Original Article

INNOVATING AFRICAN AQUACULTURE: ADDRESSING TECHNOLOGICAL SHORTFALLS AND EXPLORING FISH GUT MICROBIOTA

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Abstract: Fruit flies pose a dual threat to mango production by significantly impacting productivity and diminishing market value, thereby causing substantial economic losses in the fruit and vegetable sector across Africa (ANCAR, 2013; Tefera et al., 2018). The consequences of fruit fly infestations are particularly pronounced in Senegal, where estimates suggest losses amounting to 2 billion US dollars since 2005, with a staggering 60% to 100% reduction in mango production in various regions (ANCAR, 2011). Beyond direct production losses, fruit fly infestations wield indirect economic repercussions, including constraints on foreign exchange earnings from mango exports due to quarantine restrictions and missed opportunities in global markets (Muriithi et al., 2016; Badii et al., 2015; Ills and Peterson, 2016). Recognizing the magnitude of the damage inflicted by fruit flies on mango production and the consequential economic stakes, the research community has undertaken coordinated efforts to develop effective control technologies. These endeavors aim to fortify the capacities of stakeholders within the sector and enhance public awareness regarding the challenges and potential solutions associated with fruit fly infestations. This study critically examines the impact of fruit fly infestations on mango production in Senegal, shedding light on the economic losses incurred and the multifaceted consequences for the agricultural economy. By delving into existing control technologies and their efficacy, the research seeks to contribute valuable insights into mitigating the adverse effects of fruit fly infestations. The findings are expected to inform strategic interventions, policy frameworks, and public awareness campaigns aimed at bolstering mango production resilience in the face of persistent fruit fly threats.
Keywords: Fruit Fly Infestations, Mango Production, Economic Losses, Control Technologies, Senegal Agriculture

INTRODUCTION

Fruit flies not only impact mango productivity but also affect their market value (ANCAR, 2013; Tefera et al., 2018). In Africa, estimates indicate losses of up to 2 billion US dollars in fruit and vegetable production. Since

2005, Senegal has experienced significant losses in mango production due to fruit flies, ranging from 60% in the Niayes Dakar-Thiès zone to 80 to 100% in the southern region (ANCAR, 2011). Infestations of fruit flies can also indirectly harm the economy by reducing foreign exchange earnings from mangoes due to quarantine restrictions and the loss of export opportunities in global markets (Muriithi et al., 2016; Badii et al., 2015; Ills and Peterson, 2016). Recognizing the level of damage and the stakes involved in mango production, the fruit fly research community has made concerted efforts to provide control technologies against these mango pests. This includes strengthening the capacity of stakeholders in the sector and raising public awareness about the impact of these pests on the horticultural industry in Africa. One initial challenge was to provide stakeholders with documentation on species inventory, economic status of host plant diversity, and population dynamics of fruit flies in all ecological zones of Africa. This documentation revealed that the most representative species in Africa is *Bactrocera dorsalis*, now known as *Bactrocera invadens* (ANCAR, 2013). Previous experiences with exotic and indigenous fruit fly species in Africa had already shown that managing fruit fly pests in general would likely not be successful if it relied on a single management technique (Allwood and Drew, 1997). The International Centre of Insect Physiology and Ecology (ICIPE) in Kenya advocates for the implementation of the African Fruit Fly Programme (AFFP), which involves using a combination of management techniques based on at least two available lactic substances. The most recurrent of these technologies are classified into three groups (Badii et al., 2015) biological control through the introduction of Asian parasitoids, specifically "*Fopius arisanus*," which feed on fruit flies; chemical control involving the use of chemicals to trap or prevent fly proliferation (Ndiaye et al., 2012); and finally, mechanical or prophylactic control to ensure orchard hygiene.

In Senegal, a large-scale public intervention, namely the West Africa Agricultural Productivity Program (WAAPP), aimed to disseminate four technologies for reducing fruit fly populations, was carried out. The program was initially implemented in the Niayes zone (Dakar-Thiès) in 2010 as a pilot phase. Subsequently, it was extended to the southern regions of the country from 2013, as well as in the Niayes zone, in a large-scale diffusion phase. Three of the technologies disseminated pertain to chemical control: (i) trapping, (ii) foliar treatment, and iii) soil treatment. Another technique associated with the technology package relates to prophylactic control, sanitation. It would be essential to measure their impacts on key economic indicators, including losses, yield, and well-being. At the regional level, there has also been a desire to combat this scourge with the support of the European Union, the French Development Agency (AFD), Economic Community of West African States (ECOWAS), and West African Economic and Monetary Union (WAEMU). The aim of this initiative is to significantly reduce the fruit fly population in Africa. This regional willingness finds its motivation in a more effective regional approach, considering that fruit flies do not recognize borders. Thus, institutions have launched in Dakar this regional plan to combat and control fruit flies in West Africa. The project cost is estimated at 15 billion CFA francs and is co-financed by the European Union, French Development Agency (AFD), ECOWAS, and beneficiary states (Center for the Promotion of Imports from Developing Countries, 2019), with CORAF as the lead institution.

As part of the consolidation, expansion, and sustainability of the achievements in the fight against fruit flies in West Africa, the Syrimao Project, 'Innovative Regional System for Fruit Fly Control' of ECOWAS, took advantage of its regional workshop for annual review and planning held in Abidjan from November 7 to 11, 2022, to assess its activities and the 2022 mango campaign (Agence régionale pour l'agriculture et l'alimentation, 2023). However, empirical evidence on the socioeconomic impact of fruit fly control remains very scarce in developing countries, especially in sub-Saharan Africa, where economic responses to questions about the fruit fly issue are almost non-existent. The few existing impact studies in orchards (Fernandez-Cornejo et al., 1998; Teklewold et al., 2017; Wollni et al., 2010; Isoto et al., 2014; Sanglestsawai et al., 2015; Sharma and Peshin, 2016) have mainly focused on an impact evaluation approach using binary treatment variables, while ignoring the intensity of fruit fly control technology adoption.

Rigorous impact studies have been conducted in East Africa, notably in Kenya, where authors attempted to measure the economic impact of adopting fruit fly control technologies (Kibira, 2015). Another recent research in Kenya focused on the impact of fruit fly control methods on the environment and health, given that most chemicals are involved (Tefera et al., 2018). Such data helps policymakers and partners understand the potential of designing better policies on fruit fly control practices and encourages their adoption.

Senegal plans to invest 1.9 million dollars in the fight against fruit flies by 2023. This initiative comes at a time when the country recorded a record number of 32 interceptions on the international market in 2022, five times more than those reported a year earlier due to noncompliance with phytosanitary requirements related to fruit fly attacks. During the July campaign, there were four interceptions with 3600 tons exported. In August, at least 24 notifications were received, and approximately 30 containers were intercepted at European borders. Audits of non-compliance certificates have repeatedly revealed shortcomings in the fight against fruit flies, with stings being one of the main reasons for the ban on the introduction of mangoes into the European Union. This recurrence of non-compliance cases could prompt the European Union to take safeguard measures (DPV, 2022). It is therefore relevant to question whether the various initiatives in place are based on rigorous scientific foundations aimed at assessing the efforts already made.

Technological advancements in agriculture offer the most sustainable approach to reduce rural poverty, increase productivity, ensure food security, and stimulate overall economic growth in agrarian economies like those in sub-Saharan Africa. Studies, for example Ayenew et al. (2020), Ruzzante et al. (2021) and Abdoulaye et al. (2018), demonstrate that the adoption of improved agricultural technologies can bring direct and indirect benefits to adopting households. Direct benefits include increased productivity and reduced unit production costs, resulting in higher food security and agricultural income. This research analyzes the direct and indirect impact of adopting fruit fly control technologies in Senegal. Specifically, the research initially examines the adoption of fruit fly control technologies based on the producer's choice, and subsequently assesses the impact of this adoption on mango losses attributed to fruit flies in Senegal.

The analysis is based on the classic theory of innovation diffusion, as popularized by Rogers (2014). In terms of empirical aspects, the endogenous regime shift will be experimented with using STATA 16 software to isolate the impact of fruit fly control technologies in Senegal. This procedure aims to rigorously evaluate the effect of these technologies on the specific issue of fruit flies in the region. The results from the impact analysis will contribute to the production of scientific evidence regarding fruit fly control. The policy recommendations stemming from the research will lead to the development of more efficient policies for fruit fly control in the specific context of

Senegal. The expected impact is a significant reduction in mango losses due to fruit flies in Senegal, referring to other countries like Kenya where similar programs to fight against fruit flies were implemented.

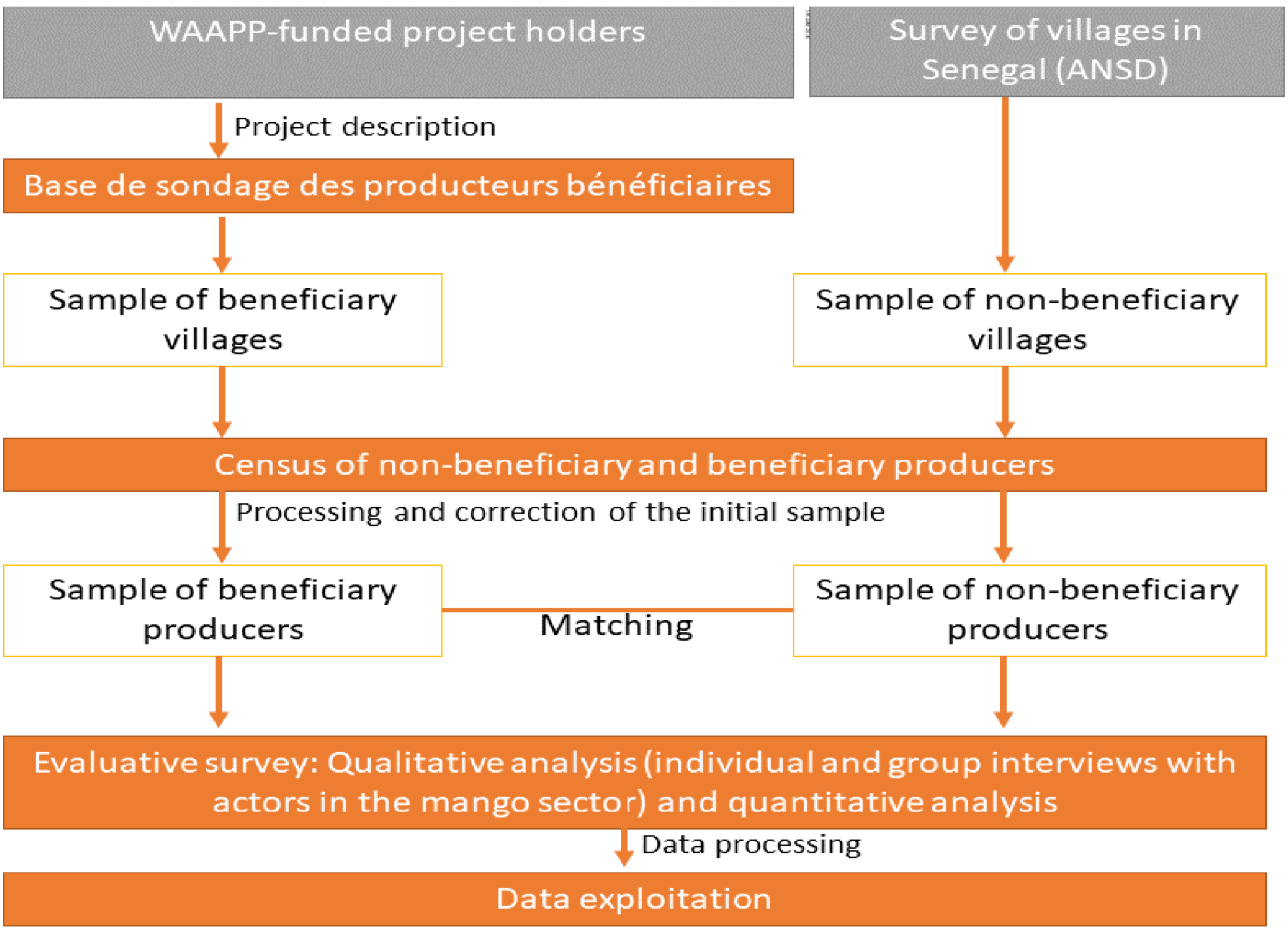

Figure 1. Sampling process of surveyed beneficiaries and non-beneficiaries.
Source: Author

MATERIALS AND METHODS

Overall, the sample consists of 491 mango producers, including 227 beneficiaries and 264 non-beneficiaries. All beneficiary producers are drawn from beneficiary villages, whereas among non-beneficiaries, 102 are drawn from beneficiary villages, and 162 are from non-beneficiary villages of the WAAPP program (Figure 2).

Sampling

The study is confined to the regions of Dakar and Thiès, encompassing both the pilot and dissemination phases of the intervention. This strategic selection facilitates a nuanced comparison between beneficiaries and non-beneficiaries across these phases. Rigorous consideration was given to ensure the representativeness of both

beneficiary and non-beneficiary categories. The survey, aligning with impact assessment objectives, covered mango producers, their households, and villages, employing a random sampling method (Figure 1).
Constructing the producer sample involved three key stages. Initially, determining the sample size should have followed a formula considering size, minimum detectable effect, significance level, and program impact capture capacity.
However, due to the relatively small study population, adopting this formula resembled a census, significantly inflating data collection costs. To overcome these cost constraints, the approach based on sampling rates was preferred. Out of 1198 project beneficiaries, a sample of 250 beneficiaries, representing a 20% sampling rate, was established.

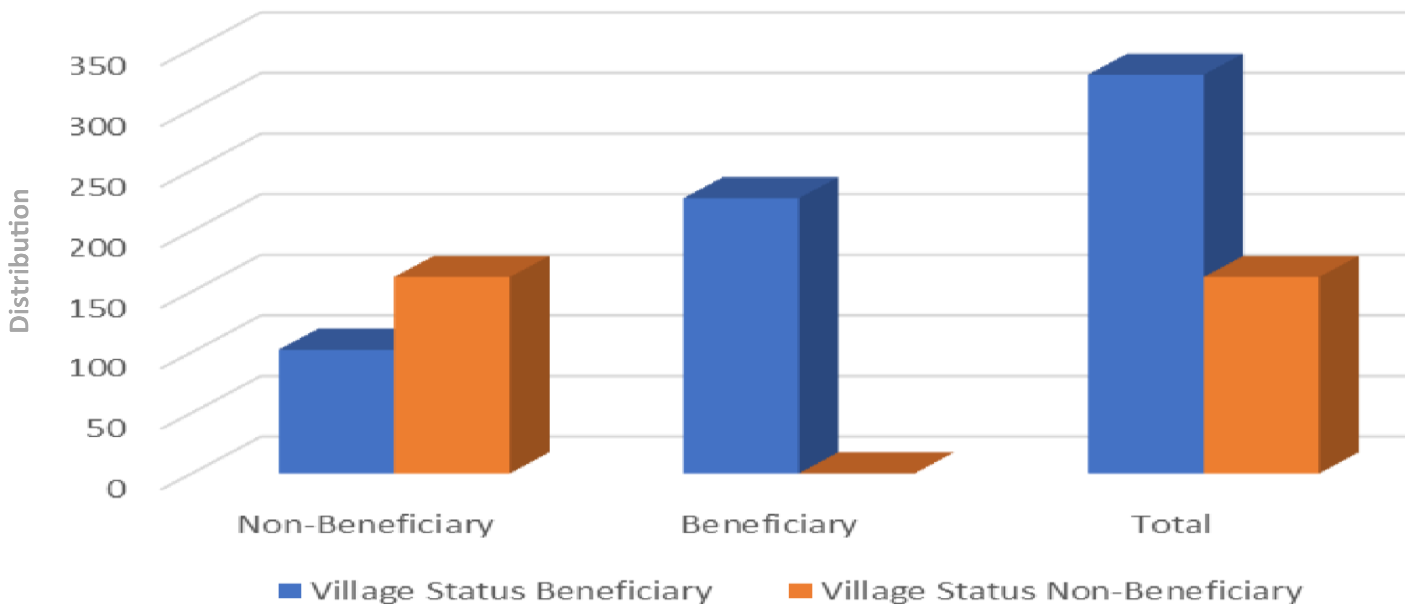

Figure 2. Distribution of the sample by producer type. Source: Author's calculations based on WAAPP'survey data.

Table 1. Producers' decision on utilizing fruit fly control technologies.

WAAPP status of the producer			
Fruit fly control technique	**Total Beneficiary**	**Non beneficiary**	
No Technology	19	182	201
Single Technology	56	48	104
Two Technologies	62	24	86
Three Technologies at least	90	10	100
Total	227	264	491

Source: Author's calculations based on WAAPP'survey data.

The second sampling stage involved selecting beneficiary producers, employing a two-stage procedure. In the first stage, villages were randomly selected proportionate to their beneficiary count. In the second stage, producers were chosen within these villages, applying a maximum threshold of 20 producers per village. In the third stage, interviewed producers were selected from both beneficiary and neighboring non-beneficiary villages. An equal number of respondents from a beneficiary village were matched with the non-beneficiary village. To ensure parity, the criteria for non-beneficiary selection mirrored those employed by the National Agency for Agricultural and Rural Advisory Services (ANCAR). These criteria included membership in a mango producer group or association, cultivating the Keit, Kent, or Séwé varieties, and owning an orchard spanning 1 to 6 ha. As a sampling frame for non-beneficiaries was unavailable, selections were made in the field, adhering to the established criteria. The survey did not involve an ethics committee. Mandated by the WAAPP program holder, CRES was responsible for data collection and the production of an evaluation report. The methodological approach was predefined, and collaboration with mango producers and stakeholders in the sector was facilitated by WAAPP. The collected data pertained to various aspects of agricultural activity and the management of fruit fly control. All surveyed producers provided their consent to participate by signing an agreement. In the quantitative survey, statisticians coded identification information, ensuring the anonymity of individuals. The qualitative survey took the form of focus groups and individual interviews conducted during fieldwork and the overall supervision of the survey.

Table 1 shows that among the four technologies disseminated by the PPAAO, the male fly elimination technique is the most widely used (184 beneficiary producers and 31 non-beneficiary producers). Next is prophylactic control (116 beneficiary producers and 45 non-beneficiary producers), followed by soil treatment (104 beneficiary producers and 40 non-beneficiary producers), with foliar treatment in the last position (66 beneficiary producers and 15 nonbeneficiary producers). The number of non-beneficiary adopting producers is very low compared to the number of beneficiary adopting producers. However, the level of usage among nonbeneficiaries informs us about the weak contamination effect among non-beneficiaries by neighboring beneficiaries, highlighting the importance of generalizing control, especially with the risk of fly movement from untreated orchards to treated ones.

Furthermore, the project recommends a combination of all four fruit fly control techniques for effective control and a significant reduction in post-harvest losses due to the fly. However, most producers use one technology (104), which is the male fly control technique, as per the results obtained in the previous table, or two technologies (86) or three technologies (100). It is also noteworthy that 19 beneficiary producers have refrained from using fruit fly control technologies. This can be explained by the complexity of good practices accompanying the technology package or the chemical nature of most elements in the technology package (Male fly technique, foliar treatment, soil treatment), which could impact the quality of the produce, especially considering the strong emphasis on organic farming practices nowadays.

Modeling the adoption of fruit fly control technologies

Theorical framework

This empirical framework is anchored in the theoretical foundations of Rogers' (1995) classic model of innovation diffusion. According to this theory, the adoption process follows four stages: knowledge acquisition, persuasion, decision, and confirmation. These processes are influenced by the information received by potential adopters, their socio-economic characteristics, the social system, and the attributes of the innovations. Given that producers in developing countries face market imperfections and uncertainties, their decisions to adopt or not adopt a new technology must be made while taking these factors into account. The decision to adopt or not adopt a new technology depends on their expectations. The degree of adoption is inherently linked to the level of diffusion, which represents the process by which an innovation is communicated through certain channels over time. The producer's behavior towards technologies is also a crucial element, including factors such as membership in a farmer organization (Sharma and Peshin, 2016; Rogers, 2003), perceived usefulness by producers according to David (1989) and Lin and Chen (2012), as well as the complexity of the innovation. Thus, the model that appears to be the most comprehensive and commonly used for analyzing the determinants of adoption, especially in the case of agricultural technologies, includes an analysis of the producer's behavior towards a technology (Rogers, 2003). Adapted to our issue, the rational producer will always seek to compare these revenues and production costs, including those related to the package of fruit fly control technologies. The analysis of the adoption factors of fruit fly control technologies and their impact will be conducted within the general framework of a production function specified as follows for a given farmer: $Q=f(X,Z,T)$

where Q represents the quantity produced, X, Z, and T are the vectors of production factors. More specifically, X represents the ordinary factors such as climate and institutional environment. The vector Z represents the socio-demographic characteristics of the producer.

This mainly includes their level of education, experience in horticulture, age, gender, income level, orchard size, labor availability, and risk aversion (Donkoh et al., 2019, Esnaashariyeh et al., 2022). Finally, vector T here represents the technologies for controlling fruit fly in mangoes (male fly elimination technique, foliar treatment, soil treatment, and prophylactic control). The importance of this vector lies in the significant role of new technologies in the emergence of agriculture in general, especially horticulture. Their direct or indirect contribution to poverty reduction is well established (De Janvry et al., 2015). In this thesis, the main parameter of interest is the variation in production losses due to fruit fly as a result of a variation in the use of technologies. Next, the well-being of Senegalese mango producers. Let T be the four fruit fly control techniques evaluated here (belonging to T), this parameter is written as: $VQ=dQdT$

As specified, this parameter represents the effect of an infinitesimal variation in at least one of the fruit fly control technologies. It is also a continuous representation. To obtain this parameter, it is necessary to have a numerical representation of the production function, from which we can evaluate elasticities or partial derivatives. This method implies a well-defined form of the production function and allows for simulating the impact of technological change.

Given the obvious difficulties in specifying and estimating a production function, another discrete method allows for calculating VQ without estimating the production function. For this method, it involves comparing producers for whom the input T takes the value 0, and those for whom T takes a positive value. We opt for this second method to evaluate the impact of adopting fruit fly control technologies on the well-being of mango producers through the reduction of production losses.

But can we exclusively attribute, assign the observed difference between the two types of producers (adopters or non-adopters) to the technologies? In other words, can we consider the existence of other factors that could also explain the observed difference between the two groups? These questions can be a source of selection bias. Assuming that the choice of a given producer is binary, so that producers choose to adopt or not adopt technologies, the adoption decision-making process and the impact on production losses and well-being can be modeled within a framework of optimization. Assuming that farmers are risk-neutral, we can evaluate the net benefit associated with adoption and nonadoption. Modeling the behavior of the producer regarding the adoption of technology(s) and identifying the key determinants of the decision to adopt a technology, which are assumed to derive from the producer's profit maximization. The literature suggests many econometric techniques, but the producer's decision is assumed to stem from the maximization of agricultural profit under the constraint of production costs, which are assumed to increase for the adopting producer.

The benefit associated with the use of technology is equal to (U):

$U = u_1 - u_2$

But the producer can also choose one, two, or at least three element(s) from the technology package, either due to budget constraints, accessibility issues of the technologies, or the complexity of usage.

Assuming that the producer chooses to adopt a technology only when the expected utility (U_1) is higher than the current utility (U_0) for non-adoption. In other words, the rationality of the producer would require $U_1 > U_0$.

The different combinations of technologies that the producer chooses to adopt are classified as follows: (i) Category = 0, for mango producers who do not use any technology on their orchards; (ii) Category = 1, for mango producers who use only one technology in their orchards; (iii) Category = 2, for mango producers who use a combination of two technologies in their orchards; and (iv) Category = 3, for mango producers who use a combination of three or more (the entire technology package) technologies in the orchards. It should be noted that the use of more than three practices is rarely observed in the field.

Depending on the producer's choice, the expression changes, and consequently, the profit function. We have the expression of profit for adopters and non-adopters, but we cannot estimate the profit of the non-adopting beneficiary. In experimental evaluation, the constraint is lifted by considering that adoption occurs randomly, regardless of the producer's status. This means that the gains obtained from non-adopting producers are representative of the gains that would have occurred without adoption.

However, adoption does not follow a random distribution between beneficiaries and non-beneficiaries, but is a function of the production decision to adopt or not adopt fruit fly control technologies. This means that adopters are different from nonadopters. In reference (Rosenbaum and Rubin, 1983), several techniques are explored to correct potential selection bias in the choice of treatment beneficiaries. In order to measure the impact of adopting fruit fly control technologies on mango losses due to fruit fly and on well-being, we can use PSM, Double Difference, endogenous regime change model, regression discontinuity, etc., or a combination of two methodologies for more reliable results depending on the nature of our data.

Methodological review

In the literature, various methodologies have been employed to isolate the impact of access interventions on fruit fly control. However, the limited research conducted by economists on fruit fly control, where impact assessment methods have been experimented with, has primarily taken place in Kenya (where fruit flies were first found in Africa) and Senegal. Notable studies including Kibira (2015) and Tefera et al. (2018) evaluated the impact of a set of integrated pest management practices on mango net income, human health, and the environment using recent survey data from Kenyan mango producers. They experimented with a multinomial endogenous switching regression model, controlling for potential selection bias.

Another study in Kenya used a Double Difference (DD) model to assess the economic impact of an integrated pest management package for fruit flies on the extent of mango product rejection due to fruit fly infestation, insecticide expenses, and net income (Kibira, 2015). This study utilized two years of panel data (2011 and 2012). The DD essentially compares participants (with) and nonparticipants (without) before and after an intervention. The analysis was conducted at two levels: starting from the basic assumption that other socio-economic variables do not change over time (unconditional), and that these variables vary from year to year and can affect the outcome of interest (conditional).

The evaluation by Tefera et al. (2018) revealed that mango farmers adopting integrated pest management not only had higher mango yields and net income but also used lower quantities of insecticide and caused less environmental harm to human health. Moreover, transitioning from one technology for fruit fly control to multiple technologies generated an even higher economic advantage for the environment and human health. These results underscore the need to intensify efforts to adopt fruit fly control technologies and encourage their use.

While these positive results can be achieved by providing adequate technical support and extension services to farmers, the evaluation conducted using the double difference method (Kibira, 2015) revealed that, on average, adopters of integrated pest management for mangoes experienced a reduction of about 54.5% in the extent of mango rejection, spent 46.3% less on insecticide per acre, and received about 22.4% more net income than nonadopters. This implies a high economic benefit of applying the integrated pest management technology for fruit flies, and mango producers would reap substantial benefits if the intervention were extended to cover a broader range of mango production areas in Kenya.

Another study conducted in Kenya assessed the impact of the Integrated Pest Management (IPM) strategy on food security using data collected from two surveys in Machakos County, Kenya. This study applied a difference-in-difference model on a randomly selected sample of 600 mango-producing households. Regression results indicate that the use of Integrated Pest Management for fruit flies had a positive effect on per capita calorie intake but did not have a significant effect on household dietary diversity compared to those who did not use this method. This suggests that farmers adopting this technology benefit from an increase in income, which improves the quantity of food consumed but does not affect the variety of foods consumed (Diiro et al., 2021).

For Senegal, the objective of the study was to measure the impact of losses incurred by mango producers in Ziguinchor over three years (2012, 2013, and 2014) and conduct an econometric analysis aimed at examining household characteristics associated with a high level of losses suffered by mango producers in Ziguinchor (Diatta et al., 2016). At the household level, the total annual losses due to fruit fly infestations represent an average of 17.09% of the average total household income in Ziguinchor (Casamance). Losses associated with production variability are much lower than losses due to the decrease in average yield (Diatta et al., 2016). Furthermore, the results show that the number of hectares, production level, and the use of Keitt varieties are three statistically significant factors with a significant positive influence on infestation losses. The use of fruit fly control technologies does not seem to significantly reduce mango losses (Diatta et al., 2016). To the best of our knowledge, this is the only econometric or economic analysis of the fruit fly issue in Senegal. Furthermore, it does not take into account the adoption or impact of fruit fly control technologies in Senegal, adding significant value to this article.

Analytical framework

Referring to the works of Kibira (2015) and Tefera et al. (2018), an endogenous multinomial switching regression model (ESRM) with an ordered probit selection rule was experimented with to establish counterfactual results, while controlling for potential selection bias in this research. It's a methodology widely used methodology in determining the factors of adoption and their impact on technology productivity (Mwungu et al., 2020; Midingoyi et al., 2019; Deng et al., 2020; Sekyi et al., 2020; Adabe et al., 2019). The multinomial treatment variable arises from the choice of sets of fruit fly control practices. Each producer chooses at least one technology from a set of technologies disseminated by the WAAPP program, which provides them with the greatest benefit or utility. These alternatives are classified as follows: (i) category j = 0, for mango producers who do not use any fruit fly control practices; (ii) category j = 1, for mango producers who use a single practice of this type on their orchards; (iii) category j = 2, for mango producers who use a combination of two technologies in their orchards; and (iv) category j = 3, for mango producers who use a combination of at least three fruit fly control technologies on their mango orchards. The use of more than three practices on a mango orchard is limited in the database.

The ordered probit model can be experimented with from a latent variable model (Wooldridge, 2010). Let the latent variable or utility that the individual producer will generate with adoption choices j=0,...,J be denoted as Ij*. This utility is determined by:

$Ij_{*}=Xij+ej, j=0,...,J$ (1).

The vector X in equation 1 represents the set of variables at the mango producer and mango orchard levels, as well as nominal location variables with corresponding estimable parameters; j is categorical variables that describe the choice of mango production adoption based on utility Ij*; and e is a disturbance term. The utility of adoption is not observed, but the decision of the i-th household is parameterized as follows:

Ij={0, if Ij*c1 1, if c1<Ij*C2 .. J, x>cj (2)

In Equation 2, c represents unknown cutoff points or threshold parameters identifying the transition boundary across different levels of adoption of fruit fly control techniques. The probabilities that the actual adoption variable Z takes on the different possible values conditional on X and the standard normal assumption of e are expressed as follows:

probXi=Φc1-Xij probXi=Φc2-Xij-Φc1-Xij probXi=Φc3-Xij-Φc2-Xij
probXi=1-Φc3-Xij (3)

The symbol Φ is the standard normal distribution function. The parameters are estimated using the "Oprobit" command available in STATA 16.

The second step of the econometric model allows for controlling selection bias by establishing the relationship between the outcome variable, which here is mango losses due to fruit flies, and a set of explanatory variables about the household, mango producers, mango orchards, etc. Outcome regression models are estimated separately for non-adopters and for the different categories of adopters for each choice of fruit fly control technologies adoption. The four elements of the fruit fly control treatment package should lead to four outcome equations.

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However, the low representativeness of producers who adopted four elements of the technology package leads us to group them with those who adopted three technologies, considering a regime where adopters of at least three fruit fly control technologies are present. These are defined as follows for each element of the technology package:

{Regime 0:Yi0=Xi00+i00+i0, if Ii=0 Regime j:Yij=Xijj+ijj+ij, if Ii=j for j=1,2,3 (4)

The symbol E represents the outcome variables (mango losses due to fruit flies) of the mango producer for the regime or element of the fruit fly control technology package adopted. J = 0 corresponds to the non-adoption of all fruit fly control technologies, while j = 1, 2, 3 represents the adoption of one or more fruit fly control technologies, respectively. The vector X represents a set of observable mango characteristics, including producer, mango orchard, and location characteristics. The variable λ denotes the inverse of the Mills ratio on the adoption of each technology j of the fruit fly control technology package obtained from the estimation of Equation 3 and included in the second-step equations to eliminate selection bias due to unobservable characteristics. β and σ are parameters to be estimated, while the coefficient F represents the covariance between the error terms of Equations 1 and 4. Although second step estimates are consistent, they have inefficient standard errors due to the two-step nature of the estimation procedure. Another potential issue with two-step estimation is that the outcome equations cannot be identified if the same set of explanatory variables is used in both steps. The selection correction terms λ are non-linear but may not be sufficient to identify the outcome equations and may lead to a multicollinearity problem. Therefore, we consider additional instrumental variables that influence adoption decisions but not outcome variables. These include membership in a farmers' organization. We will perform a simple post-estimation test to verify the validity of the instruments, followed by regression with the "etregress" command in STATA 16.

Estimating the average adoption effect requires deriving the actual and expected counterfactual results using Equation 4. The observed expected actual outcome from the data is calculated for each element of the fruit fly control technology package adopted as follows:

EIj=j=Xijj+jij (5)

The counterfactual result is defined as what would have been the result for adopters of fruit fly control techniques if the losses according to their characteristics had been identical to those of non- adopters. The expected value of the counterfactual result for each combination of fruit fly control technologies adopted is presented as follows:

EIj=j=Xij0+0ij (6)

In Equation 6, β0 and σ0 are the regression coefficients obtained from the outcome equation for regime j = 0 or non-adopters of fruit fly control technologies (Equation 4). The average adoption effect (ATT) for each element of the adopted technology package is calculated as follows:

ATTj=EIj=j-EIj=j=Xijj-0+ij σj-0) (7)

In Equation 7, the term Xijj - Xij0 and ijj σj - σ0 respectively denote the contribution of observed and unobserved heterogeneities to ATT.

RESULTS AND DISCUSSION

These data highlight significant trends in the adoption of fruit fly control technologies. This can be interpreted as a positive sign, indicating that producers are responsive to adopting these technologies.

Determining factors of fruit fly control technology adoption

Particularly, this part on the theoretical framework has demonstrated the significant interest in the issue of adoption and the factors determining it in economics, notably through the works of Rogers (1962) on the theory of innovation diffusion, delineating a process.

Also, in the works of Rogers (1962) and Rogers et al. (2014), the active role of producers, their intrinsic characteristics, and their social behavior in their environment in the face of technologies have been proven to be key factors explaining adoption. These subsidized adoption factors, along with other factors identified through field prospecting and qualitative analysis (such as the susceptibility of the Kent and Keitt varieties to fruit flies and the association of crops that promotes fly multiplication), have been considered in the regression using the "Oprobit" command to examine which factors effectively impact adoption for the issue under consideration (Table 2). The estimations reveal seven variables that positively or negatively influence the adoption of fruit fly control technologies by mango producers in Senegal, at the 1 and 5% significance levels. These variables include the producer's status (treated or untreated), orchard management and protection techniques, membership in a farmer organization, the quantity of mangoes requested by explorers, proximity to neighboring untreated orchards, number of employees, and knowledge of fruit fly control techniques.

These factors positively impact the probability that the producer will adopt fruit fly control technologies. However, Years of Experience reduce the probability of adopting these technologies. A study on "Agricultural technology adoption and its impact on smallholder farmers' welfare in Ethiopia" revealed that adopters are highly associated with lower farming experience. This leads us to conclude that farmers with fewer years of farming tend to adopt more than those with many years of farming (Ayenew et al., 2020).

Impact results

In the case of the producer's adoption choice, it defines the observed impact, and the results differ for the three groups under study. Firstly, it is important to note the significance of the sigma statistic at the 1% threshold. This proves the presence of selection bias and endogeneity, affirming the relevance of the chosen model (the endogenous regime change model), which allows for the correction of both selection and endogeneity biases (Table 3).

In terms of the Global Adoption Impact, the adoption of fruit fly control technologies, on average, leads to a 29.71% increase in mango losses at the 1% threshold. This indicates a consistent and statistically significant negative effect on mango losses across all cases of adoption. Regarding the Age of the Producer, our findings indicate a positive influence on adoption. The coefficient stands at 0.009 at the 5% threshold, suggesting that as the age of the producer increases, there is a corresponding increase in the likelihood of adopting fruit fly control technologies.

In terms of the number of employees in the Orchard, our analysis reveals a positive influence on adoption. The coefficient, standing at 0.051 at the 5% threshold, implies that orchards with a higher number of employees are more likely to adopt fruit fly control technologies. In the case of Belonging to a Farmer Organization, our findings indicate a negative influence on adoption. The coefficient, at -0.491 and significant at the 1% threshold, implies that producers associated with farmer organizations are less inclined to adopt fruit fly control technologies. In the literature, negative experiences regarding belonging to producer networks to improve the adoption of agricultural technologies are reported. Contrary to expectations, membership in a cooperative group reduces both the propensity and intensity of technology adoption (ZT). This can be explained by the fact that membership in cooperatives can provide easy and cheap access to inputs, reducing the incentive to save on production costs (Yigezu et al., 2018). Another study on the adoption of new rice technologies also showed a negative impact of belonging to a farmer organization on its adoption (Donkoh et al., 2019).

The observed impact on losses is attributed to specific factors. The orchard size, with a coefficient of -6.750 at the 1% threshold, signifies a notable reduction in mango losses. Similarly, the number of equipment, indicated by a coefficient of -0.093 at the 10% threshold, also contributes positively to the reduction in losses. On the contrary, certification emerges as a significant factor, demonstrating a negative influence on losses with a coefficient of 18.527 at the 5% threshold.

Among those who choose to adopt a single fruit fly control technology, the findings consistently reveal a substantial and adverse impact at the 1% threshold. This signifies that the adoption of a sole technology for fruit fly control leads to a notable increase in production losses, exhibiting a rise of 49.09% at the 1% threshold. This emphasizes a critical rise in losses, surpassing the overall losses observed across different adoption scenarios, as detailed in the preceding results.

This adoption is explained by belonging to a farmer organization (-0.307, at the 1% threshold) and the number of employees in the orchard (0.058, at the 5% threshold), which negatively affects the adoption of fruit fly control technologies, and the age of the adopting producers (0.007, at the 5% threshold), which has a positive effect on the adoption of a fruit fly control technology.

Furthermore, the second stage of the regression provides information on the overall significant negative impact at the 1% threshold of adopting a fruit fly control technology on production losses due to fruit flies. This impact is negatively explained by having certification (12.249 at the 10% threshold), and the number of employees in the orchard (1.654 at the 1% threshold), and positively, by the orchard size (-6.209 at the 1% threshold). The significant and positive effect of the mango orchard area on production losses due to fruit flies shows that the larger the area planted with mangoes, the more the producer invests in fruit fly control, hence the reduction in mango losses due to fruit flies by -6.209%. Moreover, the number of employees in the mango orchard and having certification negatively impact mango losses due to fruit flies, with an increase of 1.654 and 12.25% respectively.

When producers choose to adopt two fruit fly control technologies, the results highlight a substantial negative impact at the 1% threshold. Specifically, incorporating two elements from the package of fruit fly control technologies leads to a significant increase in production losses, up by 38.134% at the 1% threshold. This signifies a noteworthy rise in losses, albeit still less severe than what is observed in adopters of only one technology, where losses reach 49.428% at the 1% threshold. Nonetheless, these losses are comparatively lower than those observed in adopters of only one technology, which stands at 49.428% at the 1% threshold.

This adoption is explained by belonging to a farmer organization, which negatively affects the adoption of two fruit fly control technologies (-0.464 at the 1% threshold), just like in adopters of one technology. Next, the age of the adopting producer (0.008, at the 5% threshold) and the gender of the adopting producer (0.369, at the 5% threshold), which positively impact the choice to adopt two fruit fly control technologies.

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Furthermore, the second stage of the regression provides information on the overall significant impact at the 1% threshold of adopting two fruit fly control technologies on production losses due to fruit flies. This impact is explained by the orchard size (-5.850 at the 1% threshold) and the amount of equipment in the orchard (0.084 at the 10% threshold), which positively impact mango losses. Moreover, having certification (15.352 at the 5% threshold) increases mango losses due to fruit flies. Indeed, certification assumes that the producer equips themselves with all the means to fight against fruit flies to provide high-quality production, generally intended for export, in line with international requirements.

In the context of this analysis, the opposite effect is observed, which may be due to the low percentage of producers with certification in the sample studied.

For adopters of three or more fruit fly control technologies, the results show an overall significant impact at the 1% threshold and positive. In other words, the adoption of at least three fruit flies control technologies reduces mango losses by 26.759%. This adoption is explained by the labor force in the mango orchard (0.093 at the 1% threshold), which positively influences the choice to adopt three fruit fly control technologies. Indeed, the application of fruit fly control technologies comes with good practices that require rigorous and regular monitoring. Just the prophylactic fight should be able to mobilize enough agents to regularly clean the orchards to get rid of mangoes attacked by flies and proceed with their burial to break the cycle of multiplication of the fly.

Furthermore, the second stage of the regression provides information on the overall significant impact at the 1% threshold of adopting at least three fruit flies control technologies on production losses due to fruit flies.

This impact can be better understood by considering two key factors. Firstly, the extent of the mango area planted, indicated by a significant negative effect of 6.139 at the 1% threshold. In simpler terms, larger mango orchards tend to experience reduced losses. Secondly, the amount of equipment in the orchard has a noteworthy effect, albeit a positive one, at -0.098, significant at the 10% threshold; having more equipment seems to contribute to higher mango losses.

On the flip side, the number of employees has a negative influence on mango losses for those who have adopted the three fruit fly control technologies, echoing trends seen in earlier scenarios (1.483, significant at the 5% threshold). Similarly, the certification of the producer also shows a negative impact (17.098 at the 5% threshold).

Findings reveal that adopting one or two technologies leads to significant increases in losses, albeit to a lesser extent for those adopting two technologies (49% / 38%). This finding aligns with previous studies on exotic and indigenous fruit fly species in Africa, which showed that managing fruit fly pests is unlikely to succeed if it relies on a single management technique (Allwood and Drew, 1997). Similar results were also observed in Ziguinchor, Senegal, where there was a significant increase in mango losses with the use of fruit fly management technologies (Diatta et al., 2016).

On the other hand, adopting packages that combine at least three technologies reduces production losses due to fruit flies by 26% among beneficiaries and 27% among non-beneficiaries of the program. However, this difference is not statistically significant. This implies that effective control of mango fruit flies in Senegal requires the adoption of at least three fruit fly management technologies. This result confirms previous recommendations for fruit fly control and research findings from studies such as (Allwood and Drew, 1997; Kibira, 2015; Tefera et al., 2018; Otieno et al., 2023; Nyang'au et al. 2020) even though the context is different.

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This result considers that only 20% of Senegalese mango producers adopt three or more technologies, leaving 80% still exposed to fruit fly damage, which remains a priority for ECOWAS. Previous studies also showed similar results, with farmers seeming to adopt specific components but not the entire integrated pest management measures (Korir et al., 2015). These authors evaluated the adoption of a set of fruit fly management methods and found that the adoption rate was very low, with a significant portion of producers not adopting three means of fruit fly management.

This raises questions about whether it is an issue of access or a problem related to the complexity of the technologies, most of which are chemical and require adherence to specific best practices. Indeed, formal implementation of best practices may seem complex given the relatively low level of education among mango producers, as well as the rate of support from extension agents (CARs), estimated at 35% for beneficiaries and 4% for non-beneficiaries. A study in Kenya shows that farm size and the effectiveness of IPM positively influence the likelihood of technology abandonment, thus encouraging sustainable adoption of IPM. Therefore, the study recommends enhancing the skills of mango farmers through training and increasing access to extension services to promote the adoption of this technology and prevent its abandonment. Another study assesses the drivers of adoption and dis-adoption of Integrated Pest Management (IPM) practices in suppressing fruit fly infestation in Embu County, Kenya reveals that the cost of IPM and IPM training positively and significantly influenced adoption, while technology unavailability had a negative and significant effect on adoption. Regarding dis-adoption, the results indicate that farm size and the quality of IPM positively influenced the risk of discontinuing the use of IPM, thus promoting sustainable adoption of this method. (Otieno et al., 2023).

Furthermore, qualitative analysis from focus group discussions with producers revealed issues related to access to technology. Formally, there was only one factory, SENCHIM, which was the source of fruit fly pest management input supply. In scientific articles addressing this issue, there is no explicit mention of the access rate to fruit fly management technologies in Senegal. However, we can use the utilization rate of fruit fly management technologies among beneficiaries and non-beneficiaries as a proxy to better assess access.

The access rate to fruit fly management technologies in Senegal is estimated to be 66% among beneficiaries (with 80% of beneficiary producers having received fruit fly management technologies for free from the WAAPP/ANCAR project, while the remaining 20% purchased them either on credit or in cash) and 13% among non-beneficiaries. A study in Kenya examined the factors influencing the adoption and discontinuation of Integrated Pest Management (IPM) practices to control fruit fly infestation in Embu County, Kenya using a Correlated Random Effects Probit Model and a Discrete Time Proportional Hazards Model demonstrate that the cost of IPM and training on this method had a positive and significant impact on adoption, while the unavailability of the technology had a negative and significant effect. (Tefera et al., 2018) Still in Kenya, another study recommends strengthening farmers' knowledge by providing them with increased access to training programs and extension services to promote enhanced adoption of sustainable management practices for B. dorsalis (Wangithi et al., 2021).

These results suggest that the adoption of fruit fly control technologies has a significant impact on reducing mango losses in Senegal. Specifically, on average, adopting any technology reduces losses by approximately 26.33 percentage points (Table 4). For those who adopt at least one technology, losses are reduced by about 22.69%

points. Among those who adopt at least three technologies, losses are reduced by approximately 47.025 points. Additionally, the indirect impact (ATU) shows that even for non-adopters, being in an environment with higher adoption rates of these technologies can lead to reduced losses.

Conclusions

Results show that adopting combinations of at least three technologies resulted in a 26% reduction in fruit fly losses for beneficiaries and 27% for non-beneficiaries, with only 20% of growers adopting three or more technologies. Given these observations, the author strongly recommends that the relevant authorities intensify efforts related to awareness-raising about the benefits of diversifying fruit fly management methods and training on best practices using technologies to fight against fruit fly infestation. The research also recommends that authorities, decision-makers, and stakeholders intensify efforts in awareness, training, and facilitating access to technologies for mango growers. Furthermore, it is necessary to reconsider the relevance of project diffusion approaches, particularly the entry through farmers' organizations. The results show a negative impact on the adoption rate due to a lack of motivation related to the free provision of inputs and equipment. This is not comparable to a situation where the producer bears the production costs and makes the activity profitable.

Recommendations

This study recommends widening the dissemination and scaling of the Integrated Fruit Fly Management strategy in mango-producing regions to achieve more significant effects on household food security. It is also essential to consider scientific evidence on the issue in more effective fruit fly control policies. In its latest report on fruit fly control in West Africa, CORAF expressed concern about the reliability of data at the country level. According to CORAF (2019), efforts should be made regarding the Average Treatment Effects (ATE), Average Treatment Effects on the Treated (ATT), and Average Treatment Effects on the Untreated (ATU).

Table 3. Results of fruit fly control technologies adoption.

Variable	Global adoption	Single technology adoption	Two technologies adoption	Three technologies adoption at least
Impact equation				
Number of employees	0.361 (0.635)	1.654*** (0.640)	0.545 (0.648)	1.483** (0.641)
Orchard size	-6.750*** (1.413)	-6.209*** (1.311)	-5.850*** (1.301)	-6.139*** (1.360)
Number of agricultural equipment in household	-0.093* (0.053)	-0.067 (0.051)	-0.084* (0.050)	-0.098* (0.055)
Years of experience	-0.035 (0.082)	-0.106 (0.083)	-0.022 (0.082)	-0.040 (0.083)
Producer certification	18.527** (7.823)	12.249* (6.253)	15.352** (6.244)	17.098** (7.512)
Constant	22.351*** (4.319)	24.573*** (3.450)	30.645*** (3.323)	39.323*** (3.672)

Adoption X non non-beneficiary	5.065 (7.550)	-0.149 (2.414)	-2.889 (2.425)	2.147 (3.214)
Adoption X non-beneficiary	-1.960 (3.138)	-1.854 (5.990)	5.998 (5.252)	3.085 (3.764)
Adoption	29.714*** (6.825)	49.428*** (4.189)	38.134*** (4.658)	-26.759*** (8.356)
Selection equation				
Producer gender (Ref. Male)	0.212 (0.222)	0.123 (0.169)	0.369** (0.180)	-0.146 (0.281)
Producer age	0.009** (0.004)	0.007** (0.003)	0.008** (0.004)	-0.005 (0.005)
Producer education	0.202 (0.166)	0.159 (0.156)	0.194 (0.164)	-0.101 (0.189)
Member of a local committee (Ref. No)	-0.491*** (0.101)	-0.307*** (0.090)	-0.464*** (0.099)	0.241 (0.164)
Number of employees	0.051* (0.028)	-0.058** (0.024)	0.007 (0.028)	0.093*** (0.029)
Constant	-0.454 (0.309)	-0.952*** (0.261)	-1.500*** (0.323)	-0.832** (0.405)
Athrho	-0.723*** (0.161)	-1.194*** (0.125)	-1.172*** (0.112)	0.406*** (0.157)
lnsigma	3.387*** (0.064)	3.453*** (0.050)	3.426*** (0.045)	3.292*** (0.050)
Observations	491	491	491	491

Robust standard errors in parentheses

Table 4. Indirect impact of fruit fly control.

Statistics		Global adoption	Single technology adoption	Two technologies adoption	Three technologies adoption at least
ATE	Coeff	26.32555	48.63936	42.24262	26.32555
	P value	0.0015	0.0000	0.0000	0.0015
	IC	-42.5792 -10.0719	40.42948 56.84923	35.33891 49.14633	-42.5792 -10.0719
ATT	Coeff	22.68804	47.72245	47.02089	-25.82109
	P value	0.038	0.000	0.000	0.004

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	IC	1.261598 44.11448	35.46201 59.98289	38.67199 55.36978	-43.29704 -8.345139
		29.71356			
	Coeff	0.000	49.42776	38.13403	-26.75931
ATU (indirect impact)	P value	16.33637	0.000	0.000	0.001
	IC	43.09075	41.21812 57.6374	29.00444 47.26362	-43.13593 -10.38268

Research perspective

In future research, it may be considered to evaluate the impact of adopting fruit fly control technologies on the well-being of the producer, assess the cost of implementing widespread fruit fly control in Senegal, and conduct a gender analysis on access to fruit fly control technologies and their impact on mango losses in Senegal.

Limitations

Most fruit fly control technologies are chemical and can, therefore, impact the environment. The database used does not capture this key indicator.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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