and Southern Africa (Sétamou et al. 2005; LeRü et al. 2006). Thus, the higher the proportion of maize in the system, the more stable the pest-parasitoid system.

Between 33.8 and 48.5% of farmers in the areas ranked soil fertility, pests and erratic rainfall as the main constraint to maize production, and the rankings followed the same trends in both locations (Table 4.2). Only 15.4 and 16.4% farmers in the south and north coast, respectively, ranked poor seed quality as the most limiting factor. The pests that ranked highest in the areas were rats, cutworms and stemborers. Stemborers received similar importance in both locations (32.4 vs 28%, in the south and north coast, respectively).

Table 4.2: Farmers ranking of the perceived causes of low yields in coastal Kenya

Perceived cause of low maize yield	% of farmers					
	Impact rank$^{\varphi}$	*1*	*2*	*3*	*4*	*5*
Soil fertility	south coast	35.9	21.1	32.0	6.3	4.7
	north coast	48.5	18.4	24.3	4.4	4.4
	both sites	42.4	19.7	28.0	5.3	4.6
Pests	south coast	46.9	14.8	18.0	17.2	3.1
	north coast	48.5	14.0	15.4	16.2	5.9
	both sites	47.7	14.4	16.7	16.7	4.5
Poor seed quality	south coast	16.4	13.3	24.2	30.5	15.6
	north coast	15.4	12.5	19.9	22.8	29.4
	both sites	15.9	12.9	22.0	26.5	22.7
Erratic Rainfall	south coast	39.1	13.3	9.4	23.4	14.8
	north coast	33.8	5.1	13.2	20.6	27.2
	both sites	36.4	9.1	11.4	22.0	21.2

$^{\varphi}$ 1-very important 2-important, 3-not decided, 4-less important, 5-does not affect

4.3 Comparing farmer characteristics between users and non-users of pesticides

The average farm holding size and labor were not significantly different among the groups applying pesticides and those who did not; they were, respectively, 2.0 and 2.2 ha and 45.8 and 55.4 man-days ($P > 0.2$). Appendix II shows the yields obtained by farmers categorized in groups according to their innate characteristics and input use.

The high percentage of 59.8% of farmers with 0-10 years experience in maize production suggests sub-divisions of land by aging parents to their grown and married children. Most of the farmers (82.3%) had only elementary education but they produced significantly higher maize yields compared to the group with higher education. In most cases, in areas where agriculture was a way of life rather than a business opportunity, when education increases, the opportunity cost for using their time in farming increases and thus, educated laborers seek formal employment reducing their time devoted to farming. This was demonstrated by the positive significant correlation of 0.19 ($P = 0.02$) between education and availability of off-farm income. Eighty percent of all the farmers owned over two hectares of land. All categories in the 2.1-5 ha group obtained significantly higher maize yields, which suggest that the available farm resources were adequate to carry out farm operations in these farms. Labor was critical in maize production systems where input use was minimal like in coastal Kenya. Because the availability of cash to hire extra labor was limited, the amount of labor available depended on the family size. Correlating labor with the farm size gave a correlation coefficient of 0.31 ($P = 0.001$) indicating that farmers with larger farms had more labor. This could result from larger families those farmers were likely to rise. With an increase in labor, farmers obtained significantly higher maize yield in three out of the four categories.

Hybrid seed was planted by 41.7% of the farmers. Across all categories, farmers who planted hybrid seed obtained significantly higher yields. Similarly, application of organic and inorganic fertilizers led to an increase in maize yields in all categories. The Pearson correlation coefficient between amount of pesticide and organic fertilizer applied was –0.19 ($P = 0.02$), which means that farmers who applied organic fertilizers rarely also applied pesticides or vise versa. Grassland around a field had no clear effect on yields. There was a high variability of yields obtained by farmers in the area ranging from 0-4.7 tons/ha. Across categories, yields tended not to vary between pesticide users and non-users. Still, higher overall yields were obtained in 2005 when pesticides were applied.

4.4 The farming system, pest and parasitism situation at the Taita Hills

Maize was ranked first in importance in meeting household food and income needs by 97.5% of the farmers in the area. Legumes and vegetables were ranked second and third in that order of importance (Table 4.3). Most families grew cowpeas that were drought resistant as monocrops during fallow periods while the haricot beans were intercropped with maize during the cropping season. Vegetables were grown as monocrop or intercropped with other crops by 34.6% and 70.4% of the farmers respectively. Seventy point six per cent of all the farmers in Taita hills planted vegetables. Sixty nine point six percent of vegetable farmers used chemical pesticides to control pests and diseases.

Table 4.3: Importance of crops to farming households in the Taita Hills

Crop	% of farmers growing	% of farmers ranking crops by importance			% farmers using pesticides
		1	2	3	
Maize	99.4	97.5	1.2	0.6	54.6
Legumes	58.9	-	55.2	3.7	-
Fruits	11.0	-	2.5	8.6	-
Tubers	17.8	1.2	3.7	8.6	13.8
Vegetables	70.6	1.3	24.5	44.5	69.6
Sugarcane	8.0	-	-	3.7	-

About half of the farmers (54.6%) use pesticides in maize production. This underscores the importance of the model adopted for this study that corrects for selection bias. Because dosages sublethal to the pest may kill the natural enemies thereby aggravate the pest problem, the availability of farmers who do not use pesticides provides a conducive environment for the proliferation of parasitoid population. A factor that may limit parasitism was the use of pesticides in maize and vegetables that may kill the delicately living parasitoids. Applying more selective insecticides and better timing of insecticide use to avoid spraying when parasitoids were active, were possible ways to mitigate the negative impact of spraying of pesticides. The continuous spraying of pesticides by vegetable farmers was however, expected to have a neutral impact on activities of the parasitoids because most farmers intercropped vegetable with legumes or tubers such as sweet potatoes that were not alternate hosts of stemborers. Also, the intensity of pesticides use in the area was low because of the semi-intensive production system.

Three stemborer species were recovered from Taita hills, namely, *B. fusca, S. calamistis* and *Ch. partellus.* The stemborer incidence ranged from 23.4-41.4% with an average stemborer density at the flowering stage of 0.5-0.7 stemborers per plant. The dominant species in the area was the *B. fusca* accounting for up to 90% of total stemborer composition. Each of the *S. calamistis* and *Ch. partellus* stemborer species accounted for less than 20% of total stemborers recovered from the area in three seasons. Two parasitoid species belonging to two families in the order Hymenoptera were found to attack stemborer larvae (Table 4.4). There was no parasitism recorded in July 2004 but low parasitism of 5.1 and 2.4% was recorded in December 2004 and July 2005 respectively. Parasitism by the pupal parasitoid, *Pediobius furvus* was low (1.3%) and was only realized in July 2005. The occurrence of *S. calamistis* in the area and its suitability for parasitism by *C. sesamia* and *T. isis* is a boon since unlike the other species, it does not diapause during the off season, thus will help to perennate the two parasitoids introduced to the area.

Table 4.4: The composition and parasitism of stemborer per species at Taita Hills

	% composition per season		
Stemborer species	1	2	3
Buseola fusca	92.1	65.4	90.2
Chilo partellus	0.0	17.9	1.2
sesamia calamistis	7.9	16.7	8.5
Pest incidence (plants infested/total plants sampled)	41.4	23.4	32.4
Average no. stemborers/plant	0.7b	0.5a	0.5a
Parasitism			
Cotesia flavipes			
Buseola fusca	0.0	0.0	0.0
Chilo partellus	0.0	7.1	0.0
sesamia calamistis	0.0	15.4	28.6
Purdeovous furvus			
Buseola fusca	0.0	0.0	0.0
Chilo partellus	0.0	0.0	0.0
sesamia calamistis	0.0	7.7	0.0
Total parasitism by *C. flavipes*	0.0	3.8	2.4
Total parasitism by *P. furvus*	0.0	1.3	0.0
Total parasitism by *C. flavipes* and *P. furvus*	0.0	5.1	2.4

4.5 Benefits and costs of release of *Cotesia flavipes* for biological control of cereal stemborers in the low potential maize growing areas

4.5.1 Predicting stemborer density and parasitism

Durbin h statistic was first computed to determine whether variables in the parasitioid and host models exhibited serial correlation. The computed Durbin h statistic ranged between 0.04 and 0.11 for the two models. Since the computed values were lower than the critical value of 1.645 of the normal distribution at the 5% level, there was no reason to reject the null hypothesis of no serial correlation.

The step-wise regression showed that the number of seasons elapsed since introduction of the parasitoid, total stemborer density and parasitism by *C. flavipes* during the preceding season significantly ($P<0.1$) affected stemborer density. Parasitism was related positively to time since introduction of *C. flavipes* and parasitism during the previous season. This was due to a reduction of pest density and indicates a negative relationship between parasitism and pest density. Negative density dependence is common for efficient parasitoids and was also found for *Telenomus* egg parasitoids on *S. calamistis* and *B. fusca* (Sétamou and Schulthess 1995, Chabi-Olaye *et al.* 2005c).

Predicted mean parasitism ranged between 1.2% and 27.5% reducing stemborer densities by between 5.3 and 29.3% from the time of introduction to 2004. Results in Figure 4.1 show that although the introduced parasitoid was firmly established by 1995, total stemborer density continued to rise up to 1998. The regression coefficients (Table 4.5) imply that while parasitism by *C. flavipes* had a negative impact on total stemborer density, there was a general increase in total stemborer density with time. However, the magnitude of the negative impact by the parasitoid was higher (-2.67) than that of time trend (0.31) such that the rate of increase in stemborers was countered by the parasitism by *C. flavipes.* In this case, the reduction in stemborer density will depend on the parasitism by the parasitoid while the build up of the stemborer density will depend on the carry over population from the preceding season and the time trend. The low variance of stemborer density and the parasitism levels from the mean showed that both were homogenously distributed in the entire region.

Table 4.5: Factors affecting stem borer density and parasitism by *C. flavipes*

Variables	Dependent variable	
	Stem Borer density	Parasitism by *Cotesia flavipes*
Constant	1.07 ±0.15**	-0.003 ± 0.01
Number of seasons elapsed since release	0.31 ± 0.10**	0.15 ± 0.01**
Total stemborers at t-1	0.20 ± 0.09*	-
Parasitism by *C. flavipes*	-2.67 ± 1.63**	-
C. flavipes parasitism at t-1	-	0.63 ± 0.12**
Total stemborers	-	-0.001 ± 0.006
F	16.2	16.9
R^2	42.8	60.5

* Significant at p<0.05 ** Significant at p<0.1; - variable not included in the model

The increase in *C. partellus* density up to 1998 (Zhou *et al* 2001) requires some discussion. Although *C. partellus* was introduced to coastal Kenya in 1930s, it was only reported in 1960s (La Croix 1967). Mean densities in the late 60s to early 70s were around 0.5 (Mathez 1972). Since then it spread and steadily increased until 1998 (Zhou *et al* 2001). Jiang *et al* (2006) suggests that the pest-parasitoid system was not yet at equilibrium. In addition, as suggested by Schulthess *et al* (1997) and Zhou *et al* (2002), the increase in the stemborer density could have been a response to the increase in acreage of maize, which as a food source was considerably superior to wild host plants (Shanower *et al* 1995; Jiang & Schulthess 2005). Available statistics do not give any evidence for an increase in area under maize in the 1990s. However, Hassan (1998) found a highly positive correlation between farmers planting maize in both long and short rains and human population density. Thus it can be expected that in response to the high rate of population growth of 2.56% in Kenya (CIA 2005), households intensify production by increasing the number intercropped crops and farming times per year to meet food demand that would have lead to higher maize production in the area.

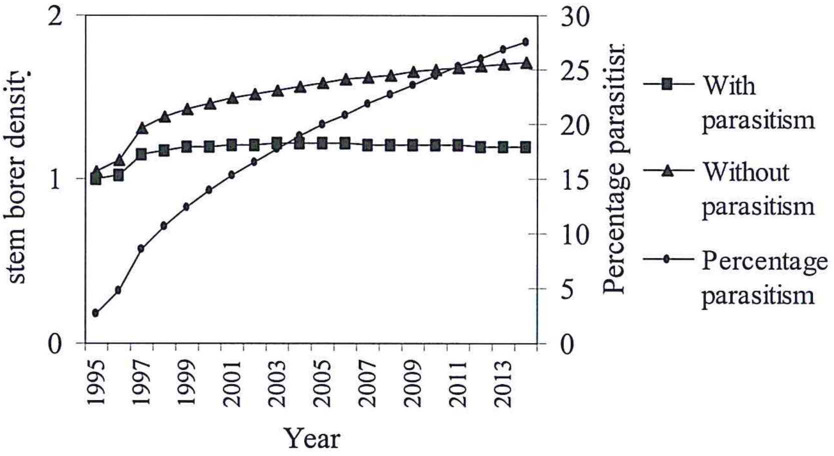

Figure 4.1: Impact of parasitoid on the stemborer density

4.5.2 Valuing the benefits and costs of the biological control program in the low potential maize growing areas

The percentage reduction in stemborer density arising from parasitism by the introduced parasitoid increased from 5.3% in 1995 to 29.0% in 2004. The model predicts that without release of the parasitoid stemborer density was expected to increase and mean yield losses were expected to reach 34.0% by 2014 (Table 4.6). However, predicted yield loss will only be 14% due to a reduction of borer densities caused by the action of the parasitoid. The economic benefits were expected to continue flowing as long as the farming environments, which affect the host-parasitoid system, remains unchanged.

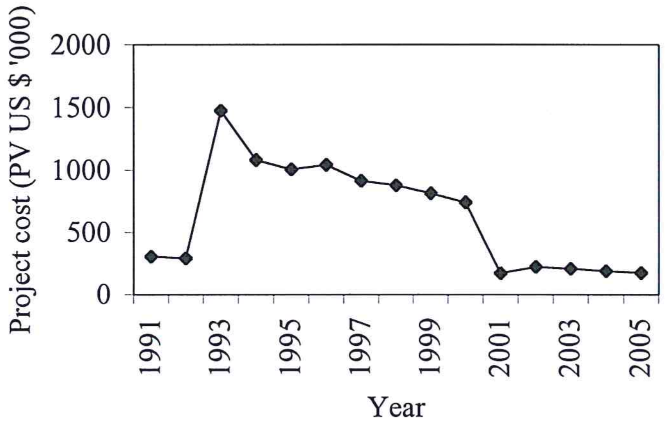

Figure 4.2: Costs of the biological control program

The present value of the cost incurred in Kenya by the project up to 2005 for the BC program was estimated at US $ 4.4 million. Most of the costs (51%) were incurred between 1991 and 1997 (Figure 4.2). During this time, the project was acquiring necessary equipments for insect rearing, parasitoid release, lab studies and monitoring. Fixed equipments comprised 7-45% of the annual costs of the project. The project cost decreased after 2001 following the successful establishment of the parasitoid and the project activities were reduced to monitoring and evaluation. By the end of the 20-year period, the biological control program will have accumulated a total net present value (NPV) of US $ 183.4 million using the 10% interest rate. The internal rate of return (IRR) of the project was 41% with the benefit-cost ratio of 19:1 when 2004 farm gate prices were used.

The benefit-cost ratio of the project was lower than that obtained by other BC programs in Africa, e.g., the coffee mealybug with a ratio of 202:1 (Huffaker *et al* 1976), the cassava mealybug with a ratio of 149:1 (Norgaard 1988), the mango mealybug in Benin with a ratio of 145:1 (Bokonon-Ganta *et al* 2002), water hyacinth with a ratio of 124:1 (De Groote *et al* 2003b) and the cabbage Diamondback moth in Kenya with a ratio of 24:1 (Macharia *et al* 2005). However, a large proportion of the classical BC successes against insects were against mealybugs, whose parasitoids were highly specific, and their impact was, thus, much faster than shown in the present project. Furthermore, the low

Table 4.6: Predicted impact of *C. flavipes* parasitoid on maize production

Year	Percentage reduction in stem borer density	Actual output (tons)	Potential output (tons)	Expected output loss (tons)	Realized output loss (tons)	Percentage increase in output
1995	5.3	321161	346731	32373	25570	21.0
1996	8.8	324372	353531	40997	29158	28.9
1997	13.8	324726	374553	72142	49827	30.9
1998	16.8	328291	382381	82374	54090	34.3
1999	19.3	331855	388867	90595	57012	37.1
2000	21.7	335420	394625	97588	59205	39.3
2001	23.8	339017	399942	103747	60925	41.3
2002	25.6	342582	404870	109272	62288	43.0
2003	27.5	346147	409527	114316	63380	44.6
2004	29.0	349712	413966	118974	64254	46.0
2005	30.6	353277	418224	123319	64948	47.3
2006	32.2	356210	421586	127177	65375	48.6
2007	33.7	359605	425366	130973	65761	49.8
2008	35.2	362999	429036	134578	66037	50.9
2009	36.6	366394	432612	138019	66218	52.0
2010	38.0	369788	436105	141315	66317	53.1
2011	39.4	373183	439524	144483	66341	54.1
2012	40.8	376578	442878	147539	66300	55.1
2013	42.1	379972	446172	150493	66200	56.0
2014	43.5	383367	449413	153356	66046	56.9

benefit-cost ratio resulted from the limited production quantities resulting from the relatively small project area and the low maize prices. Since the farmers in the project area were subsistence producers who rarely import maize from other regions, farm gate prices (US $ 125.7/ton) were used. This price was lower than the cost of insurance and freight (CIF) maize price of about US $ 267/ton used by most studies. Unlike other BC programs in Africa, this study covered only about 400,000 ha of maize production area in Kenya. The project area was small compared to the area covered by other projects; for example the cassava mealybug project whose benefits were extrapolated to the whole of Africa. The benefit-cost ratio will increase when a complete impact assessment covering all the areas, where the introduced parasitoid has spread to, were included.

The project benefits were also only confined to yield loss abated while there could be other project benefits to the environment and farmer health resulting from reduction of the externalities of pesticide use and increase in household food intake resulting from increase in maize output, whose values were yet to be established. It is worth noting also that the project costs and benefits were for operations in Kenya though 11 countries in East and Southern Africa have benefited from the project through a deliberate release of the parasitoid into these countries or through cross border spread.

4.5.3 Sensitivity of benefits and cost of biological control program to changes in economic factors in the low potential maize growing areas

A sensitivity analysis (Table 4.7) was conducted to test the impact of the variation of the factors that were held constant during the analysis and may affect the results of the economic impact assessment. Over the twenty-year analysis period, it was possible that technological changes might occur. Farmers' resource level may not change much but new advances in technologies, e.g. high yielding varieties, inorganic fertilizers and biotechnology will provide avenues to increase farm output with the same farm resources. Technological change will require farmers to invest money in order to use the technology. For African cereal stemborers, it was shown that in spite of increase in pest density, the net impact of N application on yields is always positive and yield losses due to the pest decreased with increasing nitrogen dosage. In relation to this study, the net economic impact of N application will be the decrease in both the potential and the actual yield loss to stemborers, which will decrease the economic benefits of the biological control program. If we take an optimistic adoption rate of 20% for purchased inputs, application of N fertilizers that increases yields by 20%, the NPV of the US $ 183.4 million will decrease by 3.2% to US $ 177.6 million.

Application of pesticides may improve maize yields by reducing the yield loss due to stemborers. To assess the impact of change in adoption levels of pesticides to the results of our study requires data on both target and non-target impact of pesticides. Data was required to estimate the benefits of a pesticide compared to its costs cover environmental risks of pesticide use such as persistence in soil and water, contamination groundwater, residues in and on food and hazards to non-target organisms and costs incurred by the farmer. This data was not available and therefore the sensitivity analysis of adoption of pesticides was not conclusive. Since BC acts as a substitute to pesticides, increase in use of pesticides will lead to a reduction in benefits to BC program when economic benefits were confined to yield loss abated. It was, however, highly doubtful that in the foreseeable future farmers in the area will adopt the purchased inputs even at low levels owing to the high poverty and low education level.

Net present value would increase by 7.9% if yield loss abated increases by 10% beyond the projected level after 2005. If the interest rate reduces to 5% the NPV will increase by 17%. A 10% increase in prices after 2005 will lead to a 7% increase in NPV. Increasing the period of analysis to 30 years, and assuming that the parasitoid will cause stemborer density to stabilize at an effective density of 1.1, the economic gains would increase by 170%. These results show that under all circumstances, the BC project will still be profitable.

Table 4.7: Sensitivity analysis of the economic impact of biological control of stemborers in the low potential maize growing areas of Kenya

Parameter	Baseline	Alternative	NPV (Million US $)	Benefit-cost ratio	Internal rate of return (IRR)
Interest	10%	20%	173.2	9	23
rate	10%	5%	152.3	20	56
Area under maize	Constant	Increase by 20%	212.2	21	42
Pesticide use	No	20% adoption*	154.5	15	41
Nitrogen fertilizer	No	20% adoption	62.2	6	39
Maize output price	Variable	Increase by 10%	197.8	20	78
Yield loss abated	Depends on pests density controlled	Increase by 10%	197.8	20	78
Period of analysis	20 years	30 years	496.2	46	42
Base year	2005	1995	189.8	48	71

* Adoption of a fully efficient pesticide

4.6 Comparing technical and allocative efficiency of farmers relying on biological control with users of pesticides

A production function was fit in order to establish the contribution of each independent variables to maize production. Because heteroscedasticity, whose presence may lead to Type I or II errors, is common with cross sectional data, the Breusch Pagan Test was conducted to test the null hypothesis that data was homoscedastic. The computed chi-square of 13.8 at 5% level of confidence was lower than the critical value of 14.1 and therefore, we could not reject the null hypothesis of homoscedasticity. The log likelihood function for the transcendental functional form was -307.7 while that of the translog functional form was -304.1. Because the test-statistic (λ) was 7.24 and the critical value was 7.8 the null hypothesis that the transcendental production function was adequate could not be rejected.

The regression results of the stochastic production function estimates are given in Table 4.8. The elasticities, that gives the percentage change in maize output with respect to a percentage change in the inputs of hybrid seed, labor, pesticides, land and inorganic fertilizers, had a significant positive impact on maize output. Land and labor had the highest impact on output which shows that maize production in the area depended on the size of land allocated to maize production and the amount of time farmers devoted to carry out field operations in maize fields. Larger farms have the advantage of attaining economies of scale by spreading costs over more land (Ogolla and Mugabe 1996). The availability of grassland and bushes around maize fields had a positive but not significant impact on maize yields. Correlating the stemborer density with the size of grassland surrounding maize field gave a significant negative correlation of -0.89 ($P < 0.001$).

Table 4.8: The transcendental production and efficiency function

Variable	Parameter	Coefficient	Standard error
Intercept	β_0	0.04	0.30
Hybrid seed	β_1	0.13**	0.02
Labor in man-days	β_2	0.26**	0.08
Pesticide control	β_3	0.04**	0.02
Land	β_4	0.29*	0.18
Inorganic fertilizers	β_5	0.12**	0.03
Manure	β_6	-0.06	0.16
Grass area	β_7	0.001	0.02
Labor*land	β_6	0.04	0.04
Labor*manure	β_7	-0.09*	0.05
Land*manure	β_8	0.21	0.18
Inefficiency model			
Constant	δ_0	-5.10*	3.40
Stemborer infestation	δ_1	-1.65**	0.34
No. of crops intercropped	δ_2	0.38	0.34
Age of household head	δ_3	-0.03*	0.02
Year in school	δ_4	0.13	0.10
Availability of off-farm income	δ_5	-3.72**	0.93
Farm experience	δ_6	0.001	0.03
Farm size	δ_7	-0.59**	0.14
Variance parameters			
Gamma $(\gamma) = \sigma^2_u/\sigma^2$	γ	0.93**	0.20
Ln likelihood		-189.5	

** Significant at 99% confidence level * Significant at 95% confidence level

In contrast to indigenous borer species, wild grasses act as trap plants for the exotic *C. partellus*, rather than as habitat for pest and parasitoid during the off-season; i.e., they attract the ovipositing female moth but cause high mortality among their offspring. Use of manure and the multiplicative interaction terms between land and manure, and between land and labor did not affect maize outputs. The use of manure was only significant in influencing maize yield when considered in isolation (Appendix II) but insignificant when considered in relation to other production resources in the production function. Use of manure, like other fertilizers, besides directly increasing yields, was expected to give unique advantages to the plant through enhancing the plants' capacity to withstand pest attack (Sétamou et al. 1995; Mgoo et al. 2006; Wale et al. 2006; Chabi-Olaye et al. 2007). Given the low levels of manure use in the area, insignificant coefficients for manure and its interactions with other variables were not unexpected. The rate of application was on average one ton per ha compared to the recommended rate of about 5 tons/ha needed to meet all nutrient requirements by plants.

The gamma (γ) that measures the effect of technical inefficiency in the variation of observed output was 0.93 ($P < 0.01$) (Table 4.8). The significance of the statistic shows that the frontier production function was an appropriate representation of the sample data. The value of the γ statistic shows that 93% of total variation in maize yields was due to technical inefficiency. The functional coefficients that measure the proportional change in output when all inputs included in the model changed in the same proportion was 0.9 indicating a decreasing returns to scale. Thus, farmers in the area seemed to experience scarce resources relative to land manifested in the low rates of farming inputs used per land area. Because of production inefficiency, farmers were unable to exploit the full productive potential of their resource and thus, any increase in input use lead to less than proportional increase in output.

Results of the inefficiency model reported in Table 4.8 shows that stemborer infestation, age of the household head, availability of off-farm income and the farm size of the household significantly negatively affected the TE of maize production. It was expected that in coastal Kenya, where soil fertility was dwindling as a result of continued cropping without external application of fertilizers, increase in the number of intercropped crops increased competition for light and nutrients leading to low maize yields. However, the number of crops intercropped did not significantly affect the technical efficiency of maize production. The positive correlation between the total farm size and area allocated to maize production (0.45, $P < 0.001$) indicated that as farm sizes increased the proportion of land allocated to maize increased, which lowered the input-land ratio. A lower ratio would compromise productivity of the inputs if there was no commensurate increase in farming inputs to carry out the resultant increase in field operations, thereby reducing TE.

During both years, the farmers who did not use insecticides were significantly more technically efficient compared to farmers who did (Table 4.9). The range of TE of users and non-users of pesticides was 90% and 81%, respectively, showing that farmers who did not apply pesticides experienced higher yield variability. The technical efficiency of 66.2 and 67.9% of the farmers who did not apply pesticides and 60.3 and 57.9% of farmers who did in 2004 and 2005, respectively, compared well with the mean technical efficiency estimates reported by several other frontier applications in agriculture. For example, Sharma & Leung (2000) reported a mean technical efficiency of 80.5 and 65.8% for semi-intensive/intensive and extensive carp producers respectively in India. Alene & Hassan (2005) reported a mean TE of respectively, 68 and 78% for traditional and hybrid maize producers in Eastern Ethiopia. Datt & Joshi (1992) reported a mean TE of 66% in rice production in Uttar Pradesh, India.

Table 4.9: Distribution of technical efficiency among small-scale farmers

Technical efficiency (%)	% of farmers			
	No pesticide		Use pesticides	
	2004	2005	2004	2005
<20	7.9	34.2	2.6	11.1
>20-40<	5.3	15.8	3.8	11.1
>40-60<	11.8	31.6	21.8	11.1
>60-80<	50.0	15.8	41.0	59.3
>80	25.0	2.6	30.8	7.4
Mean	66.2b	67.9b	60.3a	57.9a
Maximum	82.0	91.0	82.0	82.0
Minimum	1.0	4.0	1.0	1.2

Values followed by the same small letters in a row are statistically equal

The higher technical efficiency of farmers relying on BC can be attributed to the low cost of production by these categories. In this case, because they evaded the cost of applying pesticides, these categories of farmers obtained the same output as those who applied pesticides (Table 4.9). This result also confirms the efficacy of the natural enemies in controlling stemborers.

There was an inverse relationship between the technical efficiency and yields with farmers who obtained low yields from low input use awarded higher technical efficiency score (Table 4.10). This underlines the fact that farmers in the area use very low inputs and the model awarded higher efficiency to farmers obtaining higher yields from low inputs use. Farmers who applied inorganic fertilizers to maize fields surrounded by grass boundaries, or applied inorganic fertilizers and pesticides obtained similar yields. Thus, grassy habitats had the same effect like pesticides, and the question arises if using pesticides against stemborers was economically feasible if grasses and efficient natural enemies were present. Farmers who applied inorganic fertilizers obtained higher yields compared to those who applied organic manures alone. Farmers who did not apply any form of fertilizers and pesticides obtained the lowest yields of 0.3 tons/ha. Those who used pesticide and inorganic fertilizers to maize fields surrounded by grasslands obtained the lowest mean TE level (0.43) although they had high yields of 1.1 tons/ha indicating again that farmers in the area experience decreasing returns to scale. In this way, when farmers applied inputs they obtained less than a proportionate increase in maize output. The correlation between application of manure and inorganic fertilizers was also negative (–0.26, p=0.03) which means that whenever farmers increased the rate of application of one fertilizer type, they reduced the quantity applied of the other. Because the rate of fertilizer application was lower than the recommended rates when farmers applied both fertilizer types, farmers who applied both fertilizer types obtained lower yields.

Table 4.10: The relationship between input mix, maize yield and TE from pooled data

Pesticide	Inorganic fertilizer	Grass boundaries	Manure	Efficiency %	Yield (ton/ha)
-	-	-	-	0.67b	0.3a
-	-	-	+	0.66b	0.3a
-	-	+	-	0.64b	1.1b
-	-	+	+	0.70c	0.3a
-	+	+	-	0.76c	2.3c
-	+	-	-	0.67b	1.0b
-	+	-	+	0.66b	0.3a
-	+	+	+	0.64b	1.1b
+	-	-	-	0.70c	0.8b
+	-	-	+	0.51b	0.6b
+	-	+	-	0.63b	1.2b
+	-	+	+	0.61b	0.6b
+	+	-	-	0.81c	2.0c
+	+	-	+	0.64b	0.7b
+	+	+	-	0.43a	1.1b
+	+	+	+	0.72c	1.0b

Values followed by the same letter in a column are statistically equal

+ Input included by the farmer – input not included by the farmer

Assessment of allocative efficiency was done only for labor and inorganic fertilizers. Labor influence maize yields because when sufficient, vital field operations, e.g., weeding, were carried out in a timely manner. Inorganic fertilizer was an important purchased input recommended for use in the area to improve maize yields and reduce yield losses due to stemborers. Allocative efficiency for manure and land were not evaluated because data from a short period survey was not adequate to assess such inputs whose allocative efficiency at time *t* will depend on long-run profitability of the farm. The pesticide and hybrid seed were included in the model as dummies.

Thus, the overall semi-elasticity of pesticide was computed for these variables using the procedure suggested by Halvorsen and Palmquist (1980) whereby the value of 1 was subtracted from the antilog (to base e) of the estimated dummy coefficient, and then the difference was multiplied by 100. The semi-elasticity of pesticide was 0.041 while that of hybrid seed was 0.139 meaning that farmers who applied pesticides or those who planted hybrid seed would increase their average yields by 4.1 and 13.8%, respectively.

Table 4.11: Empirical estimates of allocative efficiency from stochastic production function

	Marginal Value Product (MVP)			
Factor	No pesticide		Use pesticides	
	2004	2005	2004	2005
Labor	43.9	52.8	72.0	60.9
	(0.4)	(0.5)	(0.7)	(0.6)
Fertilizer	239.6	252.7	601.9	-
	(8.0)	(8.4)	(20.1)	-

Values in the parentheses are the MVP/MFC ratios. – Missing yield

The ratio of the marginal value product to marginal factor cost (MVP/MFC) of inorganic fertilizers ranged from 8.0-20.1 while that of labor was 0.4-0.7 (Table 4.11). This means that farmers in coastal Kenya experienced diminishing and increasing returns to scale in respect to labor and fertilizers, respectively. The results suggest that labor was abundant in the area. The highest MVP of inorganic fertilizers was achieved by farmers who did not apply pesticides, which means that this category of farmers would obtain most returns by increasing use of inorganic fertilizers. Thus, combination of biological control and measures that improve soil fertility suffice to alleviate cereal stemborer problems in small-scale farming systems in eastern Africa. A higher return to increase in labor usage was obtained by farmers who apply pesticides. Increasing labor usage particularly during weeding, leads to improvement of yields by eliminating competition by weeds for soil water and nutrients. Moreover, very young and older larvae of *C. partellus* larvae migrate between plants. Because chances of survival of migrating stemborer larvae were reduced through exposure to sunlight or lack of alternative host plants they could feed on, clean fields should reduce pest incidence complementing the effect of insecticides.

4.7 *Ex ante* economic evaluation of biological control of cereal stemborers in the Kenyan highlands

4.7.1 Assessing the initial yield loss at the Kenyan Highlands (The results of the heckman selection model)

The results of the heckman two-stage selection model are given in Table 4.12. The Wald χ^2 was 62.5 (P=0.0002) with six degrees of freedom implying that overall the fitted model was significant. The correlation between the substantial and the selection equation given by rho was 0.67 which can be interpreted to mean the factors that affect the use of pesticides by farmers also influenced their maize production function. The functional coefficients that measure the proportional change in output when all inputs included in the model were changed in the same proportion was 0.65 that indicates decreasing return to scale. The elasticities of land (0.36), quantity of organic manure (0.09), quantity of inorganic fertilizers (0.12) and use of pesticides (0.002) were significant ($P<0.05$) in influencing maize output in the area. The coefficient of land in maize production was high implying that maize production could be increased more by allocating more land to maize production. The reasons advanced for the positive significant effect of size of land on maize production was because of price and other policy distortions that were larger in large farms (Kumbhakar and Bhattacharyya 1992), financial constraints faced by smaller farmers (Kevane 1996) and subsistence concerns of smaller farmers that lead them to specialize in less profitable crops (Omamo 1998). These reasons were valid for the Kenyan highlands where small-scale farmers comprise 89.3% of total farmers (Karanja *et al* 2003).

The coefficients of conventional inputs in the area were low resulting from the low use levels of organic manure (113.8 kg/ha) and inorganic fertilizer (37.7 kg/ha) compared to the recommended application rates of 5 tons/ha and 110 kg/ha of organic and inorganic fertilizers respectively. There was a high variability in the application of these inputs with the maximum and minimum levels ranging from zero for both inputs to a maximum of 1235 kg/ha and 370.5 kg/ha for organic and inorganic fertilizers respectively. This means that although on average farmers applied low quantitative of organic manure and inorganic fertilizers, some farmers applied in excess of the recommended quantities. This was also in the case of pesticides when highest cost incurred by farmers was Kshs. 6422 (equivalent to 10 lit/ha of standard recommended pesticides), which was far beyond the recommended rates of 2.5 lit/ha.

The availability of grassland and bushes around the maize fields and the size of farm holding size by the households were significant in determining whether farmers would use pesticides in their maize crop. Alternative wild host plants, mainly of the grass family, are the reservoir for stemborer particularly in such an area where no parasitoids of stemborers have established. This means that whenever wild host of stemborers were available near maize growing farms, pest levels would be beyond the farmers' tolerable levels that prompt them to apply pesticides. This was in contrast to situation when parasitoids exist and grasses would ensure continuous supply of hosts for the parasitoid proliferation during maize production off-season thereby avoiding the extinction of parasitoids that lead to a low pest attack during the following season.

Table 4.12: Results of the two-stage heckman selection model for use of pesticides

Variable	Mean/ha$^{\lambda}$	Parameter	Coefficient	Standard error
Land in acres	-	β_1	0.29*	0.10
Labor in man-days	253.4(19.92)	β_2	-0.15	0.13
Planting of hybrid maize seed	0.8(0.03)	β_3	0.01	0.17
Quantity of organic manure	113.8(17.60)	β_4	0.10*	0.04
Quantity of inorganic fertilizer	37.7(4.61)	β_5	0.13*	0.05
Cost of pesticide applied	653.4(85.59)	β_6	0.27*	0.11
Selection model (selection variable was pesticide in maize crop)				
Availability of off-farm income	0.3(0.04)	δ_1	-0.01	0.24
Farm employees	0.2(0.03)	δ_2	0.07	0.28
Education level of household head	2.7(0.07)	δ_3	0.09	0.09
Availability of grass near maize field	0.5(0.04)	δ_4	0.98*	0.21
Total household farm size	2.4(0.16)	δ_5	-0.08*	0.03
Rho			0.64	
Sigma			0.74	
Lambda			0.48*	0.25

* significant at $p<0.1$ $^{\lambda}$ values in brackets are the standard errors

The household farms size was a proxy for the household wealth and significant negatively influenced use of pesticides. This was contrary to the *apriori* expectation that households with larger farms would have more income therefore, likely to afford the cost of pesticides. It was noted that because of high population in the area, there was high subdivision of arable farms while farms sloping with high gradients and less arable were least subdivided. In this case, farmers with larger farms were also less likely to farm greater portions of that land.

The heckman regression coefficient of pesticide as a damage control variable use show that a one percent change in investments to control stemborers would lead to 0.1% yield loss abatement. The current maize yield in the area was one tone/ha and a total maize production was 5039 tones (RoK 1995-2004). Using the survey data, the average pesticides application rate in the area was Kshs. 138.7 (Kshs. 0.7 m for the whole area). Using the recommended rate, the total cost of pesticides required to control stemborers in the area was Kshs. 2.0 m (400/-*5039 ha). Investment of another 1.1 m (285%) in pesticides will lead to an increase in maize production by 28.5%. This was the maximum value of the yield loss abated by introduction of biological control agents in the area.

4.7.2 Evaluating the impact of parasitoids on stemborers

The percent reduction of the stemborer density depends on the initial density such that pest suppression would grow over time on a reducing stemborer density. Simulation results in Figure 4.3 based on the initial stemborer levels (Table 4.13) shows that a reduction of stemborers will be achieved faster if both parasitoids establish. Pest density declines faster if higher pest suppression rate was achieved by the parasitoids. In this case, with at least 20% pest suppression by *T. isi*, and 10% pest suppression by *C.sesamia* output loss to stemborers in the area will be under 5% 10 years later. This means that in order to achieve significant pest reduction, other parasitoids were needed to augment achieved parasitism when low pest suppression was achieved by one parasitoid. This argument was better seen from the results in Table 4 whereby when each parasitoid achieve pest suppression of at least 20% or one parasitoid achieve pest suppression of 40%, total stemborer density was reduced by 87.9 and 90.5% respectively.

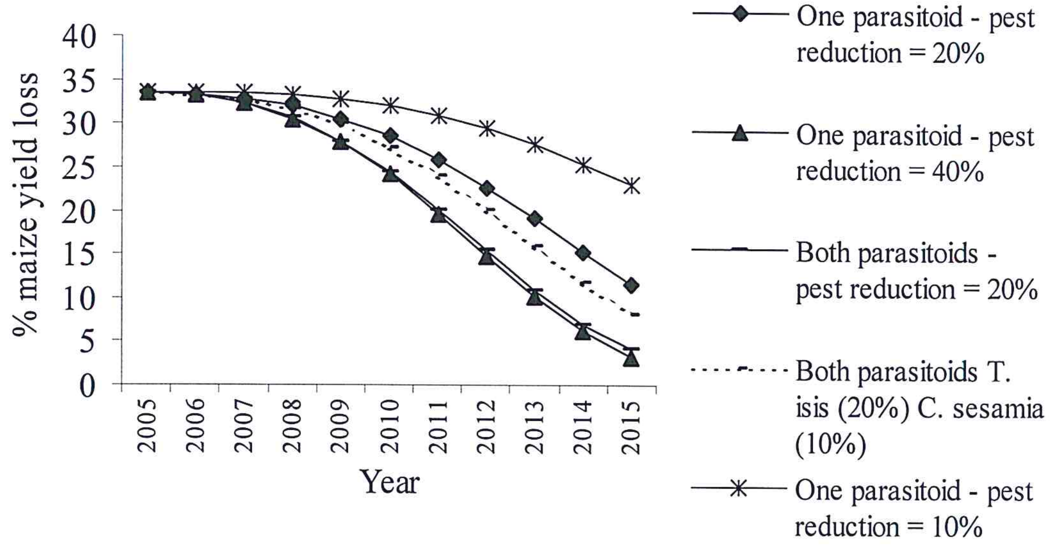

Figure 4.3: Reduction in the maize output loss resulting from suppression of stemborers

The lag period before the impact of the parasitoids was felt was one year that was less than that reported by Zhou *et al* 2001b and Zeddies *et al* 2001 who observed that the establishment of biological control usually takes several years before significant control level was achieved. Bruce (2006, unpublished data) found up to 60% parasitism of egg batches by *T. isis* during the following season after first release of the parasitoids at Taita Hills. Unlike parasitoids studied by Zhou *et al* and Zeddies *et al* which were exotic to the continent and therefore, required more time to adapt to the environment, the parasitoids of this study were indigenous to Africa while *C. sesamia* is indigenous to Kenya, thus, were expected to establish immediately because they were already adapted to the environment and also there could be other coevolved hosts in the area.

Table 4.13: Temporal reduction of stemborer density and the economic indicators under different pest suppression scenarios at Taita Hills

Year	One parasitoid - pest reduction = 10%	One parasitoid - pest reduction = 20%	Both parasitoids *T. isis* (20%) *C. sesamia* (10%)	Both parasitoids - pest reduction = 20%	One parasitoid - pest reduction = 40%
0	0.60(0.0)	0.60(0.0)	0.60(0.0)	0.60(0.0)	0.60(0.0)
1	0.60(0.1)	0.60(0.4)	0.60(0.4)	0.59(0.9)	0.59(0.9)
2	0.60(0.2)	0.59(1.8)	0.59(2.0)	0.58(3.5)	0.58(3.5)
3	0.59(0.9)	0.57(4.3)	0.57(5.2)	0.55(8.5)	0.55(8.6)
4	0.59(2.2)	0.55(8.6)	0.54(10.6)	0.50(16.4)	0.50(16.6)
5	0.57(4.3)	0.51(14.6)	0.49(18.3)	0.44(27.1)	0.43(27.6)
6	0.56(7.5)	0.47(22.5)	0.43(28.3)	0.36(39.9)	0.35(41.0)
7	0.53(11.8)	0.41(32.0)	0.36(40.0)	0.28(53.8)	0.27(55.5)
8	0.50(17.2)	0.34(42.8)	0.28(52.6)	0.20(67.3)	0.18(69.6)
9	0.46(23.8)	0.28(54.1)	0.21(65.0)	0.13(79.0)	0.11(81.7)
10	0.41(31.3)	0.21(65.2)	0.14(76.1)	0.07(87.9)	0.06(90.5)
		Taita Hills			
Net Present Value (US $)	43315	413128	545977	797587	825167
Benefit-cost ratio	1.7	4.4	5.4	7.0	7.2
Internal rate of return (IRR) %	2.5	15.2	18	22.9	23.3
		All areas			
Net Present Value (US $)	13838474	39491007	51730953	74408364	79189583
Benefit-cost ratio	67.7	191.3	250.2	359.5	382.5
Internal rate of return (IRR) %	58.7	89.8	95.3	109.7	110.2

Values in the brackets are the % pest density reduction

4.8 Costs of the biological control in the Kenyan Highlands

In order to ensure attribution of costs, the costs incurred by the BC program of ICIPE for the three years during the suitability studies of the parasitoids were evaluated to determine the actual cost associated with the release of the two parasitoids. The cost of the project was shared among the five project activities associated with biological control agents; *Mussidia nigrivenella* Ragonot, *C. flavipes, S. calamistis, T. isis,* the larger grain borer *Prostephanus truncatus* (Horn) and other stemborer control agents and the student supervision. Activities associated with biological control using *T. isis* and *C. sesamia* accounted for 22% of the administrative cost and 20% of the costs associated with insect rearing. The present value of the cost of the BC was US $ 152,041. A high proportion of total cost (76%) was incurred in the laboratory studies. The administrative cost accounted for 12.4% while insect shipping in and population build up, field release and monitoring and evaluation each accounted for 5.8% of the total cost.

4.9 Valuing yield loss abatement in the Kenyan Highlands

The value of maize output loss abated by the introduction of the two parasitoids for the control of cereal stemborers based on the five scenarios analyzed was presented in Table 4. Each of the scenarios assumes different pest reduction regimes. The value of yield loss abatement rages from US $ 0.4 million when only one parasitoid was established and achieve a maximum pest reduction of 10% to a maximum present value of US $ 0.8 million when each of the parasitoids achieve pest reduction of 20% in 10 years of introduction. The B/C ratio under all the scenarios range between 1 and 4.3. However, when whole the region that the parasitoid was expected to establish in the Kenyan highlands was included, the B/C ratio increases to a range of between 351.6 and 1070.1 while NPV increase to up to US $ 157 million. The B/C ratio of this program was larger than that obtained by other BC programs in Africa, e.g., the coffee mealybug with a ratio of 202:1 (Huffaker, *et al* 1976), the cassava mealybug with a ratio of 149:1 (Norgaard 1988), the mango mealybug in Benin with a ratio of 145:1 (Bokonon-Ganta *et al* 2002), water hyacinth with a ratio of 124:1 (De Groote *et al* 2003b), the cabbage Diamondback moth in Kenya with a ratio of 24:1 (Macharia *et al* 2005) and the control of *C. flavipes* in the low potential maize growing areas of Kenya (Kipkoech *et al* 2006). World wide, the B/C ratios of BC programs reported have been as high as respectively 12,698 and 11,464 for the control of Citrophilus mealybug (*Pseudococcus fragilis*) and Klamath weed (*Hypericum perforatum*) in the USA.

The NPV was less than that obtained from the comparable BC program by *C. flavipes* in the low potential areas of Kenya that reported NPV of US$ 180 million (Kipkoech *et al* 2006). This was because stemborers in the low potential areas were causing yield losses ranging from 10% to total loss (Kfir *et al* 2002) while only about 30% yield losses was achieved in the Kenyan highlands. Furthermore, unlike the former project that analyzed the benefits and costs of the BC program involving parasitoids that had a higher lag period, the parasitoids in the current project got established immediately, and thus, a 10-year period when the parasitoid was projected to have reduced output losses to insignificant levels was considered by the current project. The high difference in the change of the B/C ratio when a small area (5039 ha) was considered shows that the benefits of the biological control was positively scale dependent while the cost was generally scale irresponsive. By including the entire country in the analysis, the costs of biological control increased by 12.8% while benefits increased on average by over 8000%. Because maize was also a staple crop in Kenya grown by almost all households, its cumulative production volume in the high potential areas was high (1.7 million tons) compared to for example 265,000 tons of cabbages in Kenya (Macharia *et al* 2005) and 105,000 tons of all fruits in Benin (FAO 2004). The price (US 219 $/ton) of maize was also higher than that of an equivalent volume of other crops targeted by other BC programs in Africa such as US $ 66.3/ton of cabbages. With the high production volume and price, B/C ratio of biological control of maize pest was not surprisingly high. The same trend was found with the IRR whereby with the limited area of analysis, the rate of 3.2-15.6% was obtained compared to the IRR of 114-254.1% obtained when the entire highland areas of Kenya were included in the analysis. The high internal rate of returns shows that the results were expected to be positive under all likely economic situations. The IRR was over 10 times higher than returns to many public of private investments in Kenya. These results corroborates results by Karanja *et al* (2003) who observed that technologies in high potential areas was likely to have substantially greater positive impacts on aggregate farm profits and real incomes.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

The parasitism by the introduced parasitoids increased linearly to reach over 10% in 1998. It was apparent that a minimum of about 10% parasitism was required to keep stemborer population at some equilibrium. However such equilibrium was achieved at a high stemborer density and yield loss was significant. Beyond the 10% parasitism, stemborer population fall over time with partial equilibrium at each parasitism level. Efforts to improve the parasitism level in the field through adoption of farm practices such as modification of farming system can be studied.

The increase in the percentage of yield loss abated arose from the increase in parasitism that helped to diminish the population density of total stemborers. For every increase in stemborer density, the expected yield loss also increased. *Cotesia flavipes* has been found to parasitize the stem bores of *Chilo* family and *Sesamiae calamistis* (Ngi Song *et al* 1995). There has been no evidence to show any reduction in parasitism efficiency by the indigenous parasitoids. The generally stable parasitism by the locally occurring *C. sesamia,* show that the introduced parasitoid does not affect the efficiency of the local parasitoid. This is possible when the saturation level for the parasitoids has not been reached and the hosts are still more abundant compared to the parasitoids. The parasitism level was therefore still expected to rise. The ability of *C. flavipes* to reduce total stem borer density once it was established shows that *C. flavipes* was a superior parasitoid compared to the indigenous parasitoid. Studies to establish whether there is some synergism between the indigenous parasitoids and *C. flavipes* need to be carried out. The project also needs to maintain a parasitoid monitoring team to establish periods of low parasitoid population for augmentative releases if the parasitoid is to be sustained in all favorable ecosystems in all seasons.

The redistribution of the virulent strains to the Kenyan Highlands will not bring in any new species but will benefit the parasitoid through reintroducing genes that could have been lost by the existing parasitoid strain. There is however, the risk of infecting the new generation of *C. sesamia* with *Wolbachia* or the *Microsporadia* virus if at all the inability of the ivirulent strains to develop in *B. fusca* was associated with the viruses. This will however, have no effects on the impact of the parasitoid on yields because although when the males from Kitale were crossed with females from the study area they produce sons only, the reciprocal crossing produces viable sons and daughters (Ngi-Song *et al* 1998). Because of the long time that the host and parasitoid have been associating, the suppression of stemborers by the parasitoid will be faster as compared to use of exotic parasitoids that took time to adapt and cause significant reduction in stemborers population. This was also the case with *T. isis* which was imported to the country from areas with the same environmental conditions and got established immediately after introduction to the Highland area (Bruce 2006, ICIPE, unbpul data).

The greatest achievement by the project in the low potential areas has been the suppression of the stemborer populations, which were still on the increase. From the analysis, parasitism by the introduced parasitoid was still growing and pest densities are expected to continue decreasing. It can be expected that parasitoid species targeting all stages of the stemborer life cycle will speed up pest suppression and push yield losses by stemborers to an insignificant level. Thus, together with the exotic solitary braconid pupal parasitoid *Xanthopimpla stemmator* Thunberg imported by ICIPE in 2000 for classical biological control of *C. partellus* and released in Kenya in 2005 other parasitoids need to be sought and released. *Xanthopimpla stemmator* has successfully established on *Chilo sacchariphagus* (Bojer) in sugarcane fields (Conlong and Goebel 2002) and recently on *C. partellus* on maize in Mozambique (D. Cugala 2006, ICIPE, unbpul data). Previous laboratory work by Gitau (2002) indicated that this endoparasitoid would attack and develop in *C. partellus*, *B. fusca* and the noctuid *S. calamistis*, thus, it might also reduce total borer densities in the area afflicted.

The similar maize yields obtained by users and non-users of pesticide in three out of the four categories of farmers was an indication of the success of biological control in the area. The higher yields obtained by users of pesticides in only one production season could be attributed to the seasonal fluctuation of pest and parasitoid populations, especially in a system where the pest-parasitoid populations were not yet at equilibrium (Jiang *et al.* 2006).

The range of average TE of 57.9 and 67.9% indicates the potential of farmers to increase their maize yield by up to 42% by improving their production efficiency. The variation in yields obtained by farmers in Coastal Kenya regardless of their pest control strategy was attributed to technical and allocative inefficiencies. Use of inorganic fertilizer provides the highest economic returns, but it was doubtful whether farmers in this area will adopt use of inorganic fertilizers owing to the financial constraints. For the resource poor farmers, cost neutral technologies for conservation and improvement of soil fertility will be most appropriate. Replenishment of soil fertility will lead to increase in yields while reducing the impact of stemborers on maize yield.

The low marginal value of chemical crop protection, demonstrated by the low semi-elasticity of pesticides, can be attributed to two factors; first, the success of the introduced parasitoid such that the yield loss abated by pesticides was small, and, secondly, by the low yields the yield loss abatement was based on. The introduced parasitoid *C. flavipes* has achieved high pest control levels and the impact of the stemborers on yields was now low. At the beginning of the BC project, studies had showed that yield loss to stemborers was up to 78% compared to the control (Seshu Reddy & Walker 1990). Coastal Kenya was the first release point of the parasitoid and studies in various parts of Kenya has shown that the pest and parasitoid population were not yet at equilibrium though the pest densities were declining. In order to increase the marginal value of the pest control, BC should be promoted as part of a whole package strategy to improve maize yields. BC control will ensure yield loss to stemborers is perpetually held at insignificant levels while yield gains from adoption of other interventions were not lost to stemborers.

From the analysis, it was evident that the BC programs gives high returns to investment from a relatively low cost. The scientist year cost for the BC programs in the low potential areas was about a quarter of the cost incurred in biological control programs in developed countries. Andres (1977) reported that the USDA invested $ 80,000 per scientist for 1 year in 1976 for biological control. The low cost of the project resulted from the economies of scale achieved by the project from the wide area of project operations that included 11 countries of Africa. All cost components incurred for the programs that involved all the countries was shared proportionately according to their operations. The high IRR obtained by the project signify the low financial risks involved in investing in biological control program. With the benefits, the Project can be rated as one of the successful projects in biological control in Africa that has direct impact on the local community since maize was a staple food in all households. The stream of economic benefits was expected to increase in perpetuity since the parasitoid has permanently been established in the ecosystem.

The estimated benefits of BC as the value of yield loss abated was just a proportion of a stream of benefits that were not quantified but result from adoption of BC. The importance of maize to small scale farmers in the area shows that loss of maize output to stemborers have severe economic and social impacts to the local community such as reduced revenue and household food per capita. This factor was reinforced by the fact that most farmers plant maize during all cropping seasons regardless of the availability of relatively higher value crops such as vegetables. This assessment indicated the potential of biological control to contribute into the welfare of the local community with no investment from the part of the farmers. This study has shown that there were occasional cases where farmers overuse pesticides. Because insects treated with insecticides were likely to develop insecticide resistance (Gutierrez *et al* 1979), and the health implication for improper use of pesticides as confirmed in this study, BC was expected to mitigate costs accruing from use of pesticides.

Thus, the BC was particularly attractive in solving the classical policy objective of equitable distribution of income. A mixture of large-scale farmers who were resource endowed and the poor small-scale farmers who use low levels of purchased inputs including pesticides characterizes the Kenya. Most of the technologies developed in the market require farmers to incur a cost in order to benefit from the technology and thus, benefit only the endowed farmers who have the means to buy the technologies. Conversely, the BC program is expected to first benefit the small-scale farmers who do not use pesticides and the benefits accruing to them will narrow the gap between the rich and the poor. The perpetual reduction in stemborer attack will motivate large-scale farmers to reduce the pesticide use, which will lead to increase in benefits of the program associated with reduction in use of pesticides.

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Appendix I: Variables included in the production function, expected signs and justification

Variable	Expected sign	Justification
Production function		
Land size allocated to maize production (ha)	+	Farmers benefit from economies of scale as area allocated to maize increase
Use of hybrid seed	+	Hybrids are higher yielding than local varieties
Labor (man-days)	+	Determines how best farm operations are undertaken
Use of pesticides	+	Pesticides reduce yield losses to pest
Quantity of inorganic fertilizer (kg)	+	Fertilizers increase soil nutrient and yields that improve plant vigor and reduce impact of pests
Quantity of organic manure (kg)	+	As for inorganic fertilizers
Presence of grass boundaries	+	As trap or barrier plants harbor natural enemies, thus reduce pest populations on crops
Inefficiency model		
Stemborer infestation	+	Stemborers reduce yields directly by damaging grains or indirectly by affecting translocation of nutrients and reducing photosynthetic area
Number of crops intercropped	-/+	Increasing the number of antagonistic crops that increases competition for light and nutrients reduce production efficiency and vice versa
Age of household head (years)	-	Older farmers are likely to work full time to produce and manage their maize farms
Years in school	-	Educated farmers are better managers and are risk takers adhering to important agronomic practices
Availability of off-farm income	-	Avails funds for purchase of inputs and hiring of extra labor
Experience in farming (years)	-	Experienced farmers produce more under prevailing technologies
Total household farm holding size (ha)	-	Determines the number and scale of farm enterprises the household can undertake that determine how much resources will be available for maize production

Appendix II: The link between agricultural inputs, household resources and farmers' characteristics, and yields

Variable	Class	% Total	Yields obtained (Tons/ha)[ω]			
			No pesticide		Use pesticides	
			2004	2005	2004	2005
Farming experience (years)	0-5 years	28.0	0.4a	0.5a	0.8a	1.0a
	6-10 years	31.8	1.6c	1.1c	1.5c	2.1b
	>10 years	40.2	0.8b	1.0b	1.1b	1.0a
Age of household head (years)	< 30	13.6	0.8a	1.1b	0.8a	1.0a
	31-55	50.0	0.8a	0.7a	1.0a	1.3a
	>55	36.4	1.2b	1.0a	1.6b	1.5b
With off-farm income	No	58.3	0.7a	1.2b	1.1a	1.3b
	Yes	41.7	1.1b	0.7a	1.1a	0.7a
Education level	No school	40.9	1.5b	1.2b	0.7b	1.8b
	Primary	42.4	0.5a	0.5a	1.4c	1.6a
	Beyond primary	16.7	1.9b	0.6a	0.4a	1.5a
Farm size (hectares)	< 2	19.7	0.8a	0.5a	0.6a	0.8a
	2.1-5	51.5	1.3b	1.3b	1.4b	1.7b
	> 5	28.8	0.7a	0.8a	0.5a	0.7a
Labor (man-days)/ha	< 50	46.7	1.0b	1.2b	0.9a	1.1a
	50-100	23.5	0.3a	0.6a	0.9a	1.2a
	> 100	31.8	1.4c	0.9a	1.7b	1.8b
Plant hybrid seed	No	58.3	0.5a	0.7a	0.8a	0.8a
	Yes	41.7	1.7b	1.8b	1.3b	1.9b
Apply manure	No	77.3	0.5a	0.7a	1.0a	1.3a
	Yes	22.7	1.1b	1.1b	1.1b	1.4b
Apply inorganic fertilizers	No	7.6	1.0a	0.9a	1.0a	1.4
	Yes	92.4	0.9a	1.6b	3.3b	-
Maize planted within 1st week of rains	No	42.8	0.8a	0.8a	1.2a	1.1a
	Yes	57.2	1.1a	1.0a	1.0a	1.6a
Grass boundaries near maize fields	No	81.8	1.6b	0.4a	0.9a	0.7a
	Yes	18.2	0.9a	1.1b	1.4a	1.0a
Have edge rows around maize farms	No	88.6	0.9a	0.9a	0.9a	1.5a
	Yes	11.4	1.5a	1.2a	3.0a	0.5a
No. of plants intercropped	No intercrop	21.1	1.0a	1.4d	0.7a	1.0a
	1 intercrops	40.9	1.1a	1.0c	0.8a	1.4a

	2 intercrops	30.4	0.8a	0.8b	1.2b	1.0a
	>3 intercrops	7.6	1.2b	0.5a	2.7c	1.6b
Average yields (Tons/ha)$^{\phi}$			0.96a	0.95a	1.08a	1.37b
N			76	78	56	54
Standard deviation			1.3	0.9	1.3	1.5

$^{\omega}$Values followed by the same letter in the column of a variable are statistically equal (P<0.1) $^{\phi}$ Values followed by the same letter along the row are statistically equal (P<0.05)