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Assessing the long-term welfare effects of the biological control of cereal stemborer pests in East and Southern Africa: Evidence from Kenya, Mozambique and Zambia

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ABSTRACT

The International Centre of Insect Physiology and Ecology (*icipe*), undertook a biological control (BC) programme for control of stemborers from 1993 to 2008, to reduce cereal yield losses due to stemborer attack in East and Southern Africa. The programme released four biological control agents—the larval parasitoids *Cotesia flavipes* and *Cotesia sesamiae*, the egg parasitoid *Telenomus isis* and the pupal parasitoid *Xanthopimpla stemmator*—to control the economically important stemborer pests *Busseola fusca*, *Chilo partellus* and *Sesamia calamistis*. Two of the natural enemies that were released got established and spread to many localities in the region. This study adopted the economic surplus model based on production, market and GIS data to evaluate the economic benefits and cost-effectiveness of the programme in three countries—Kenya, Mozambique and Zambia. Findings show that the biological control intervention has contributed to an aggregate monetary surplus of US$ 1.4 billion to the economies of the three countries with 84% from maize production and the remaining 16% from sorghum production. The net present value over the twenty years period was estimated at US$ 272 million for both crops and ranged from US$ 142 million for Kenya to US$ 39 million for Zambia. The attractive internal rate of return (IRR) of 67% compared to the considered discount rate of 10%, as well as the estimated benefit–cost ratio (BCR) of 33:1, illustrate the efficiency of investment in the BC research and intervention. The estimated number of people lifted out of poverty through the BC-programme was on average 57,400 persons (consumers and producers) per year in Kenya, 44,120 persons in Mozambique, and 36,170 persons in Zambia, representing an annual average reduction of poor populations, respectively of 0.35, 0.25 and 0.20% in each of the three countries. These findings underscore the need for increased investment in BC research to sustain cereal production and improve poor living conditions.

1. Introduction

In East and Southern Africa (ESA), cereals, especially maize [*Zea mays* L.] and sorghum [*Sorghum bicolor* (L.) Moench] are among the most important field crops that commercial and small-scale farmers grow (Karanja et al., 2003; Taylor, 2003). These food grains are used to a large extent for subsistence and represent an important calorie intake source for poor rural farm families (IITA, 2013); however, biotic and abiotic problems constrain their production. Among the biotic constraints, insect pests represent an important challenge, and lepidopteran stemborers are the major injurious pests that occur when maize and sorghum are cultivated (Kfir et al., 2002; Polaszek, 1998; Songa et al., 2001). Field infestation of stemborers ranges from 30% to 100%, and the resulting yield loss may reach up to 88% (Kfir et al., 2002; Seshu

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Reddy, 1990; Youdeowei, 1989). In Kenya, the estimated yield loss due to stemborers is equivalent to KShs 7.2 billion (US$ 90 million) annually (EPZA, 2005). Odendo et al. (2003) examined the economic value of loss due to stemborers and found that the average loss in maize was 14%, and ranged from 11% in the highlands to 21% in the dry areas. An extrapolation to the Kenyan national production in maize revealed that about 0.44 million tonnes valued at US$ 25–60 million, which is enough to feed 3.5 million people per annum are lost. Other estimates on four seasons of crop loss gave 13.5%, equivalent to quantity loss of 0.4 million tonnes, which is worth US$ 80 million (De Groote et al., 2011), which corroborates the economic importance of stemborer pests.

Integrated pest management (IPM) including chemical and cultural controls was among the management strategies (Polaszek, 1998). However most of them had a lower adoption rate due to constraints associated to their use that make them impracticable and unattractive to farmers (van den Berg et al., 1998). The use of synthetic insecticides is associated with potential threats such as pest resistance, adverse effects on non-target organisms, hazards of pesticide residues, limited success in application, insecticide overuse, and application of insecticide mixtures (van den Berg and Nur, 1998; Varela et al., 2003). Even though insecticides are effective in managing stemborers in commercial agriculture, many resource-poor farmers cannot afford them. Considering these constraints, and the potentially negative impact of chemical control on human health and the environment, biological control is the appropriate method of control. Classical biological control involves introducing an exotic natural enemy, such as a predator or parasitoid, into a new environment where it did not exist (Lazarovitz et al., 2007). Because of its self-perpetuating characteristic and no additional investment, classical biological control (BC) remains an appropriate strategy of pest control for resource-poor farmers (Hajek, 2004; Kipkoech et al., 2009).

Since the early 1990s, the International Centre of Insect Physiology and Ecology (*icipe*) has made important progress in exploring the suitability and effectiveness of pest management using natural enemies. In partnership with national agricultural research systems (NARS) and universities, *icipe* implemented the biological control (BC) of stemborers through different projects by releasing natural enemies in the major maize and sorghum producing areas in East and Southern Africa (Omwega et al., 2006). Following the introduction of natural enemies, post-release surveys and studies were carried out, reporting establishment, acceptable levels of parasitism and decrease in stemborer densities (Bonhof et al., 1997; Cugala and Omwega, 2001; Cugala et al., 2006; Emana et al., 2002; Jiang et al., 2006, 2008; Odendo et al., 2003; Omwega et al., 1997, 2006; Seshu Reddy, 1998; Sohati et al., 2001; Songa et al., 2001; Zhou et al., 2001). Almost all the studies emphasized the first biological control agent that was released, *Cotesia flavipes (Cameron)* and focused on its short-term assessment (10 years after release), but economic assessments on the real social advantage were not carried out. Kipkoech et al. (2006) to some extent assessed the economic advantages of the natural enemies released using cost–benefit analyses based on yield loss reduction and predictions of parasitism levels and pest densities. The latter ex-ante study lacked results from exclusion experiments, which help in strengthening impact evaluations. Moreover, it was limited to the coastal region of Kenya, yet Omwega et al. (2006) had demonstrated the dispersal of the natural enemies to a wider area in East and Southern Africa.

To fill the knowledge gap regarding the long-term advantages of the biological control intervention, this research sought to assess the ex-post impact on social welfare in Kenya, Mozambique and Zambia. The specific objectives of this study were to: (i) estimate the social gain from the BC implementation and its distribution among consumers and producers, (ii) establish the effect of the intervention on reducing poverty, and (iii) determine whether the investment in BC research was socially worthwhile.

2. Background

2.1. Stemborers

Due to their feeding on plants during their larval stage, stemborers cause important physical and economic damage on cereal crops. Studies have revealed the presence and high diversity of stemborer species in East and Southern Africa (Le Ru et al., 2006a,b; Matama-Kauma et al., 2008; Moolman et al., 2014; Ong'amo et al., 2006), but the most economically important species are the crambid *Chilo partellus* (Swinhoe), and the noctuids *Busseola fusca* (Fuller) and *Sesamia calamistis* Hampson (Kfir et al., 2002; Ong'amo et al., 2006). A summary of their main characteristics is presented in Table 1.

2.2. Biological control

2.2.1. Definition and examples of BC implementations

Biological control is recognized as an ecosystem service of immense economic value (Jonsson et al., 2014). According to the International Biological Programme (1964–1974), biological control denotes the use of living organisms in the control of a pest or use of biota to control biota (Simmonds, 1967). DeBach and Rosen (1991) defined biological control as the use of predators, parasitoids, nematodes, and pathogens to maintain the population of a species at a lower density than would occur in their absence. Lazarovitz et al. (2007) defined biological control as managing a pest by deliberate use of living organisms.

Using this principle, many pest management programmes have been implemented. Well-known examples include control of water hyacinth with the release of *Neochetina* species (*Neochetina eichhorniae* (Warner) and *N. bruchi* (Hustache)) in Benin and East Africa (De Groote et al., 2003), control of the cassava mealybug

Table 1
Origin, infested crops, damages and distribution of the most economically important stemborers.

Stemborer	Origin	Crop infested	Damage on crops	Distribution
Chilo partellus (Swinhoe) (Lepidoptera: Crambidae)	Exotic (Accidentally introduced into Africa through Malawi during the 1920s)	Maize, sorghum, rice, sugarcane	Leaf damage, deadheart, direct damage to grain, increase susceptibility to stalk rot and lodging	East and southern Africa in warm and low altitudes
Busseola fusca (Fuller) (Lepidoptera: Noctuidae)	Indigenous to Africa	Maize, sorghum, millet	Feed on stem and leaves	Sub-Saharan Africa, in cool high altitude area in eastern Africa
Sesamia calamistis (Hampson) (Lepidoptera: Noctuidae)	Indigenous to Africa	Maize, sorghum, finger millet, rice, sugarcane	Attack a number of young stems, feed on stem	Sub-Saharan Africa, prevalent in medium and low altitude areas

(*Phenacoccus manihoti* Matile-Ferrero (Hemiptera: Pseudococcidae)) using *Apoanagyrus (Epidinocarsis) lopezi* De Santis (Hymenoptera: Encyrtidae) in 27 African countries (Zeddies et al., 2001), control of the cabbage pest *Plutella xylostella* Linnaeus (Insecta: Lepidoptera: Plutellidae) using *Diadegma semiclausum* (Hellén) (Hymenoptera: Ichneumonidae) in Kenya (Asfaw et al., 2011; Macharia et al., 2005), and control of the invasive fruit fly *Bactrocera dorsalis* (Hendel) using the bio-agents *Fopius arisanus* (Sonan) and *Diachasmimorpha longicaudata* (Ashmead) in citrus (Ekesi, 2015).

2.2.2. Released bio-agents for control of cereal stemborers in East and Southern Africa

The exotic larval parasitoid *Cotesia flavipes* Cameron (Hymenoptera: Braconidae) was imported from Asia in 1991 and released from 1993 onwards in East and Southern Africa. The first releases were done in the coastal region of Kenya (Omwega et al., 2006; Overholt et al., 1994; Overholt et al., 1997). The egg parasitoid *Telenomus isis* (Polaszek) (Hymenoptera, Scelionidae) is one of the most important stemborer natural enemies found in West Africa (Bruce et al., 2009; Schulthess et al., 2001), and *icipe* introduced it to East Africa in 2005. In addition, the virulent strain of the indigenous larval parasitoid *Cotesia sesamiae* Cameron from western Kenya was introduced in Taita Hills in Kenya. Before redistribution of *C. sesamiae*, the solitary pupal parasitoid *Xanthopimpla stemmator* Thunberg (Hymenoptera, Ichneumonidae) was released in the early 2000s in many East and Southern African countries, including Mozambique and Zambia (Cugala, 2007). The release sites in the study countries (Kenya, Mozambique and Zambia) are shown in Fig. 1.

Evidence of the establishment and spread following the release of biological control agents has been highlighted in several studies and surveys (Assefa et al., 2008; Cugala, 2007; Getu et al., 2003; Mailafiya et al., 2011; Moonga, 2007; Omwega et al., 1995, 1997; Omwega et al., 2006; Sallam et al., 2001). In addition, the parasitism-effect and suppression-effect of the released biological control agents has been demonstrated and confirmed the effectiveness in reducing pest densities (Cugala, 2007; Jiang et al., 2006; Zhou et al., 2001). For instance, Zhou et al. (2001) and Jiang et al. (2006) reported that *C. partellus* density had been reduced by 50% following the release of *C. flavipes*. However, during a recent insect sampling survey, *T. isis* was found only in the sites where it had been released and *C. sesamiae* was not recorded (Ongamo et al., unpublished data). Consequently, the present impact evaluation was carried out on only two species, *C. flavipes* and *X. stemmator*, which had established and spread.

3. Methods

3.1. Economic surplus model

The economic surplus model is used to evaluate commodity-related technological progress in agriculture (Alston et al., 1998; Norton and Davis, 1981). Using this model, the aggregate benefits for socio-economic agents can be estimated after introducing a research innovation or development intervention in a targeted social environment (Akino and Hayami, 1975; Maredia et al., 2000).

In most of East and Southern Africa countries, maize and sorghum productions are in priority for home consumption and rarely for export. According to FAOSTAT (2014), from 2000 to 2010, the estimated average proportions of exported crops relative to the total production were 0.56, 1.27 and 4.88% for maize, and 3.37, 0.20 and 1.91% for sorghum, respectively in Kenya, Mozambique and Zambia. Only a small proportion of the production of these crops was exported, which led us to assume the closed economy approach in the development of our framework. Under this assumption, and following Alston et al. (1998), Masters et al. (1996) and Mensah and Wohlgenant (2010), and assuming linear curves[1] of supply and demand, we determined that surplus change from the biological control (BC) results from the change between two market equilibriums. An initial market equilibrium is obtained by equating the total demand to the total supply equations, yielding the initial price p^* (before the intervention). A second market equilibrium is obtained following the BC-induced shift of the supply curve, yielding $p^*_{BC}$the second equilibrium price

The changes in economic surplus following the parallel supply-shift generated by the BC intervention are analytically expressed as follows:

- Change in consumer surplus:

$$\Delta CS = (p^* - p^*_{BC})\left[q^* + 0.5(q^*_{BC} - q^*)\right] = p^*q^*Z(1 + 0.5Z\eta) \qquad (1)$$

- Change in producer surplus

$$\begin{aligned}\Delta PS &= (k + p^*_{BC} - p^*)\left[q^* + 0.5(q^*_{BC} - q^*)\right]\\ &= p^*q^*(K - Z)(1 + 0.5Z\eta)\end{aligned} \qquad (2)$$

- Change in total surplus

$$\Delta TS = \Delta CS + \Delta PS = p^*q^*K(1 + 0.5Z\eta) \qquad (3)$$

where$Z = -\frac{p^*_{BC} - p^*}{p^*} = (K\varepsilon)/(\varepsilon + \eta))$ the relative reduction in price between the two market equilibria (before and with BC); p^*, p^*_{BC} respectively the initial and after BC equilibrium prices; q^*, q^*_{BC} respectively the initial and after BC equilibrium quantities; ε the price elasticity of supply and η the price elasticity of demand, and K, the supply-shift factor (Alston et al., 1998; Masters et al., 1996; Mensah and Wohlgenant, 2010).

3.2. Return on investment, and cost–benefit analysis

Benefits in surplus are compared to monetary investments, to help evaluate the efficiency of the implemented programme and measure its return on investment. This economic assessment was extended to estimating and analyzing the Net Present Value (NVP), the Internal Rate of Return (IRR), and the Benefit–Cost Ratio (BCR) (Jones et al., 2006; Masters et al., 1996).

3.2.1. Net present value (NVP)

NPV measures surplus earned compared with costs of research, and is estimated based on a given interest rate. This must reflect opportunity cost of funds invested, namely the profitability rate of funds invested in research to generate a technology. The NPV is expressed as:

$$NPV = \sum_{t=0}^{T} (B_t - C_t)(1 + r)^{-t} \qquad (4)$$

where B_t is benefits or the total surplus generated by the technology, C_t represents the technology costs, r is the discount

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

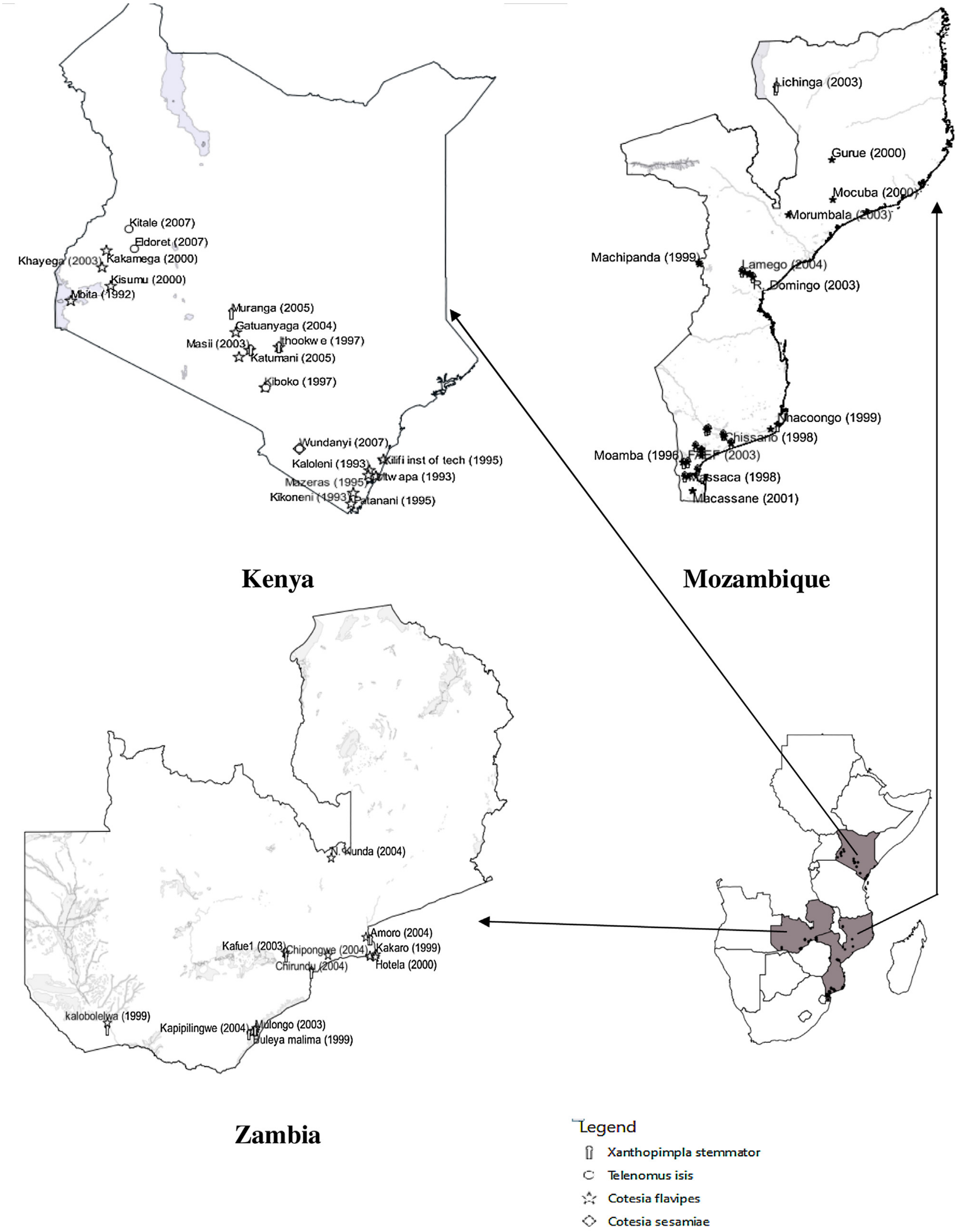


Fig. 1. Classical biological control against stemborers: Points of release of parasitoids in Kenya, Mozambique and Zambia.

rate, and *t* is the time period for which the biological control (BC) occurs. A technology is profitable and acceptable if the NPV exceeds zero.

3.2.2. Internal rate of return (IRR)

IRR measures the interest rate at which present value of investments in BC is equal to present value of benefits. IRR can be compared to any other interest rate that commercial banks charge, or interest rates of private investments. If IRR is greater than these rates, one should conclude that investments in BC in the studied countries are relevant.

3.2.3. Benefit–Cost ratio (BCR)

BCR measures the relative value of benefit generated per investment unit. It is expressed as a ratio of the sum of a BC intervention's discounted benefits to the sum of discounted costs of research and releases. A ratio greater than one justifies the relevance of investment in BC programme in the selected countries. The BCR is expressed as:

$$BCR = \left[\sum_{t=0}^{T} B_t(1+r)^{-t}\right] / \left[\sum_{t=0}^{T} C_t(1+r)^{-t}\right] \quad (5)$$

3.3. Potential effects on poverty reduction

Changes in welfare have been calculated as total monetary value associated with the BC of stemborers in maize and sorghum production. This social benefit can also be described as accrued surplus that allows households to escape poverty. The BC intervention can reduce poverty by raising the income of farming households, reducing purchasing price for consumers, or creating new job opportunities in the maize or sorghum value chains. Alene et al. (2009) provided a formula that allows deriving the number of poor people that could be lifted out of poverty from the change in surplus due to a new technology:

$$\Delta P = \left({}^{\Delta}TS \big/ {}_{A}gGDP \times 100\%\right) \times {}^{\partial}ln(N) \big/ {}_{\partial}ln(AgGDP) \times N \quad (6)$$

where ΔP is the number of poor that could be lifted out of poverty, ΔTS is the change in economic surplus due to the biological control programme, $AgGDP$ is agricultural gross domestic production in year t, and N is the total number of poor in the country. The term ${}^{\partial}ln(N) / {}_{\partial}ln(AgGDP)$ represents the poverty elasticity, which stands for percentage reduction of total number of poor due to 1% increase in agricultural productivity. This equals 0.72 for sub-Saharan Africa (Thirtle et al., 2003) and was used in the estimation.

3.4. Stochastic dominance analysis

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

4. Data and parameters

4.1. Maize and sorghum cropped areas and yields

Data on cultivated area and yield of maize and sorghum in the three study countries were sourced from the FAO database (FAOSTAT, 2014) (Figs. 2–4). The total cropped area under maize stagnated during the 1990s, but a slight increase was reported from 2008 in Kenya. In Mozambique, the area under maize increased from 1990 to 2008 before decreasing during the last five years. On the other hand, the area under sorghum stagnated from 1990 to 2001 but increased from 2001 to 2013. The area under maize in Zambia showed a fluctuation before 2008 but increased from 2008 to 2011. In this country, sorghum production is low compared to maize, even though the crop is ranked second after maize (Hamukwala, 2010).

4.2. Biological control-induced supply shift parameter

While referring to the theoretical framework and the formula obtained for the producers, consumers and total surplus in Eqs. (1) and (2), the K_t parameter representing the BC-induced supply shift parameter was found to be critical in determining the benefits from using biological control. The supply shift parameter (Alston et al., 1998) is equal to:

$$K_t = (j_t/\varepsilon) - c_t \quad (7)$$

where j_t is the proportionate change in production due to BC intervention at time t, ε the price supply elasticity of the product, and C_t the increase in cost incurred by the presence of the BC agent,

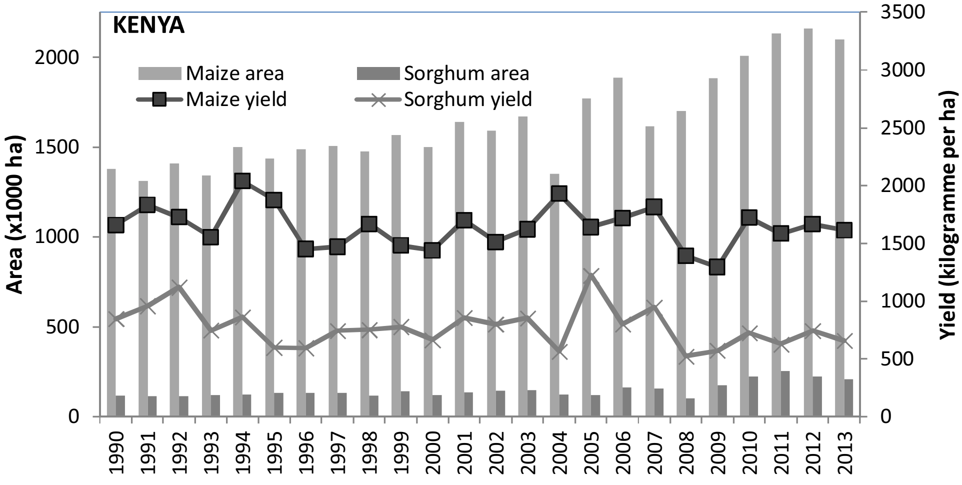


Fig. 2. Trends in maize and sorghum cultivated area and yield in Kenya.

Source: FAOSTAT database 2014

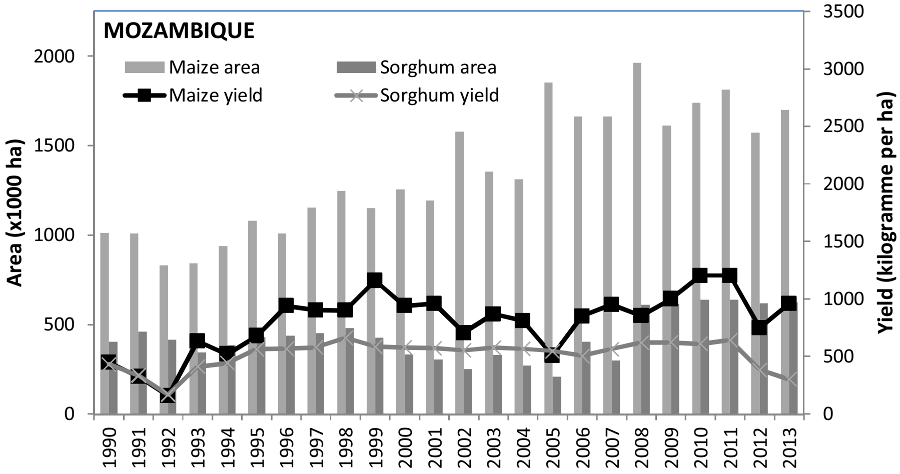


Fig. 3. Trends in maize and sorghum cultivated area and yield in Mozambique.

Source: FAOSTAT database 2014

or average change in variable cost to achieve the yield increase. Biological control is a self-spreading and self-sustaining technology and prevents the farmer from incurring any additional cost. In addition, production increase due to BC is unrelated to any other additional input, implying that the total cost of production remains unchanged, rendering the parameter c_t in Eq. (7) to be equal to zero; consequently, the supply shift equation is reduced to the ratio (j_t/ε).

While the literature on maize and sorghum supply provides ε, one still needs to estimate the parameter j_t. The parameter represents the total increase in production attributable to the BC intervention. Where multiple BC agents have been released with different performances, Eq. (8) is used to calculate the total increase in production:

$$J_t = \sum_{i}^{n} (\Delta BC_{it} \times S_{it} \times A_t) \tag{8}$$

with ΔBC accounting for yield increase due to the presence of a biological control agent or combination of agents, i the released and established species of the biological control agents [*C. flavipes* (*Cf*) and *X. stemmator* (*Xs*)], as well as their combination (*Cf, Xs*). S is the rate of BC area coverage, which is the ratio of the total area covered by a released BC agent (or combination of agents) and the total acreage A under cultivation of the considered crop (maize or sorghum), while t represents the time. The parameter j_t is then derived from Eq. (8) as the proportion of total production in year t $(j_t = J_t/Y_t)$ where Y_t stands for the total production of maize or sorghum at the defined year t. Therefore, the overall formula for estimating the BC-research supply shift becomes:

$$K_t = 1/\varepsilon \times Y_t \left(\sum_{i}^{n} (\Delta BC_{it} \times S_{it} \times A_t) \right) \tag{9}$$

4.3. Yield gains or abated losses attributable to the BC-agents (ΔBC)

To evaluate the impact of biological control, many studies have used the host–parasite relationship model to demonstrate the effect of parasitism by the natural agents on the stemborer density reduction (Gitau et al., 2005, 2007; Jiang et al., 2008; Zhou et al., 2001). However, little is known about the causal effect of the density reduction on crop yield loss abatement or the gain attributable to the parasitism effect. Researchers conduct the so-called exclusion experiments (Cugala, 2007; Kfir, 2002) to determine the intrinsic gain due to parasitism by the biological control agents, which involves three treatments. Plots are set in fully protected, unprotected, and exclusion plots as treatments. The

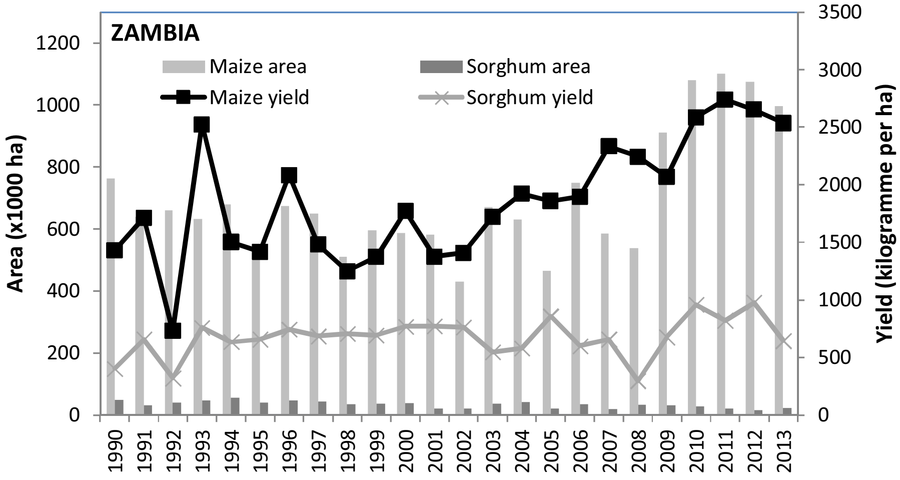


Fig. 4. Trends in maize and sorghum cultivated area and yield in Zambia.

Source: FAOSTAT database 2014

unprotected plots are those without plant protection, and represent where the BC activities occur naturally. The exclusion plots are sprayed with selected insecticide to partially eliminate the natural enemies, and are referred to as the non-BC plots. On the fully protected plots, natural enemies and stemborer pests are removed. Yield losses due to stemborer attack in the absence of natural enemies are obtained from the difference between the yield from the protected and exclusion plots. This difference is of high interest for the present study, as it represents the yield gain due to the biological control action at plot level. Using this approach, the yield gains due to the stemborer parasitism were estimated as 26.1% in Chokwe, 11.2% in Machipanda and 7.6% in Lichinga in Mozambique (Cugala, 2007). The average of these three percentages (14.96%) was considered in this study for *X. stemmator.* Zhou et al. (2001) estimated the yield gain due to *C. flavipes* at 10%. In this paper, we consider the average yield gain for the two biological control agents combined.

4.4. Measuring dispersal area of the BC agents

Biological control is a self-perpetuating technology, and consequently, the evaluation of its impact depends on the extent to which the released natural enemies reproduce and spread. Measuring the area covered by BC in this impact evaluation constituted a challenge, as data on the follow-up and yearly monitoring of the dispersal movements were missing. Dispersal can occur in two ways: self-movement (flying or walking) and long distance dispersal caused by abiotic factors (such as wind) and biotic factors (such as animal or unintentional transportation of infested stems and grains containing parasitized pests or eggs) (Petit et al., 2009). Models used to estimate the temporal area occupied by a released biological agent include, among others, the diffusion process spread function of Waage et al. (2005) and the Chock exponential function (Chock et al., 2010). Because these functions fail to integrate the diversity of the released biological control agents and the overlapping probability of the spread area of different biological control agents, we adopted the spatial modelling analysis using GIS software. With the GIS coordinates of all the release points, we modelled the spread around each release point in the four cardinal directions using concentric circles respecting the year of release and the appropriate specific annual dispersal rate (Gichini et al., 2008; Nordblom et al., 2002). Omwega et al. (1997) found the dispersal rate of *C. flavipes* to be 60 km per year whereas Assefa et al. (2008) found it to be higher than 200 km per year. Later, Omwega et al. (2006) estimated this dispersal distance to be 11.23 km per year. Applying the principle of the ‘least favourable assumption’, we selected the minimum rate of 11.23 km per year for *C. flavipes*, and based on findings of Cugala (2007), we selected 8.3 km per year for *X. stemmator.* Based on these spread distances, we modelled the area the biological control agents had covered for all of the release points for each year, to calculate the area the biological control agents had spread (Fig. 5).

In Kenya, maize occupies over 22% of total farmed land (Mbithi and Huylenbroec, 2000). We used the yearly proportions of acreage under maize and sorghum compared to the entire land for Mozambique and Zambia. These coefficients were then used to calculate the annual maize and sorghum area under BC, and the proportions of maize and sorghum land under BC (Fig. 6). The trends in these proportions show a higher BC cover for Kenya compared to Zambia and Mozambique.

4.5. Price elasticity of supply and demand, and prices for maize and sorghum

As mentioned in Section 2.1, price elasticity of supply and demand (ε and ŋ) is key in the estimation of consumer, producer, and overall social benefits. The estimates of these parameters are available from recent published studies for the three countries, and the selected ones for the present assessment are summarized in Table 2. Maize and sorghum time-series data on prices (Fig. 7) have been assessed from FAOSTAT (2014). These prices were converted to real prices using the food consumer price indexes accessed from the FAO and African Development Bank databases (AfDB, 2014).

4. research investments

The required activities for implementing BC involved investments in personnel, including scientists, administrative staff and technicians, as well as investments in laboratory equipment and vehicles, importation and mass rearing of natural enemies, basic surveys, studies and consultations, and training of national scientists, extensionists and farmers. Data on the annual total cost of these activities were assembled from different project documents and evaluation reports. The Biological Control Programme comprised of four projects that were implemented from 1990 to 2008: the first started in 1990 and ended in 1992 at a cost of US$ 0.6 million, the second from 1993 to 1996 at a total cost of DFI 3.87 million (DFI is the Dutch guilder, the former currency of the Netherlands until 2002, where 1 unit is worth US$ 0.56, as per the value of 23 February 2015), the third from 1997 to 2001 with a total cost of DFI 7.5 million, and the fourth from 2002 to 2008 with a total cost of US$ 52 million. The total annual expenses were divided based on the 10 countries (Kenya, Eritrea, Madagascar, Malawi, Mozambique, Somalia, Tanzania, Uganda, Zambia, and Zimbabwe) that benefited from the programme, and the portion of the three study countries was considered in the present evaluation.

5. Results and discussion

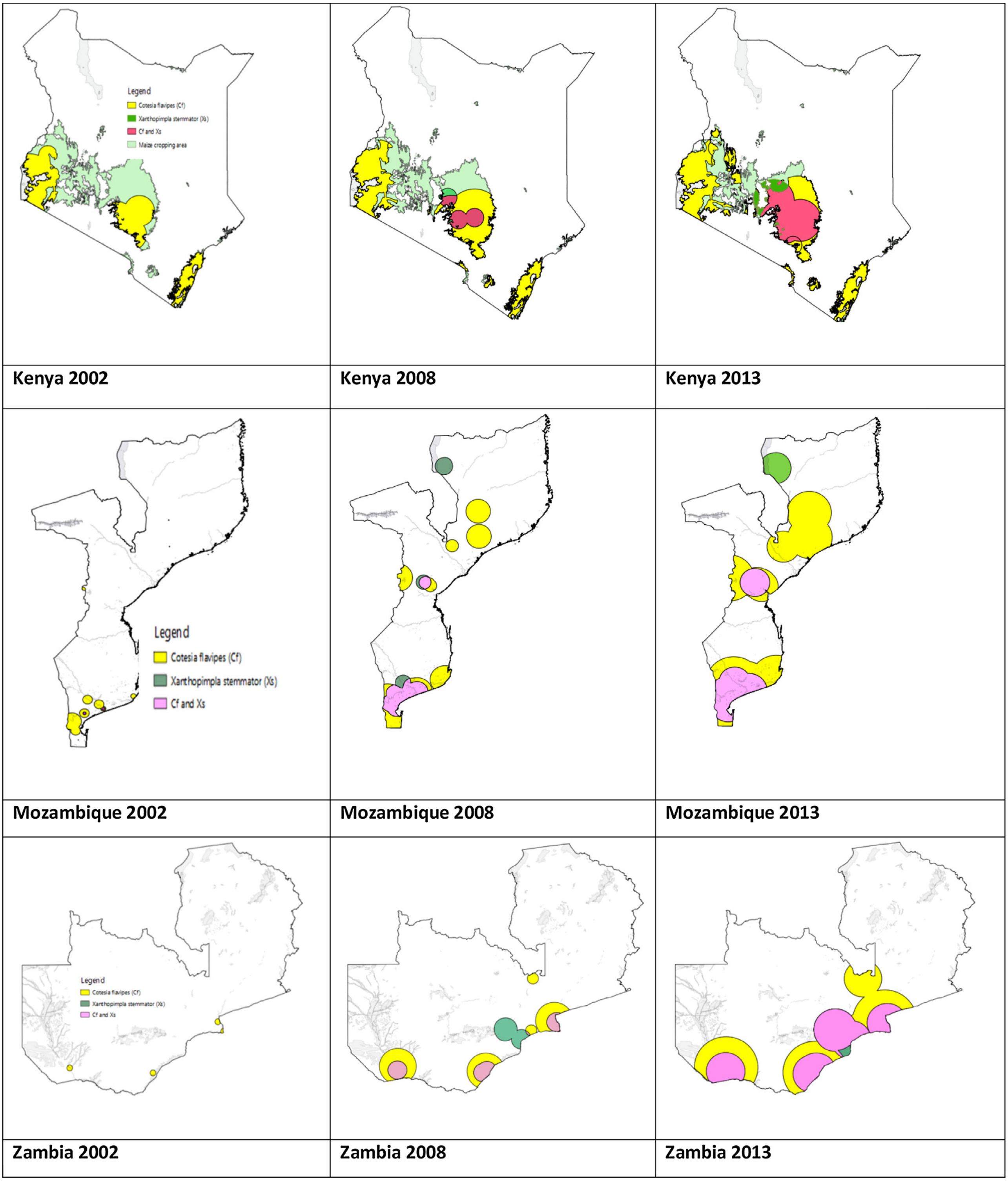
5.1. Welfare change due to biological control of stemborers

The *icipe* biological control intervention contributed to an aggregate value of US$ 1358 million to the economy of the three countries from 1990 to 2013 with 84.24% (US$ 1144 million) from maize production and the remaining 15.75% (US$ 214 million) from sorghum production (Table 3). These results show that the Biological Control Programme has had a positive impact on welfare in the three countries. Producers gained 57.7% of the total surplus, confirming that they are the major beneficiaries of the BC research.

At country level, Kenyan maize farmers gained an average of US $ 15.39 million annually from 1993 to 2013, whereas sorghum producers gained an average of US$ 5.84 per year during the same period due to biological control of stemborers. The annual gains were US$ 6.82 and US$ 15.77 million for maize production, and US$ 1.04 and 0.31 million for sorghum production, respectively for Mozambique (from 1996 to 2013) and Zambia (from 1999 to 2013). Maize and sorghum consumers also gained from the decrease in price due to the higher supply induced by the biological control of stemborers. Annual surplus gains were, respectively, US$ 13, 5.80 and 10.07 millions for maize consumers, and US$ 2.07, 0.98 and 0.18 million for sorghum consumers in Kenya, Mozambique and Zambia (see also Tables A1 and A2 in Supporting material).

5.2. Net benefits and rates of return to investment in BC of stemborers

We estimated the total net present value (NPV) of *icipe*’s biological control programme over the period 1990–2013 at US$ 175.66 million for maize and US$ 46.56 million for sorghum, accruing to US$ 271.76 million for both crops (Table 3). At country level, the NPVs reached US$ 141.52, US$ 33.02 and US$ 38.98 million for both crops in Kenya, Zambia and Mozambique,



Kenya 2002 **Kenya 2008** **Kenya 2013**

Mozambique 2002 **Mozambique 2008** **Mozambique 2013**

Zambia 2002 **Zambia 2008** **Zambia 2013**

Fig. 5. Classical biological control against stemborers: Spread of parasitoids after release in the study areas in Kenya, Mozambique and Zambia observed in 2002, 2008 and 2013.

respectively. The higher net benefits for Kenya are due to the scattered release sites that allowed the natural enemies to spread and cover more extended agricultural areas. The spread started from the coastal region (Overholt et al., 1994), and at Mbita, in western Kenya where the BC agents inadvertently escaped from the laboratory colony (Omwega et al., 1995), followed by spread from other well-distributed release sites in Central, Eastern and the Rift Valley of Kenya. In Mozambique, the majority of the release points were concentrated in the south, and in Zambia, most releases were done near the border; consequently, the BC agents spread to the neighboring country. The earlier start of the BC programme in Kenya could also justify the higher net present value for that country.

By calculating the internal rate of return to the investment, we were able to recognize the value of the efficiency of investment in the BC research. The overall internal rate of return of 67% obtained

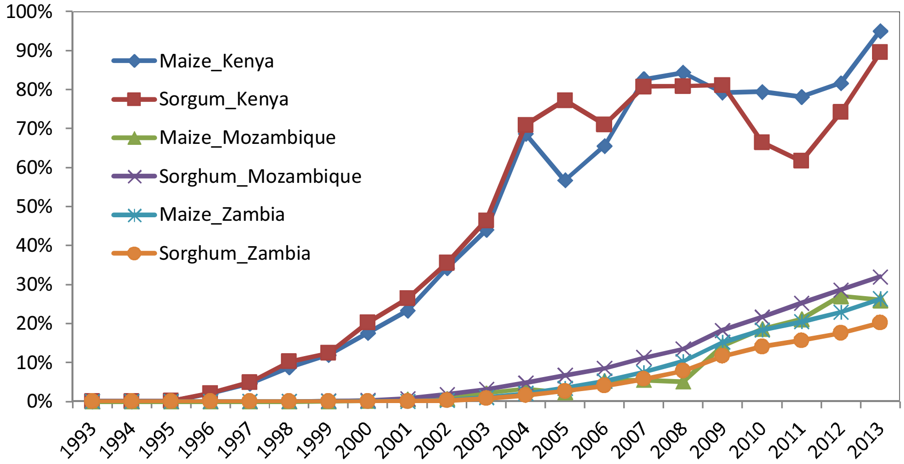


Fig. 6. Trends in estimated proportions of area under crop covered by biological control agents.

Table 2
Price elasticity values used in the surplus calculation.

Parameter	Value	Crop	Country	Source
Supply elasticity	0.53	Maize	Kenya	Mose et al. (2007)
	0.2	Sorghum	Kenya	Diao et al. (2008)
	0.4	Maize	Mozambique	Diao et al. (2008)
	0.4	Sorghum	Mozambique	Diao et al. (2008)
	0.3	Maize	Zambia	Dorosh et al. (2009)
	0.24	Sorghum	Zambia	Simatele (2006)
Demand elasticity	−0.8	Maize	Kenya	Nzuma and Sarker (2010)
	−0.42	Sorghum	Kenya	Diao et al. (2008)
	−0.47	Maize	Mozambique	Diao et al. (2008)
	−0.424	Sorghum	Mozambique	Diao et al. (2008)
	−0.47	Maize	Zambia	Dorosh et al. (2009)
	−0.424	Sorghum	Zambia	Diao et al. (2008)

for the three countries is attractive because it is above the prevailing discount rate of 10%. In addition, for all countries and both crops, the internal rate of return, ranging from 16.11% for sorghum in Zambia to 108.80% for maize in Kenya, is higher than the considered interest rate of 10%, which makes the investment in *icipe*'s biological control research worthwhile.

The Benefit–Cost Ratio (BCR), another efficiency measure for funds used in research, was found to equal 33.47, meaning that each dollar invested in the biological control programme generated an additional value of 33.47 dollars for the three countries combined. For each country, the BCRs, ranging from 5.18 for sorghum in Mozambique to 589 for sorghum in Kenya, were much higher than 1, confirming the profitability of investing in *icipe*'s biological control research and releasing the natural enemies in these countries.

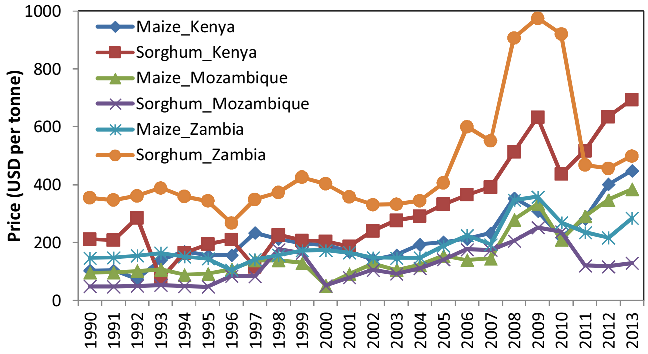


Fig. 7. Trends in maize and sorghum prices in Zambia, Kenya and Mozambique. Source: FAOSTAT, 2014

However, the figures for Zambia and Mozambique (Table 3) are much lower than those obtained in many other BC programme impact assessments. De Groote et al. (2003) estimated a BCR of 124:1 for the biological control programme of water hyacinth undertaken in Southern Benin. Bokonon-Ganta et al. (2002) found a BCR of 145:1 for the biological control programme of mango mealybug in Benin and Norgaard (1988) estimated a BCR of 149:1 for the biological programme against the cassava mealybug in Africa.

5.3. Effect of biological control of stemborers on poverty reduction

To estimate the potential annual reduction of poverty due to *icipe*'s BC programme, we accessed data on the share of agricultural gross domestic product (AgGDP) and the trends in poverty incidences in the three countries from the World Development Indicator database. The calculated trends of potential poverty reduction impacts of BC research over the period 1993–2013 are presented in Fig. 8 (see also Table A3 in Supporting material). Poverty reduction is expressed here as the proportion of poor people that could be lifted out of poverty,[2] and ranged from 0.05% in 1996–0.81% in 2013 for Kenya, 0.01% in 1999–0.49% in 2013 for Mozambique, and 0.02% in 2002–0.79% in 2013 for Zambia. For each country, the reduction in poverty reached 0.1% after 6–7 years,

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

Table 3
Welfare change, benefits and return on investment.

Country	BC-induced change in			Net Present value (NPV) (US$ millions)	Internal rate of return (IRR)	Benefit–Cost Ratio (BCR)
	Producer surplus (US$ millions)	Consumer surplus (US$ millions)	Total surplus (US$ millions)			
Kenya						
Maize	307.98	260.08	568.06	108.80	108.23%	238.80
Sorghum	116.82	55.63	172.45	32.65	118.99%	584.52
Total	424.80	315.70	740.50	141.52	113.08%	276.45
Mozambique						
Maize	115.95	98.68	214.63	28.52	30.66%	20.71
Sorghum	17.73	16.72	34.45	4.50	24.25%	8.36
Total	133.68	115.40	249.08	33.02	29%	11.57
Zambia						
Maize	220.89	140.99	361.88	38.34	18.76%	8.08
Sorghum	4.47	2.53	7.00	0.64	16.11%	5.18
Total	225.36	143.52	368.88	38.98	18.69%	4.51
Aggregate						
Maize	644.82	499.75	1,144.57	175.66	31%	11.60
Sorghum	139.01	74.88	213.89	46.56	81%	49.57
Total	783.83	574.63	1,358.46	271.76	67%	33.47

confirming the long-term benefit effect of BC programme found to approximate 7 years in Zhou et al., 2001. The average potential annual poverty reduction is presented in Table 4. Estimated potential impact on poverty was on average 0.35% per year in Kenya, 0.25% in Mozambique and 0.20% in Zambia. The relatively higher poverty reduction found for Kenya compared to Mozambique and Zambia is in line with the broader area covered by the BC in that country. The better results obtained for maize compared to sorghum confirm its importance as food crop for resource-poor people, who improved their welfare with the yield gain resulting from BC of cereal stemborers. Poverty impacts from the BC programme have increased with time, confirming that the intervention is a sustainable course of action for promoting poverty reduction.

5.4. Sensitivity analysis

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

Results of the sensitivity analysis (Table A4 in Supporting material) show that the welfare change, the efficiency of investment in BC research, and the potential poverty reduction are sensitive to change in proportional yield gain (or abilities of the BC agents to parasitize). Reducing the yield gain attributable to parasitism by the biological control agent *Cotesia flavipes* by 50%, results in reduction of 47%, 37% and 34% of the total social benefits; and 48%, 41% and 46% of the net present value of benefits for both crops, respectively for Kenya, Mozambique and Zambia. Reduction

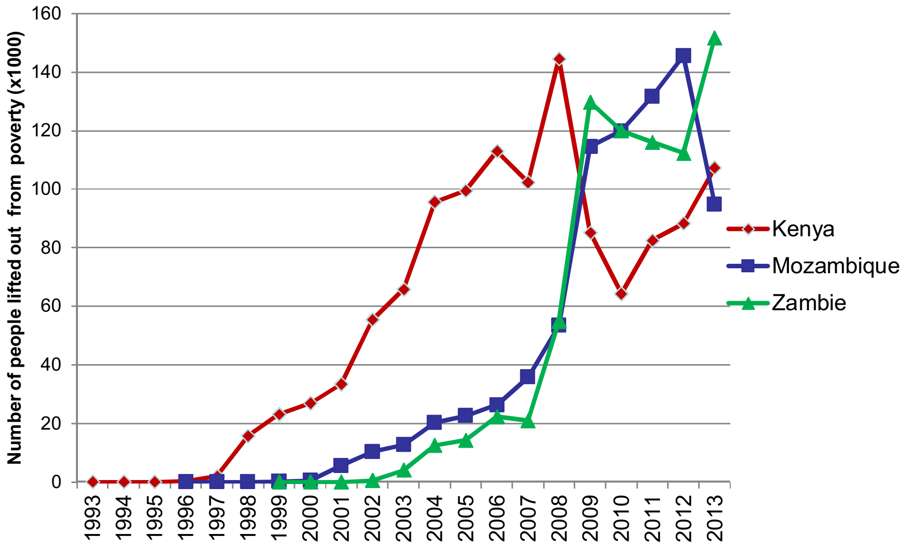

Fig. 8. Trend in poverty reduction due to the BC intervention.

Table 4
Poverty reduction due to BC.

Country	Average annual number of poor (x 1000)	Potential average% of people lifted out of poverty
Kenya		
Maize	43.98	0.27
Sorghum	13.42	0.08
Total	57.40	0.35
Mozambique		
Maize	37.24	0.22
Sorghum	6.88	0.05
Total	44.12	0.25
Zambia		
Maize	35.46	0.37
Sorghum	0.71	0.01
Total	36.17	0.20

is also observed with the internal rate of return that decreased from 113%, 29% and 19% to 93%, 25% and 16%, respectively for each country. The potential poverty reduction also decreases by 48%, 38% and 34% respectively for Kenya, Mozambique and Zambia.

When assuming a 50% increase in crop yield gain due to each parasitoid, the welfare change, the efficiency of investment in BC research, and poverty reduction, to some extent, increase in the same proportions as in the case of 50% reduction of yield gain. The magnitude of changes according to the biological control agents shows higher changes for *C. flavipes* than for *X. stemmator.*

Change in the value of the price elasticity of supply results in a large change for surplus as well as net present value mainly for maize in the different countries (Table A5 in Supporting material). For a value of inelastic supply of 0.1 (initial value of 0.59), the social benefits, the net present value benefit and the potential poverty reduction increase by more than 5, 4 and 3 times compared to their initial estimated values for maize in Kenya, Mozambique and Zambia, respectively. The same results were obtained for sorghum in Mozambique and Zambia. Shifting from the models' base values to the unitary price elasticity of supply (1: relatively elastic) reduced the benefits, research investment efficiency, and potential poverty reduction by more than 40%. For the price elasticity of demand, a slight increase was noted concerning the inelastic demand of 0.1 (Table A5 in Supporting material). In addition, assuming an elastic demand (1.5) leads to a reduction in the impact estimates. The responsiveness of the supply of the studied cereals to a change in price has a larger effect on the impact results than the responsiveness of their demand. This result confirms the features of agricultural food crop commodities.

5.5. Stochastic economic surplus

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

We then ran six models (Maize in Kenya, Maize in Zambia, Maize in Mozambique, Sorghum in Kenya, Sorghum in Zambia and Sorghum in Mozambique), setting 10,000 iterations. As outputs for each of the three indicators of interest (NPV, IRR, BC ratio), we got the summary statistics of their distribution, their cumulative probability distribution, and the relative impact of the considered parameters' mean. The results of the cumulative probability distribution are summarized in Figs. A1 and A2 . For the maize models, the range of distributions of the NPV (US$ 51.7 million to US$ 936.2 million for Kenya, US$ 4 million to US$ 215 million for Mozambique, and US$ 16.6 million to US$ 68.4 million for Zambia) was positive, indicating that there is no probability of getting a negative return with the *icipe*'s Biological Control Programme. A similar result was obtained for the IRR (85.8% to 178.9% for Kenya, 21.3% to 41.7% for Mozambique, and 15.5% to 21.4% for Zambia), indicating there is no probability of having an inferior rate to the current 10%, meaning that it will always be profitable to invest in BC interventions. As for the BCR, the minimum values of the distribution ranges (116–1955 for Kenya, 5–102 for Mozambique and 5–12 for Zambia) are all greater than 1, indicating that each invested dollar in the biological control programme will always result in gain.

Similar results were obtained for sorghum (Figure A2) in the studied countries except for Zambia where some minimum values of the cumulative distributions were negative (-0.1 million US$ for the NPV, 8% for the IRR). However, the probability of getting NPV greater than 0 and IRR greater than 10% was higher than 95%.

6. Conclusion

Under the assumptions of closed economy, parallel shift of supply and demand and the linear supply and demand curves, findings from the economic modeling of the BC-induced shift in maize and sorghum supply in Kenya, Mozambique and Zambia, provide evidence that producers and consumers have benefitted from the biological control of stemborer pests. The estimate for the internal rate of return and the benefit–cost ratios revealed high efficiency of the invested funds, and justified the cost-effectiveness of the BC programme. The net present value also confirmed high profitability of the investment. Moreover, the results showed a yearly increase in number of people that could be lifted out of poverty with the spread of BC, which indicates that BC interventions remain important policy and self-sustainable tools to help promote and contribute to poverty reduction in the region. The worst-case scenarios in the sensitivity analysis still maintained positive impacts and lent credence to the described results. An advanced sensitivity analysis integrating stochasticity due to nonhomogeneous or uncertain parameters' values confirmed the certainty of the positive benefit from BC intervention in our studied countries.

This study explored the implications of using an ecologically based host–parasitoid interaction on the welfare of communities in East and Southern Africa, and showed that the ecosystem service provided by beneficial insects was advantageous to farmers as well as consumers. To our knowledge, no comparable empirical studies on ex-post economic impact of the *icipe* classical biological control programme on cereal pests has been undertaken or published, but the cost–benefit analysis provided by Kipkoech et al. (2006) is a reference point in such a discussion. The cited ex-ante analysis predicted the benefit–cost ratio to reach 19:1 by the end of the 20-year period for maize in coastal Kenya. Findings from our study show higher figures for maize, and this could be explained by the spread of the natural enemies to more cultivated zones. Comparison with the findings of the biological control in other crops shows various results. Based on the benefit–cost ratio, the BC programme on maize and sorghum in Zambia and Mozambique was less expensive than other BC programmes implemented in other African countries, such as the biological control programme of water hyacinth in southern Benin (De Groote et al., 2003), the biological control programme of mango mealybug in Benin (Bokonon-Ganta et al., 2002), and the biological control programme against the cassava mealybug in Africa (Norgaard, 1988).

However, the findings on the returns on BC can be considered as conservative, since we used the reasonable least favourable case principle (the lower dispersal rate of the released biological control agents) in the calculation. The benefits would have increased if the advantages due to the spillover effect into neighboring countries were considered. Additional benefits from the reduced health hazards and other benefits linked to the reduction of risks to the environment have not been included as well.

One of the methodological innovations in this assessment was the use of GIS-based modeling to simulate the geographical spread and determine the overlapping build-up of the parasitoids from release points. This was valuable in determining the area covered by the BC intervention per year, and the cultivated cereal area under BC per year, which are important data in determining the supply shift and in computing the surplus. There is room for improvement in future studies, when conducting regular follow-up surveys following a BC intervention. The 'extensive survey' should be undertaken regularly to offer the possibility of testing and correcting the GIS-modelling, and enhancing the confidence on assumptions on dispersal rates and spread of the biological control agents (Nordblom et al., 2002). Moreover, the existence of possible variability in yield gain or loss abatement across regions (an important shortcoming in economic surplus analyses), should guide assessors to conduct at least one exclusion experiment in each agroecological zone in future.

Evidence from this study shows an improvement in the welfare of producers and consumers through implementing a sustainable and cost-effective BC programme, which implies that efforts should be made to scale up BC interventions to other areas with serious stemborers problem, and that more funds could be invested in biological control programmes in East and Southern Africa and employing the release sites distribution pattern used in Kenya for maximum impact. Furthermore, while the biological control agents *C. flavipes* and *X. stemmator* got established and are contributing to reducing yield loss, two other biological control agents (*C. sesamiae* and *T. isis*) have been found within the confines of their release points. To optimize on the advantages from BC, activities to ensure establishment and spread these biological control agents, especially for the control of *B. fusca* in high-altitude zones, are required.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.05.026.

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