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REVIEW

Economic impact of a classical biological control program: application to *Diachasmimorpha longicaudata* against *Batrocera dorsalis* fruit fly in Kenya

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Abstract Classical biological control (CBC) has been exploited as a safer alternative for suppressing the oriental fruit fly, *Bactrocera dorsalis,* by importing, rearing, and releasing the larval parasitoid, *Diachasmimorpha longicaudata*. Although *D. longicaudata* has been released in Kenya through the Africa Fruit Fly Programme, the extent of its dispersal and subsequent economic benefits have not yet been established. This paper models the spatio-temporal dispersal of the parasitoid using the fuzzy cellular automata approaches and estimates the net benefit from each dollar invested in the CBC approach. We calculated the return on investment based on funding into the programme between 2006 and 2015 and the result of the dispersal range of the parasitoid predicted using an artificial intelligence algorithm. The investment yielded a significant net present value of US$42.8 million over the 16 years. Besides, the cost–benefit ratio showed that for every US$1 invested, the return benefit was US$93**,** confirming the profitability of the CBC program. The economic gains are significant considering that there is no environmental contamination and possible adverse effects from the CBC intervention. The study findings support investment in biological control strategies for the eco-friendly and area-wide management of *B. dorsalis.*

Keywords Artificial intelligence · Cost–benefit analysis · Return on investment · Classical biological program

Introduction

The horticulture sub-sector plays a vital role in providing nutritious food, generating income, and enhancing the profits of farmers and other

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stakeholders across the value chain in Africa (van den Broeck and Maertens 2016; van den Broeck et al. 2018). This sub-sector is acknowledged for its significant contribution to the gross domestic product (GDP) of African nations, essential for the economic transformation of the continent as outlined in several policy documents (such as the Maputo Declaration on Agriculture and Food Security; the Comprehensive African Agricultural Development Programme (CAADP); the Malabo Declaration on Accelerated Agricultural Growth; and the Africa Union (AU) Agenda 2063).

Although Africa's horticulture sector holds immense promise, pest incursions pose a significant obstacle to achieving comprehensive food and nutritional security. A prime example is the fruit fly, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae), native to Asia and first identified in Kenya in 2003 (Lux et al. 2003). This invasive species causes severe damage to mangoes, as well as other fruits and vegetables, resulting in up to 80% crop loss and in some cases total crop failure without proper management interventions (Ekesi et al. 2009).

In addition to the immediate impact on horticultural crops, foreign species invasions, such as *B. dorsalis*, can lead to negative consequences for ecosystem function and environmental health due to the high application of chemical pesticides to control the insect pests. On the other hand, indirect losses can stem from trade restrictions, the loss of valuable export markets, and heightened production costs as farmers often turn to excessive use of synthetic chemical insecticides. These pesticides can be both ineffective and unsustainable, posing risks to human health and the environment. The estimated annual financial burden of export bans related to *B. dorsalis* is approximately US$2 billion, which has far-reaching socio-economic implications for the countless individuals who depend on the horticulture industry in Africa (Ekesi et al. 2016).

In general, invasive alien pests like *B. dorsalis* enter new environments without their naturally co-evolved natural enemies that keep them in check in their native habitats. Local parasitoid species, such as *Psyttalia cosyrae* (Wilkinson), *Psyttalia phaeostigma* (Wilkinson) (Hymenoptera: Braconidae), and *Tetrastichus giffardii* Silvestri (Hymenoptera: Eulophidae), have been found to be ineffective against *B. dorsalis* due to the pest's robust immune response (Mohamed et al. 2006; Mohamed et al. 2016). Moreover, the exploration to find an effective local parasitoid proved unsuccessful (Rwomushana et al. 2008; Mohamed et al. 2016), supporting the laboratory findings.

As a result, it became necessary to import and release more efficient classical biological agents, such as *Fopuis arisanus* (Sonan) (Hymenoptera: Braconidae) and *Diachasmimorpha longicaudata* (Ashmead) (Hymenoptera: Braconidae), to control the *B. dorsalis* fruit fly (Mohamed et al. 2006, 2016). One benefit of using parasitoids for biological control is their ability to spread from the release point, providing a cost-effective crop protection medium among farmers affected by the target pest. For example, in Kenya, after the release of *D. longicaudata*, the parasitoid was found up to 8 km away from the release site after a year, with reported parasitism rates of up to 64% on *B. dorsalis* (Ndlela et al. 2020). The efficiency of the use of the classical biological control (CBC), therefore, also benefited mango growers situated far from the release points.

While the use of natural enemies in pest management has been acknowledged as a viable strategy, the subsequent economic impacts of such releases are often not thoroughly investigated (Niassy et al. 2022). The rationale for conducting an economic assessment after the deployment of biological control agents is crucial for several reasons. First, it quantifies the return on investment from implementing these eco-friendly pest management strategies. This data provides critical insights for farmers who bear the costs of adoption and for policymakers who seek cost-effective and sustainable solutions to support (Midingoyi et al. 2016). Second, it allows us to evaluate the economic feasibility and competitiveness of these practices compared to conventional chemical-based pest management techniques (Muriithi et al. 2016). In essence, an economic study post-release underscores the financial viability of these biocontrol strategies, which is as important as their ecological effectiveness (Midingoyi et al. 2021). The assessment of economic impact ensures the comprehensive appraisal of the technology, contributing to a holistic understanding of its implications on farming systems. Therefore, the need for such an economic study is not just desirable, but indeed, essential.

Numerous investigations (e.g., Norgaard 1988; De Groote et al. 2003; Macharia et al. 2005; Midingoyi et al. 2016; Muriithi et al. 2016; Naranjo et al. 2019;

Niassy et al. 2022) have employed a variety of methodological techniques to estimate the socio-economic advantages of introducing biocontrol agents against diverse pests in Africa. While these studies have considerably advanced our understanding, they often make assumptions about the parasitoids' area coverage based purely on a predetermined radius. This could potentially lead to inaccuracies in the estimation of their effective impact and the resulting economic assessment. An adaptive approach that considers dynamic, spatially variable factors, such as pest suitability, crop characteristics, and micro-climatic conditions, can provide a more precise and context-specific estimation of parasitoid coverage (Agboka et al. 2022). Such a nuanced approach might yield a more accurate and comprehensive understanding of the real-world effectiveness of these biological control strategies.

In a recent study, Agboka et al. (2022) designed an innovative and reliable approach for measuring the dispersal of parasitoids on a large scale using an artificial intelligence (AI) algorithm, specifically the fuzzy cellular automata mechanistic models. This allowed them to estimate the number of beneficiaries impacted by the intervention from a pixel analysis of the simulated areas covered by *F. arisanus*. Compared to previous studies, this method was more precise, as it directly assessed the benefits provided by the natural enemies to farming households based on their spatial dispersal effectiveness. This was done by tracking the movement of the natural enemies from their release point to crops situated at different distances within the release area using an AI algorithm. However, their study focused solely on *F. arisanus*.

The current research aims to leverage the AI-based methodology proposed by Agboka et al. (2022) and incorporate economic data related to the research and release of the underappreciated parasitoid *D. longicaudata*. By doing so, we seek to forecast the return on investment resulting from the influence of the expanded range of the parasitoids.

Materials and methods

Overview of the methodology

The study estimated the economic impact of biological control agents (*D. longicaudata*) for the management of invasive fruit flies (*B.dorsalis)* in Kenya. To estimate the benefit–cost ratio (BCR) and the net present value (NPV) of the CBC we follow Masters (1996) and Jones et al. (2006) to assess the impact of the expanded range of the parasitoids. The dispersal range of *D. longicaudata* was modeled using the methodology developed by Agboka et al. (2022). The aforementioned study simulates parasitoid dispersal using a set of rules defined from the bioecology of the parasitoid and its host pest using a fuzzy cellular automata algorithm. The estimate of the BCR and the NPV was calculated using the net income derived from Muriithi et al. (2016). The former study used data collected from mango farmers in Meru County, Kenya, to investigate the impact of an Integrated Pest Management (IPM) strategy for controlling fruit flies in mango production. The IPM strategy consisted of the use of parasitoids, *Metarhizium anisopliae* (Metchnikoff) Sorokin (Clavicipitaceae) -based biopesticides, orchard sanitation, spot spraying of food bait, and the male annihilation technique. The authors employed difference-in-difference and household fixed effects regression models to evaluate the effects of combinations of the different IPM components on three key indicators: farmers' pesticide expenditure, farm-level mango fruit yield losses, and profit.

Dispersal modeling of *D. longicaudata* in Kenya's fragmented landscape

Dispersal modeling for *D. longicaudata* was conducted using PiDisp software version 0.1, found at https://github.com/komimensah/software. PiDisp is an open-source visual data analytics tool designed for spatio-temporal dispersal modeling in Python. The user interface enables swift and interactive spatio-temporal analyses of species dispersal, incorporating pertinent bio-ecological and climatic information. The fuzzy cellular automata form the core principles of PiDisp.

The primary premise posits that the parasitoids' survival is contingent upon its thermal tolerance and the availability of its host pest, *B. dorsalis*, which relies on its host crop (fruit) for reproduction. Specific assumptions made when selecting input parameters for the dispersal model included: (1) temperature ranges between 10.00 and 33.69 °C are suitable for parasitoids survival (Ndlela et al.

2021), (2) parasitoids can disperse up to 8 km annually (Ndlela et al. 2020), (3) the host plant (fruit) of the target insect *B. dorsalis* constrains the parasitoids dispersal, and (4) a habitat suitability cell with an optimal probability greater than 0.3 indicating the presence of the parasitoids' host *B. dorsalis* (Agboka et al. 2022). To predict the dispersal of the released parasitoids, the following data was used: the global positioning system (GPS) coordinates of the parasitoids retrieved from the icipe database, the annual mean temperature from the WorldClim platform (https://www.worldclim.org/) at approximately 1 km^2 of spatial resolution (Fick and Hijmans 2017; Booth 2018), the level of habitat suitability of the pest host *B. dorsalis*, and the host crops of the pest, both retrieved from Agboka et al. (2022).

To validate the model, we extracted the values predicted by the model (0 or 1) for each recovery point from the follow-up field recovery exercise using the R statistical software (R Core Team 2020). This follow-up exercise was conducted randomly to identify parasitoids' occurrences far away from the release locations. The ratio of the "True" (i.e., predicted occurrence converges to observed occurrence) to the total number of observations was used to quantify the model's overall accuracy.

To ascertain the dispersal area covered by the parasitoids, we first used the R statistical software (R Core Team 2020) to obtain the dispersal range. Next, we calculated the number of pixels and subsequently converted this figure into an area in km^2 by utilizing the pixel resolution characteristics.

Estimating the return on investment and benefit–cost analysis

To evaluate the effectiveness of the CBC initiative, the gains from the intervention were weighed against financial commitments to establish the return on investment. The positive outcomes encompassed the yearly variation in crop production (specifically mango) as a result of minimal or non-existent pest invasions due to the introduction of parasitoids, while the expenses involved the annual funding for CBC research and dissemination. The estimation of return on investment is accomplished through the application of two quantitative economic efficiency metrics: NPV and the BCR (Jones et al. 2006).

NPV represents a projection that takes into account a specified interest rate to determine the excess earnings relative to research expenses (Midingoyi et al. 2016). This calculation must consider the opportunity cost associated with investing funds in research, which essentially means the expected return from the investment in technology development. The efficiency metric reveals the extent to which the program enhances the financial worth of the current system (Midingoyi et al. 2021). When the NPV of a given technology surpasses zero, it is deemed profitable and suitable for implementation. The NPV is formulated as follows:

$$NPV = \sum_{t=0}^{T} \left(B_t - C_t\right)(1 + r)^{-t} \tag{1}$$

where B_t is the benefits generated by the CBC intervention, r is the discount rate, C_t is the CBC investment costs, t is the period for which the biological control occurred and T the maximum period.

The BCR measurement calculates the comparative advantage of the returns produced per investment unit (Morin et al. 2009). This metric is represented by dividing the intervention's adjusted gains by the total of its adjusted expenses. If the ratio is greater than 1.0, the intervention is deemed financially viable. The BCR formula can be described as follows by Midingoyi et al. (2016):

$$BCR = \sum_{t=0}^{T} \left(B_t\right)(1 + r)^{-t} / \sum_{t=0}^{T} \left(C_t\right)(1 + r)^{-t} \tag{2}$$

Estimating the return on investment of *D. longicaudata* release in Kenya

NPV and BCR (Eqs. 1 and 2) were estimated using the information on costs and benefits of CBC investment obtained from existing CBC literature and icipe data on monetary funds allocated for the implementation of the CBC programme as follows: (1) We presumed a suitable discount rate of 12% for the duration of the study, as per the Central Bank of Kenya in 2021. The study encompasses the period from 2006 (initial parasitoids' research including field experiments) to 2021. (2) Assuming constant benefits over the period under consideration, we used the Muriithi et al. (2016) estimate of US$205 per acre for mango crops as the annual benefit after the first release of the parasitoids in 2013. Effective agricultural practices, such as pruning and hedging, were expected to be employed by farmers on at least 1 acre of land with fruit fly host crops, leading to the anticipated benefits starting in 2014. To estimate the potential benefit resulting from the yearly dispersal of the parasitoids, we utilized the data on the area covered by the parasitoids yearly during its dispersal. These values were multiplied by the estimated worth of the mango crop, which is US$205 per acre according to the valuation provided by Muriithi et al. (2016). Originally, Muriithi et al. (2016) reported 23,514 Kenyan shillings per acre, which we converted to US$ using the exchange rate of 114.7 Kenyan shillings for a US$ on March 24, 2022. This foreign exchange conversion allows for comparison with other international studies and overall ease of understanding, considering the global reach of this research study. The resulting benefit is further adjusted considering a discount rate r of 12% as per Eqs. (1) and (2). It is crucial to clarify that the parasitoids were mass released between 2013 and 2018. Therefore, there is no benefit to farmers prior to the release period because the parasitoids were not present in the environment. (3) The project spans from 2006, when the parasitoids were imported to Kenya, to 2015, the final year of funding. Based on our records, 25% of the overall funds were dedicated solely to research, evaluation, and dissemination of the CBC. This covered investments in personnel (scientists, administrative staff, and technicians), laboratory equipment, importation fees, rearing, transportation, field release expenses, monitoring surveys, and the training of extension officers and farmers.

Results

Predicted dispersal of *Diachasmimorpha longicaudata* in Kenya

Individuals of *D. longicaudata* were recovered far away from the release locations, within the predicted presence area defined by the dispersal model. Hence, the assumptions made on the parasitoid bioecology were correct, as evidenced by the recovery of the parasitoids within the predicted presence area, far from the release sites. The dispersal model used for predicting the parasitoids'presence was remarkably accurate, yielding a precision of 100%. This suggests that the model accurately predicts the dispersal of the parasitoids from the release locations to the current locations.

Inference from actual simulations showed that *D. longicaudata* has dispersed over a total of 638.5 km^2 from the release locations (Fig. 1). This result underscores the effectiveness of the model in understanding the insect's bioecological patterns and their dispersal behaviour. In addition, the success of the model in predicting the parasitoids' presence can be attributed to a comprehensive understanding of the insect's biology and ecological requirements. By integrating knowledge about the insect's habitat preferences, host behaviour, and host crop, the model was able to generate accurate predictions about its dispersal patterns (Fig. 1).

Table 1 presents the yearly expansion of the area covered by the parasitoids during its dispersal and the resulting annual benefit. The results indicate that as the parasitoids spread throughout the mango farms, it offers advantages to an increasing number of farmers. This increase in benefits is directly proportional to the expansion of the coverage area each year. The expansion of the parasitoids' dispersal range not only showcases its adaptability to different environments but also highlights its potential as an effective biological control agent. The growing coverage area also suggests that the parasitoids are successfully establishing themselves within the mango farm ecosystem, contributing to improved pest management and ultimately leading to enhanced mango yield for the farmers.

Return on investment analysis

Acquired from a variety of project documents and reports, the cost information for the CBC initiative includes multiple funding sources provided to the icipe-led African Fruit Fly Program, dating back to the introduction of the parasitoids. In Table 2, an analysis of the return on investment is presented, based on discounted cost of the 25% of research funds invested towards fruit fly CBC activities. This assessment takes into account the benefits realized following the release of the parasitoids on agricultural lands.

The BCR for the CBC investment was determined to be 92.67:1 indicating that for every dollar invested in the program, an additional $93 in value

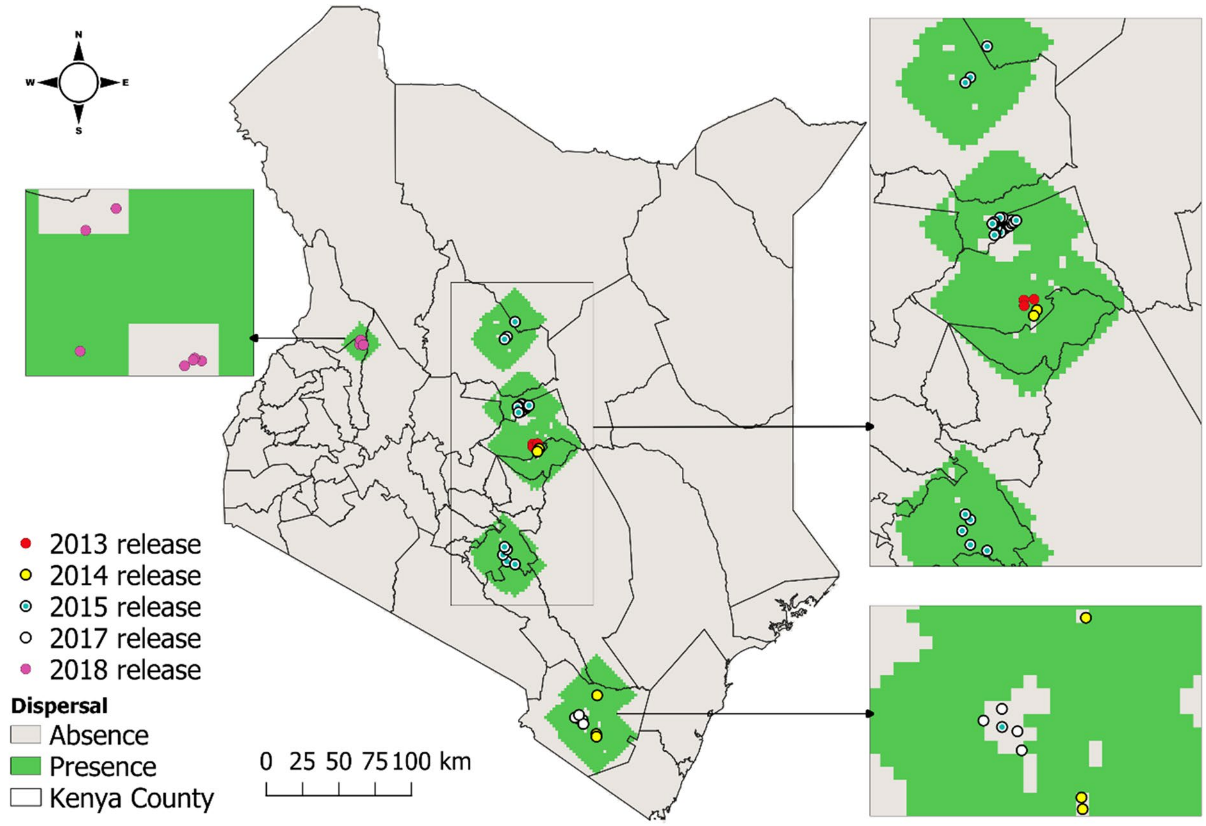

Fig. 1 *D. longicaudata* dispersal in Kenya's tropical fruit growing areas: the green represents the dispersal range of the parasitoids. The colored dots represent the locations of release and the respective release years

Table 1 The potential annual increase in parasitoids-covered area and the annual benefit during dispersal within the mango farm ecosystem of Kenya

Years	Dispersal range in acres	Annual benefit in US$
2014	19,471.48	4,867,870
2015	39,437.16	9,859,290
2016	59,155.74	14,788,935
2017	78,874.32	19,718,580
2018	98,518.77	24,629,693
2019	118,336.19	29,584,048
2020	138,054.77	34,513,693
2021	157,773.35	39,443,338

was generated. A BCR that exceeds 1.0 indicates that the investment in importing and releasing parasitoids for the control of fruit flies is financially rewarding. Moreover, the assessment reveals a considerable NPV of US$42.8 million spanning over the 16-year period, further suggesting the need to encourage investment in the CBC.

Discussion

This study conducted a cost–benefit analysis of classical biological control using the parasitoids *D. longicaudata* to manage mango-infesting Oriental fruit fly, *B. dorsalis.* The aim was to establish the return on investment for the ecologically friendly intervention for the management of *B. dorsalis*. Various studies have provided insights and avenues into measuring success (e.g., Midingoyi et al. 2016). Our study established for the first time an estimate of the total return on investments from parasitoids' dispersal at the landscape level using an AI algorithm. Using the fuzzy cellular automata approach to estimate parasitoids' dispersal, the BCR and the NPV of the biological control investment in Kenya, a BCR metric of up to

Table 2 Return on biological control investment (benefit–cost analysis)

Time** (year)	Costs (C_t) in US$	Discounted Costs (C_t) in US$	Benefits (B_t) in US$	Discounted Benefits (B_t) in US$
2006	28,000	28,000	0	0
2007	317,000	$317{,}000/(1.12^{*})^{1}=283{,}035$	0	0
2008	292,000	$292{,}000/(1.12^{*})^{2}=232{,}780$	0	0
2009	350,000	$350{,}000/(1.12^{*})^{3}=249{,}123$	0	0
2010	347,000	$347{,}000/(1.12^{*})^{4}=220{,}524$	0	0
2011	360,000	$360{,}000/(1.12^{*})^{5}=204{,}273$	0	0
2012	364,000	$364{,}000/(1.12^{*})^{6}=184{,}413$	0	0
2013	460,000	$460{,}000/(1.12^{*})^{7}=208{,}080$	0	0
2014	509,000	$509{,}000/(1.12^{*})^{8}=205{,}576$	4,867,870	$4{,}867{,}870/(1.12*)^{8}=1{,}966{,}051$
2015	150,000	$150{,}000/(1.12^{*})^{9}=54{,}091$	9,859,290	$9{,}859{,}290/(1.12*)^{9}=3{,}555{,}359$
2016	0	0	14,788,935	$14{,}788{,}935/(1.12*)^{10}=4{,}761{,}641$
2017	0	0	19,718,580	$19{,}718{,}580/(1.12*)^{11}=5{,}668{,}620$
2018	0	0	24,629,692	$24{,}629{,}692/(1.12*)^{12}=6{,}321{,}829$
2019	0	0	29,584,047	$29{,}584{,}047/(1.12*)^{13}=6{,}779{,}900$
2020	0	0	34,513,692	$34{,}513{,}692/(1.12*)^{14}=7{,}062{,}185$
2021	0	0	39,443,337	$39{,}443{,}337/(1.12*)^{15}=7{,}206{,}150$
Total	\$3,177,000	\$1,869,895		\$43,321,735
Cost allowed only for the biological control program		$0.25\times 1{,}869{,}895=\$467{,}473$		
Benefit–cost ratio (BCR): discounted benefits/discounted costs				92.67
Net present value (NPV)				\$42,854,260

*12% discount rate account

**2006 represents the initial year of funding, with each subsequent year progressing in sequence, up to 2021, which signifies the final year of impact assessments

92.7:1 was realized. This implies that for each US\$1 invested in the CBC program, it generated benefits worth US\$93. In addition, the investment in CBC yielded an NPV of US\$ 42.8 million over a period of 16 years.

Previous studies on the economic impact of CBC programs in Africa similarly reveal positive returns on investment. For instance, Norgaard (1988) estimated a benefit–cost ratio of 149:1 on the use of CBC to manage cassava mealybug, *Phenacoccus manihoti* Matile-Ferrero (Hemiptera: Pseudococcidae) in several African countries. Furthermore, a quantitative study of CBC of the mango mealybug *Rastrococcus invadens* Williams (Hemiptera: Pseudococcidae) in Benin yielded a BCR of 145:1 (Bokonon-Ganta et al. 2002). Macharia et al. (2005) found a positive economic impact of introducing *Diadegma semiclausum*, exotic parasitoids for management of the diamondback moth (*Plutella xylostella*, DBM), on Kenyan cabbage production. These authors estimated a net present value of US\$ 1.2 million, with an economic surplus generated by the parasitoids' release estimated to be US\$ 28.3 million over 25 years. In addition, the CBC yielded a positive BCR of 24:1, with an internal rate of return of 86%. Midingoyi et al. (2016) used GIS market and production data to estimate the cost-effectiveness of the stemborer infesting parasitoids (*Cotesia flavipes, Cotesia sesamiae, Telenomus isis,* and *Xanthopimpla stemmator*) in Kenya, Mozambique, and Zambia. Using the economic surplus model these authors estimated a BCR of 33:1. Midingoyi et al. (2016) attributed the higher benefit to the parasitoids' spatial release on a wider scale, contributing to better dispersal, covering larger crop farm areas. Furthermore, the BCR and NPV generated from our study aligns with previous studies in the region and corroborates conclusions from a global synthesis by Naranjo et al. (2019) that demonstrated the immense economic benefits of CBC programs for arthropod pests. These authors reviewed 44 published studies on a range of pests from across the globe and reported that the NPV of individual programmes targeting single pest species on single crops ranged from US$ 150,000 to over US$ 9 billion based on a conservative 30-year time horizon with a 10% discounted rate.

As demonstrated in this study, the economic returns for a relatively low-cost, classical biological control program can be immense. This CBC approach, within the framework of holistic IPM strategies, enhances fruit yield and quality and minimizes insecticides, thereby increasing the net income of the fruit growers and reducing environmental damage (Midingoyi et al. 2019). Our results call for the need to further releases of *D. longicaudata* across major fruit production regions in countries affected by the invasive *B. dorsalis*. Furthermore, reducing pesticide application can help farmers meet the rigorous standards of profitable foreign export markets, thus contributing to the considerable inflow of foreign exchange that contributes to the GDP.

In acknowledging the limitations of our study, we recognize that the assumption of a constant dispersal rate of 8 km year^{-1} in our model might constrain its adaptability and realism. Although this value was based on the best available data and research at the time of model development, it does not fully capture the inherent variability and uncertainty that exists in real-world scenarios. To gain a more nuanced understanding of the dynamics involved, future iterations of this model should incorporate a more flexible approach, considering 8 km year^{-1} as an average dispersal rate. This could be achieved through sensitivity analysis, which explores how changes in the dispersal rate may impact the outcomes and conclusions. By doing so, we can ensure that our model is robust and adaptable to various scenarios.

In addition, our analysis focuses on the impact of a single parasitoid species on net income from mango production. However, the estimate of net income used as a basis for our calculations was derived from a study that examined the impact of two biological control agents. Without distinct data on the independent impact of each agent, it was not feasible to disaggregate their individual contributions on net income. As a result, the net income values used in our study may overestimate the potential benefits of biological control when using a single parasitoid. Therefore, it is important to interpret our findings as indicating the potential maximum benefits under these specific circumstances. Future studies should strive to quantify the individual impact of each natural enemy to provide more precise estimates of their economic benefits.

Despite these limitations, our study offers valuable insights into the economic impacts of Integrated Pest Management strategies. It serves as a foundation for future work for deeper insights into the economic and ecological dynamics of pest management. The study measured the benefits of classical biological control by estimating the return on investment (ROI) of the release of the biological control agent *D. longicaudata* for the management of invasive oriental fruit flies (*B. dorsalis*). Our study contributes to the existing literature on the benefits of classical biological control by employing spatial and temporal algorithms grounded in a dynamic cellular automata framework, which eliminates the need for expensive field retrieval of parasitoids and socio-economic data collection. This approach is well-suited for delivering valuable ROI insights to governmental and developmental stakeholders, enabling them to make well-informed choices regarding technological solutions.

The analysis estimated a BCR of 92.7:1 by the end of the 16 years and an NPV of US$ 42.8 million. The positive BCR and the NPV of the ecologically based parasitoids quantify the confirmed high profitability of the classical biological control of *B. dorsalis,* thus encouraging areawide scaling-up of the intervention to other mango growing regions in sub-Saharan Africa that are affected by the pest.

While we apply a unique methodology to estimate the return on investment for biological control, we acknowledge that our model is conservative as it did not capture other spillover benefits associated with the biological control of pests. These include the health and environmental benefits associated with reduced risks of using synthetic chemicals to manage pests. Future studies, therefore, could consider conducting an economic cost–benefit analysis of a wide-scale application of classical biological control interventions.

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Data availability The data presented in this study are available on request from the corresponding author.

Declarations

Conflicts of interest The authors have no conflict of interest.

Ethical approval Ethical review and approval of this study were done by the *icipe* review board. As the data required for the study was obtained from icipe's scientists, no oral or written consent was required during the study.

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