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ORIGINAL RESEARCH ARTICLE

Assessing the potential economic benefits of classical biological control of the invasive fruit fly *Bactrocera dorsalis* by *Fopius arisanus* in Kenya

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Abstract
This study proposed a spatially explicit non-linear function for estimating the benefits following the release and establishment of the koinobiont endoparasitoid, *Fopius arisanus* at a landscape scale in Kenya to control the oriental fruit fly, *Bactrocera dorsalis*. The proposed model relates the bioecology of the parasitoid to its impacts on fruit growers' economic benefits per fruit farm. In addition, we used financial information attributed to the cost of importation, conducting associated research, and the release of *F. arisanus* to estimate the return on investment from the parasitoid's release in Kenya. We observed distinct variations in potential annual benefits across the diverse mango cultivation regions throughout Kenya. In Kenya, the potential benefits range from negligible benefit to high benefit per acre (US$201- US$255) annually when classical biological control is applied. Furthermore, the cost-benefit ratio analysis showed that in Kenya, for every US$1 invested, the return benefit was US$33.92. In addition in Kenya, the investment yielded a significant net present value of US$13.7 million over a 16-year period and an attractive internal rate of return of 73% compared to the reference discount rate of 12%. The study suggests the need to facilitate further release of the parasitoid (*F. arisanus*) across major fruit production regions of countries affected by the invasive fruit fly (*B. dorsalis*).

Highlights
- This study presents a spatially explicit non-linear function for estimating the economic benefits at scale following parasitoid release and establishment to control an invasive fruit fly.
- Costs incurred in the exploration, importation, lab research, and field release were employed to estimate the return on investment in the bio-control of fruit flies using *F. arisanus* as an agent in Kenya.
- The findings will stimulate government investment in mass rearing of the parasitoid for up-scaling sustainable biological control techniques of invasive agricultural pests.

Keywords Spatial · Temporal · Regression · Net benefit · Return on investment · Biological control · Fruit fly

Introduction

Bactrocera dorsalis (Hendel) (Diptera: Tephritidae), a native fruit fly to Asia is a devastating pest of mango and other fruits and vegetables that causes losses of up to 80% (Ekesi et al. 2009). In addition to direct losses in horticultural crops, invasions by alien species such as *B. dorsalis* often have broader ecological consequences. These include disruptions to the pollination of crops and native plants, competition with native species for food resources, and potential impacts on the overall health and diversity of ecosystems.

Samira A. Mohamed and Sunday Ekesi contributed equally to this work.

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Such disturbances can indirectly affect crop productivity and stability. In the absence of effective management strategies, these invasions can even lead to complete crop loss (Ekesi et al. 2009).

Generally, non-native invasive species such *B. dorsalis* management is a difficult but critical task, given the potential for economic and environmental harm (Marten and Moore 2011). For instance, the collection of massive volumes of the host fruit and potential host plants of this pest in Africa yielded no single suitable and effective native parasitoid (Mohamed et al., 2016; Rwomushana et al. 2008). Hence after *B. dorsalis* was first detected in Kenya in 2003 (Lux et al. 2003), suitable classical biological agents against the fruit fly, such as the parasitoids *Fopius arisanus* (Sonan) and *Diachasmimorpha longicaudata* (Ashmead) both Hymenoptera: Braconidae were imported and released in Kenya. In the absence of heavy applications of broad-spectrum synthetic insecticides, which kill both pests and beneficial insects, the economic benefits of pest control by parasitoids could be significant through the parasitoid's ability to disperse from the release point unaided, often covering several kilometers within a single fruiting season after a successful establishment (Agboka et al. 2023).

Recent research by Agboka et al. (2022a), 2023) has pioneered innovative methodologies using computer algorithms to assess the impact of using parasitoids for pest control. However, these studies have not specifically delved into quantifying the benefits on a per-pixel spatial basis or thoroughly examining the return on investment for the secondary parasitoid *F. arisanus*. Our current study seeks to extend this existing research by integrating these critical, yet previously unexplored, elements. This study aimed to integrate the economic information attributed to research and release of the parasitoid *F. arisanus* to project the potential fruit growers' economic benefits at scale following the intervention efficiency in controlling the invasive fruit fly *B. dorsalis*. The study proposed a spatially explicit non-linear function for estimating the potential benefits following the release and establishment of *F. arisanus* at landscape in Kenya and estimated the return on investments from the parasitoid *F. arisanus* released in Kenya. Our study breaks new ground in estimating the spatial economic benefits of the classical biological control (CBC) program to farmers. The focus on economic impact assessment is driven by the scarcity of empirical data on the financial outcomes of CBC interventions. This research aims to bridge this gap, providing essential insights into the net economic benefits and potential returns of CBC, thereby supporting more informed agricultural policy and investment decisions.

Methods

The study estimates and maps the potential socio-economic impact of a biological control agent *F.arisanus* in managing *B. dorsalis* using a non-linear equation of the potential net annual benefit. Further, the study estimates the global return on such CBC investments using the overall benefit-cost ratio (BCR), the net present value (NPV), and the internal rate of return (IRR) as a result of parasitoid impact on its host.

Spatial socio-economic impact of *Fopuis arisanus* in Kenya

To predict the attainable benefits following the parasitoid establishment, we estimated a non-linear function relating the parasitoid's bioecology to the potential impacts on fruit growers' economic benefits.

Ecological data

The primary information used to create the function was related to the post-release assessment of *F. arisanus* in some key African fruit producer countries. For example, in the coastal region of Kenya, up to 40% parasitism has been reported on *B. dorsalis* on mango (Ekesi et al. 2009; Ekesi 2010), while 52% have been reported in central Kenya (Agboka et al. 2022a). In Benin, 46.5% parasitism has been achieved on bush mango, *Irvingia gabonensis* Aubry-Lecomte (Irvingiaceae) (Gnanvossou et al. 2016), and 49% parasitism on mango in Casamance (Senegal) (Vargas et al. 2016).

In addition, since the target host (in this case *B. dorsalis*) of the parasitoid is very polyphagous we assume that the biological control agent *F. arisanus* development at its immature stage depends exclusively on its host. Therefore data on *F. arisanus* suitability to Kenya agroecology was hypothesised as the presence of the host (*B. dorsalis*) of the parasitoid. This dataset was sourced from Agboka et al. (2022a) and processed as a prediction domain (space). Habitat suitability with an optimum probability greater than 0.3 is expected to signify the presence of the target pests, i.e. *B. dorsalis*.

Socioeconomic data

The objective was to develop a predictive model to estimate the potential financial benefits for mango growers in Kenya based on the parasitism rates of *F. arisanus*. Variations in agroecological conditions across Africa typically lead to disparities in parasitism rates, which in turn influence the potential annual financial benefits that accrue to individual households. For instance, the estimated benefits for fruit growers, specifically for mango (*Mangifera indica L.*) crops, were determined to be US$ 205 per acre per farmer, as outlined in the study by Muriithi et al. (2016). This estimate corresponds to a parasitism rate of approximately 52%, as reported by Agboka et al. (2022a). Hence the analysis commenced with the generation of a dataset that captures the relationship between parasitism rates and the benefits to the growers. This dataset was constructed using the known data point where a 52% parasitism rate corresponded to a benefit of $205 per acre and additional non-published data from the International Centre of Insect Physiology and Ecology (*icipe*) database to approximate benefits accrued by farmers using a linear regression to establish a statistical relationship between the parasitism rate and the financial benefits (Fig. 1).

Weather data

We further linked this parasitism information to the specific agroecology where the parasitoid was recovered. Specifically, we used key information on the efficacy of a parasitoid in these different agro-ecologies, i.e., temperature and relative humidity (Nanga et al. 2021). Other variables that could have impacted the parasitism were assumed negligible. We sourced our Surface air temperature and relative humidity at 0.25° spatial resolution for the year 2021 from the Copernicus Climate Data Store (CDS) (Hersbach et al. 2018). We then resampled our data to 0.009° spatial resolution using the cubic resampling method using Python (Van Rossum & Drake Jr, 1995).

Model developpement

We implemented a symbolic regression (SR) approach (Lughofer et al. 2016) to establish the relationship between these two climatic variables and the potential economic benefit to fruit growers from the parasitism rates using Python (Van Rossum & Drake Jr, 1995). The SR is an algorithm that uses an empirical data-driven approach to explain the relationship between response and predictor variables effectively (Agboka et al. 2022b). The SR algorithm advances our capability to discern complex patterns within data by leveraging both computational power and pre-established domain knowledge, leading to models that reflect the underlying principles governing the system (Ashok et al. 2020). The SR algorithm integrates optimization methods such as genetic programming (Schmidt and Lipson 2009), Bayesian methods (Jin et al. 2019), physics-inspired approach (Udrescu and Tegmark 2020), and simulated annealing for approximating the optimum values of the given function. Specifically, we used symbolic regression (SR) to create our mathematical model. SR explores a range of expressions to find the best fit for the data, using the evolutionary algorithm. It starts with a diverse equation pool, refining them

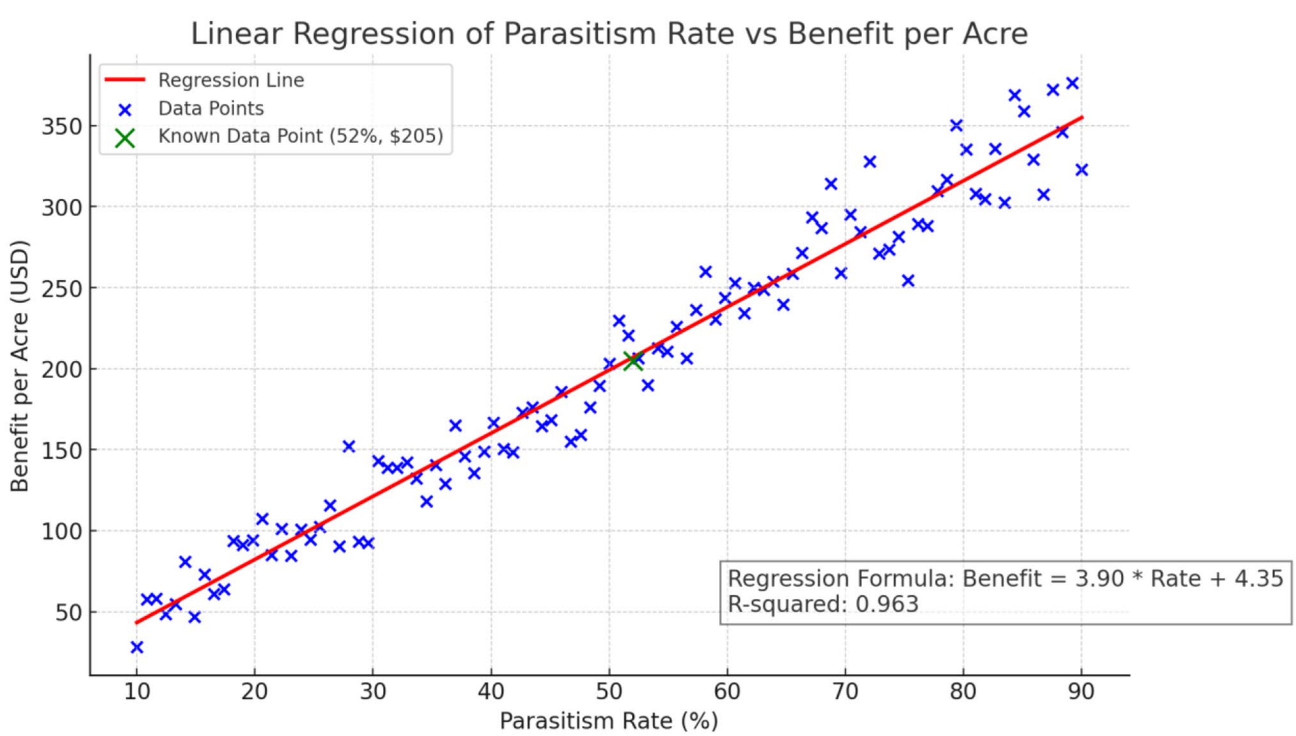

Fig. 1 Correlation between parasitism rates and predicted economic benefits for mango growers. The regression line, depicted in red, represents the model fit, while the individual blue points illustrate the data

iteratively. The final equation (Eq. 1), balancing simplicity and accuracy, is the outcome of this process. The generated model was obtained with high accuracy ($R^2 > 0.90$).

The mathematical formulation of the developed model is shown below:

$$\text{Benefit} = 265.3884 - 0.0001 \times RH - 0.0023 \times T^2 - 0.0057 \times T \times RH - 0.0140 \times RH^2 \quad (1)$$

where *RH* is the relative humidity, and *T* is the temperature.

Moreover, to mimic the bioecology of *F.arisanus* there is a need to impose some limitations on growth in benefit due to the development rate i.e., the extreme temperatures (or lower and upper thermal thresholds) that affect the parasitoid's development, reproduction, or survival. According to Nanga et al. (2021), *F. arisanus* completed development between 15 and 30 ◦C but the performance starts decreasing at 28 ◦C. Therefore temperatures lower than 15◦C and greater and equal to 28◦C are considered outside the validity domain of the developed function.

Furthermore, we assessed the stability or the range of validity for the provided function using a simulation approach (sensitivity analysis) to explore the values of temperature (*T*) and relative humidity (*RH*) for which the function yields meaningful outcomes, and the computed benefits fall within a practical or predefined range. This sensitivity analysis aims to evaluate how variations in temperature (*T*) and relative humidity (*RH*) influence the benefit function. The simulation begins by defining the Benefits function and specifying a valid range for *T* and *RH*. Subsequently, it systematically perturbs these parameters within the valid range and calculates Benefits for each combination. The results (Fig. 2) are visualized using a contour plot, providing insights into the validity of the provided function.

Mapping the benefit per farmer from *F. Arisanus* establishment in Kenya

To map the attainable benefit per farmer from *F. arisanus* establishment, a 1 km spatial resolution grid using the "Research tools: create grid" in QGIS (Team 2009) was created for Kenya. The generated stable model was then extrapolated using Python programming language (Van Rossum & Drake Jr, 1995) over the grid to provide a spatial visualization of the economic benefit to fruit growers within fruit-growing areas in Kenya.

Estimating the return on investment (RoI) and benefit-cost analysis of the biological control agent *F. arisanus*

The cost information for the CBC program was sourced from the findings presented by Agboka et al. (2023). Additionally, the data regarding the number of beneficiaries, as reported by Agboka et al. (2022a), was utilized and multiplied by the benefit of US$ 205 per acre per farmer, a figure derived from Muriithi et al. (2016). This approach integrates both cost and beneficiary data to provide a comprehensive economic assessment of the CBC program. The return on investment was estimated using the two quantitative economic efficiency indicators reported in Agboka et al. (2023) viz. the Net present value (NPV), the Benefit–Cost Ratio (BCR), in addition to the internal rate of return (IRR). The IRR is the interest rate at which the present value of

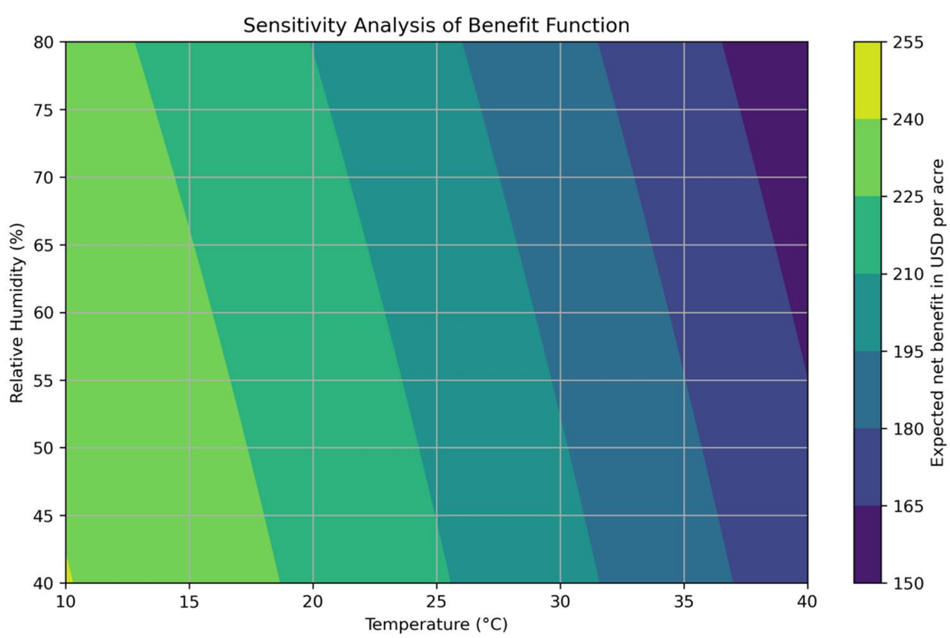

Fig. 2 Sensitivity analysis of benefit function. This figure illustrates the sensitivity of the benefit function to variations in temperature (°C) and relative humidity (%). The colormap represents the expected net benefit in USD/acre across different combinations of temperature and relative humidity

the CBC investments equals the present value of benefits (Midingoyi et al., 2016a). The IRR is compared to the interest rate charged by commercial banks, private investment interest rates, or agriculture financing institutions. If the IRR is greater than these rates, it is reasonable to conclude that investments in the CBC in the studied countries are worthwhile.

Results

The spatial benefits of biological control agents *F. Arisanus* in Kenya

The model outputs, as shown in Fig. 3, represent the net benefits in USD/acre for the year 2021, illustrating the landscape-level potential outcomes of the CBC program in the final year of our study.

The spatial heterogeneity in net benefits is evident, with variations directly proportional to the parasitism rates influenced by the regional temperature and humidity profiles. Higher parasitism rates, favored by optimal ecological conditions, correspond to increased economic benefits. The varying intensities of color on the map reflect these categories, where the biological control program potentially yielded the highest net benefits. Specifically, regions in the west (including Homa Bay, Bungoma, Migori, and others) were forecasted to reap significant benefits. In central Kiambu, Embu, Meru, and surrounding areas were forecasted to reap significant benefits and no benefit dominating mostly the surrounding areas. On the coast notably Mombasa, Kilifi, and adjacent regions the benefits were forecasted to be significant with porches with negligible benefit due to the potential effective implementation of the CBC program.

Return on investment analysis in Kenya

The BCR of the CBC investment was calculated at 33.92: 1 (Table 1), implying that each USD invested in the

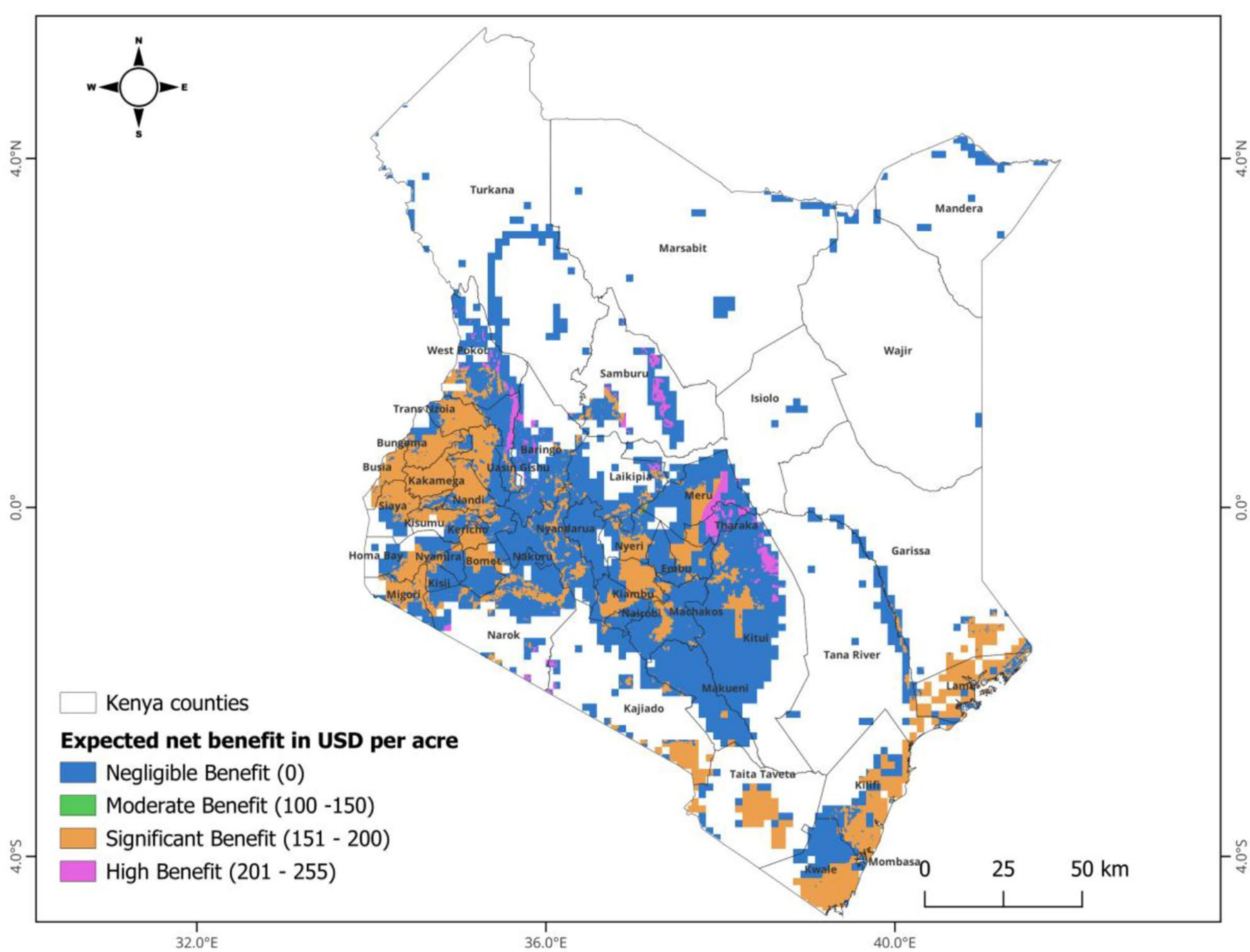

Fig. 3 Expected economic benefits per pixel in USD per acre in fruit farms from the release of *Fopius arisanus*, as a classical biological control agent, in Kenya (2021)

Table 1 Return on classical biological control investment (benefit-cost analysis) in Kenya

Time (year)	Costs (Ct) in USD	Discounted Costs (Ct) in USD	Benefits (Bt) in USD	Discounted Benefits (Bt) in USD
(2006–2021)	$3,177,000	$467,473	$64,917,145	$15,856,458
Benefit-cost ratio (BCR)				**33.92**
Net present value (NPV)				**$13,740,166**
Internal rate of return (IRR)				**73.37%**

[*] 12% discount rate account

programme generated an additional value of about US$34. The BCR is greater than 1.0, suggesting that investing in the fruit fly parasitoid *F. arisanus* importation and subsequent release is profitable. The analysis further shows a significant net present value of US$13.7 million over the 16 years and an attractive internal rate of return (IRR) of 73% compared to the reference discount rate of 12%.

Table 1 shows the return on investment analysis from an assumed discounted cost of the 25% allocation to CBC activities and benefits accrued after the release of the parasitoid in Kenya.

Discussion

This study used a spatially explicit non-linear function for estimating the benefits per pixel at the landscape level following parasitoids' release and potential establishment in Kenya. The proposed model relates the bioecology of the parasitoid *F. arisanus* to measure the potential impact on fruit growers and then maps the economic benefit in fruit farms at landscape. We also used available time series data on costs of baseline research, exploration, importation, quarantine processing, mass rearing, field releases, and post release evaluation of *F. arisanus* to estimate the return on investments in the CBC program in Kenya. The findings revealed variabilities of annual economic benefits across mango growing areas (Coastal areas, Murang'a, Thika, Taveta, Lower Embu, Machakos, Makueni, Kitui). The observed variabilities from one location to another are because the spread of biological organisms and their efficacy in managing the population of the target pest is significantly influenced by abiotic factors such as climate variables and host habitat characteristics (Agboka et al. 2022a), as well as biotic factors such as the physiological state of the parasitoid (Chidawanyika et al. 2019) and their ability to avoid predation (Lindstedt et al. 2019).

The areas predicted for a potential high level of benefits represent areas with potential high efficiency of the parasitoid, while the inefficiency of the parasitoids characterizes regions with low benefits. The benefit level is directly proportional to the ability of the parasitoid *F. arisanus* to suppress the invasive fruit fly *B. dorsalis*. Hence this analysis provides a clear visualization of the economic impact

of the parasitoid's release, emphasizing the significance of temperature and humidity in driving the effectiveness of biological control measures. Such detailed spatial information is instrumental for identifying areas where CBC application has been economically beneficial, guiding more efficient resource allocation for future interventions.

Despite the positive benefits displayed by the model some limitations on their validity can be raised. This non-linear model assumes that the benefits for mango growers are only dependent on the parasitism rates of the fly by the parasitoid and the benefit is a non-linear function of annual mean temperature and humidity which may not be realistic as other parameters such as the ability to evade predation(Lindstedt et al. 2019) and farmers practices contribute to parasitoid performance.Agboka et al. (2022a) report that incorporating pesticide usage frequency and its effect on parasitoid performance should result in a more refined prediction. So, the net benefit model may not only depend on temperature and humidity. Nevertheless, this study targeted the potential benefit of fruit growers due to *F. arisanus* in controlling *B. dorsalis*. The study provides light on the potential benefit farmers could get from the establishment of *F. arisanus* against *B. dorsalis*. However, the parasitoid could also control a wide range of pests including tephritids such as Medfly(Harris et al. 2007) leading to improved crop produce. Besides, it is also important to highlight that the developed function in the present manuscript only holds true within the defined temperature threshold of the parasitoids.

Moreover, at a temporal scale, the study aligns with the findings of prior research, such as those byNorgaard (1988), Bokonon-Ganta et al. (2002), (Macharia et al. 2005, () Naranjo et al. (2019), and Agboka et al. (2023) in establishing the profitability of biological control programs over time. This consensus across various studies emphasizes the economic viability of such programs in pest management.

Overall, although the research question of this study is being addressed and potentially of interest to provide a general overview of the benefits of the CBC program, due to the lack of field validation, the results of this study are subject to the quality of the data and assumptions used. Therefore proper field data collection could be done in further study and the methodology developed in the present work could be upgraded and validated properly.

Conclusions

The study measured the monetary benefits and estimated the return on investment in CBC program using *F. arisanus*, to provide evidence on the profitability and efficiency of public expenses or donors funding in CBC intervention. Even though our models demonstrated positive benefits, some limitations on their validity can be raised. For instance, notwithstanding the scarcity and clustering of data used to develop the spatial model, a better prediction would suppose having well-distributed data across Africa. However, field data collection is relatively expensive and time-consuming, especially for large-scale landscape studies. Nevertheless, we believe that the study's results will stimulate government investment in mass rearing parasitoids for up-scaling sustainable control techniques of invasive agricultural pests to reduce their overall economic impacts.

Authors' contributions Komi Mensah Agboka: Conceptualization, Data curation, Formal analysis, Methodology, Writing– original draft, Writing– review & editing. Henri E.Z. Tonnang: Methodology, Supervision, Writing– review & editing. Beatrice Muriithi: Methodology, Writing– review & editing. Saliou Niassy: Writing– review & editing. Shepard Ndlela: Writing– review & editing. Elfatih M. Abdel-Rahman: Supervision, Writing– review & editing. Samira A. Mohamed: Funding acquisition, Project administration, Resources, Writing– review & editing. Sunday Ekesi: Funding acquisition, Project administration, Resources, Writing– review & editing.

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

Code availability The codes used in this study are available on request from the corresponding author.

Declarations

Conflicts of interest/Competing interest We, the authors of this manuscript would like to declare a potential conflict of interest. Dr. Saliou Niassy holds the position of Chief Editor in the journal. We understand the importance of maintaining the integrity of the peer-review process and ensuring transparency in our academic endeavors. As such, we would like to state the following:
Dr. Saliou Niassy despite being a co-author of this manuscript, has not and will not be involved in any of the editorial decisions related to this manuscript. Dr. Saliou Niassy recused himself from all editorial processes and discussions related to this submission, ensuring a fair and impartial review. We confirm that the research findings and statements made in this manuscript have not been influenced by Dr. Niassy's position in the journal, and all authors have contributed to the research and writing process with full academic freedom. We assure the readers and the academic community that all measures have been taken to uphold the integrity and transparency of this submission.

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