Qualitative modeling of fruit fly injuries on chayote in Réunion: development and transfer to users

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Summary

Intensive chayote cultivation in Réunion almost disappeared in the 2000s due to significant yield losses from fruit flies attacking this historically important crop (*Dacus ciliatus*, *Zeugodacus cuurbitae* and *Dacus demmerezi*). Since the late 2000s, the adoption of agroecological crop protection practices have led to the effective management of fruit fly populations, a significant reduction in pesticide use, an increase in chayote production and plantations, and the development of organic production. To assist in fruit fly management, a qualitative model which simulates fruit fly damage to chayote crops, known as IPSIM-chayote, was developed, providing satisfactory prediction results. It has a user-friendly interface and is now available free of charge online, in three languages (French, English and Spanish): https://pvbmt-apps.cirad.fr/apps/ipsim-chayote/?lang=en. The IPSIM-chayote modeling platform can be used by farmers as a tool to simulate fruit fly damage to their crops and also as a decision-making tool for their agricultural practices. The model can be used as a training resource in agroecological crop protection. Public authorities and local government can use it as a tool in planning and forecasting agricultural development. Finally, researchers can use it as a prediction tool and a resource for the exchange of information, allowing them to review scientific knowledge or identify new, relevant research areas suited to the context and challenges. IPSIM-chayote can be considered as a forum for exchange and can stimulate collaborative work between individuals. It is a flexible model, as it allows variables to be added. IPSIM-chayote is the first qualitative model developed for crop pests in a tropical environment. It could serve as a basis for the development of other similar models simulating crop pest incidence, thus contributing significantly to the development of agroecological crop protection.

Key Words: IPSIM-chayote, Injury Profile SIMulator, Tephritidae, *Sechium edule*, agroecological crop protection, R Shiny app

1. Introduction

Sechium edule (Jacq.) Swartz is a plant belonging to the Cucurbitaceae family and is native to Mexico. It has been cultivated for several millennia in South America. Today, chayote is cultivated in many tropical and subtropical countries (Monnerville et al., 2001) and all parts of the plant can be eaten (Saade, 1996; Sharma et al., 1995). In Réunion, chayote is a popular, historically important crop, where its leaves and fruits are traditionally consumed. Since the 1980s, chayote has been cultivated intensively on trellises, using significant quantities of pesticides, mineral fertilizers and water (Deguine et al., 2015). In the 2000s, chayote production collapsed. Cultivation declined sharply in the Entre-Deux area and Cirque de Salazie, the two main traditional cultivation areas (Deguine et al., 2015). The chayote sector has attributed the 50 to 90% decline in production to fruit fly damage (Diptera, Tephritidae), despite repeated treatments with insecticides. In the case of fruit flies on chayote crops, injuries correspond to damage since only one oviposition puncture on a fruit prevents it from being sold to consumers. The incidence of punctured fruits thus directly corresponds to relative yield loss in terms of number of fruits harvested per surface unit.

Since 2009, studies have begun to investigate the agroecological management of fruit flies on chayote crops in Réunion. These studies have made it possible for producers to move from agrochemical crop protection (ineffective as fly populations are not eliminated despite numerous treatments while natural enemies have disappeared; harmful to the environment and to human health) to agroecological crop protection (more efficient, profitable, and easy to set up in the field and safe for consumers (Deguine et al., 2017, 2019)).

To sustain an agroecological approach, information, knowledge and training for all involved in the chayote sector, producers in particular, will be required. Since 2015, a new resource has been proposed via a model to simulate fruit fly damage to chayote crops in Réunion (Deguine et al., 2015). This tool should be accessible by all in the chayote sector to help farmers simulate fruit fly damage to their chayote crops and to help with their decision making for control of fruit flies. Agricultural transfer and educational organizations can use the tool as a training resource in agroecological crop protection. Public authorities can use the tool for planning agricultural development. Researchers can use the tool as a resource to review knowledge and skills and to identify new research areas suited to specific contexts and challenges.

Agroecological approaches rely on complex interactions between various components of agroecosystems: soil, plants, microorganisms (bacteria, fungi, viruses) and animals (vertebrates, arthropods, molluscs, annelids), and are influenced by weather, cropping practices and the surrounding landscape. In order to help decision making in crop management, modeling has been used for decades (Donatelli et al., 2017). In the field of crop protection, a wide range of epidemiological models for diseases (Madden et al., 2007), population dynamic models for animal pests (Chander et al., 2007), and models for weed population dynamics (Holst et al., 2007) have been deployed. They have often been used to help choose pesticide treatments as a function of observed crop injuries or pest population, and expected damage (e.g. Zadoks, 1981). However, these models generally do not accurately take into account cropping practices (Aubertot et al., 2005) or often ignore crop losses (Savary et al., 2006). On the other hand, specific damage mechanisms have been incorporated into some crop growth models to simulate yield losses (Savary et al., 2018). In addition, these models often take into account only one pest and a limited number of processes.

In order to overcome these limitations, the IPSIM modeling platform was proposed (Aubertot and Robin, 2013). This innovative model allows users to combine four sources of knowledge: (1) expert knowledge (from researchers, agricultural engineers, crop advisers, farmers); (2) scientific and technical literature; (3) datasets from field experiments and commercial field regional diagnoses (i.e. date obtained from qualitative field oservations performed by agricultural extenders and advisers), and (4) simulation models. The primary characteristic of this approach is that it considers nominal or ordinal input variables to predict classes of injury. In IPSIM approaches, accuracy is preferred to precision. This allows users to benefit from a broader source of information (notably datasets), and helps to promote adoption of the model. It generates transparent, flexible, and easy-to-understand hierarchical aggregative models that can be designed collectively by practitioners. These properties make models designed with the IPSIM approach great qualitative predictive tools to aid in decision making, and the model is also adapted for communication and teaching for a range of stakeholders.

Based on a literature review of fruit fly models on horticultural (fruit and vegetable) crops with emphasis on cucurbits, thermal time (TT), regression, mechanistic and artificial intelligence (AI) models have been proposed (Inayatullah et al., 1991; Duyck and Quilici, 2002; Koyama et al., 2004; Sutherst et al., 2007; Vayssières et al., 2008; Lux, 2014; Mokam et al., 2014; Sridhar et al., 2014; De Villiers et al., 2016; Bana et al., 2017; Bolzan et al., 2017; Choudhary et al., 2017; Remboski et al., 2018; Choudhary et al., 2019, Vanoye-Eligio et al., 2019). The literature on modeling the damage of cucurbit flies is limited and no study mentions chayote. The reported modeling work only relies on numerical variables from statistics, data mining, or mechanistic modeling. In addition, each study only considered variables of one component of an agroecosystem only, namely the soil, weather, cropping practices or field environment.

IPSIM (Injury Profile Simulator) is a generic modeling approach which describes the damage profile on a crop relative to cropping practices and production situation (Aubertot and Robin 2013). Models developed using the IPSIM approach can thus contribute to the design of cropping systems which can better resist pests and are therefore less dependent on pesticides. The approach is generic; it can be easily adapted to all types of pests and all crops (Robin et al., 2013; Aubertot et al., 2016; Robin et al., 2016; Demesthias, 2017; Robin et al., 2018; Vedy-Zecchini, 2020), including fruit flies on chayote crops in Réunion. The main hypothesis of the approach is that the damage intensity of any pest is determined only by three main groups of factors: agricultural practices, the pedoclimate, and the landscape. The spatial scale considered is the plot because this is the scale on which the cropping system is applied, even if the same cropping system can be applied to several plots (Sébillote, 1990). The temporal scale of the model depends on the biology of the pest, i.e. its level of endocyclism (Aubertot and Robin, 2013). It can range from the crop cycle to several years. IPSIM models are deterministic and static models. A unique feature of IPSIM is that it is able to accommodate a high level of complexity within revised or even redesigned agroecosystems, as the agroecological approach implies (Hill and McRae, 1995). The strength of the approach is that the predictive models obtained are very close to conceptual models reflecting the available knowledge.

In this study, we propose to build a predictive model for the agroecological management of fruit flies on chayote crops in Réunion, based on the IPSIM qualitative modeling approach. The objective of this study is to develop a model to predict fruit fly damage on chayote, with qualitative attributes related to cropping practices, pedoclimate and landscape conditions. The development of such a model involves three main phases: i) the design and evaluation of the predictive quality of the model; ii) the construction of a simple, user-friendly interface which can be used online as a training tool; iii) the transfer of the model to end users.

2. Materials and methods

2.1. Model building process

After reviewing the literature and acquiring expertise on the subject (Supplementary data, Section 1), the IPSIM-chayote model was built using the method described on the IPSIM website (www6.inra.fr/ipsim, Robin et al., 2018) and in previous studies (e.g. Robin et al., 2013). It is based on the DEX method, implemented with the DEXi software (Bohanec, 2020). DEXi software can support hierarchical qualitative models, such as DEXiPM (Pelzer et al., 2012) which was initially used for the assessment of agroecosystems described by expert knowledge (Angevin et al., 2017). IPSIM-chayote was designed in four phases which are presented in the following sections (Bohanec, 2003): (i) identification and organization of attributes (main variables that may affect fruit fly damage intensity and their interdependent relationships), (ii) definition of qualitative attribute scales for each attribute, (iii) definition of aggregative tables that synthesize the impact of combinations of attributes to determine the final intensity and (iv) calculation of the attribute weights in order to summarize the influence of each attribute to the final output.

2.1.1. Identification and organization of attributes

The first phase in the design of the model involves choosing the attributes to be considered as well as their hierarchy in the tree of attributes. This stage requires gathering worldwide bioecological knowledge available on fruit flies on chayote. A literature review was carried out to identify the biotic and abiotic factors that may affect the intensity of fruit fly infestations. In addition, experts in chayote cultivation (farmers and advisers) and agro-ecological entomologists specialized in fruit fly management pooled their knowledge during the course of several workshops to identify the main attributes and their relative importance (see Supplementary data). Finally, the factors judged to be the most relevant to experts were selected and organized to construct the model. Developers then applied the tree of attributes under DEXi and finally into an online application.

2.1.2. Attribute scales

The scales used in the model were ordinal or nominal. They have from two to five classes. For instance, the final output (the intensity of fruit fly injuries) has five classes: “very high”, “high”, “medium”,” low”, “zero” for its. In any scale, a "favorable" value means that the attribute is favorable for the development of fruit flies and is therefore potentially detrimental to chayote cultivation. In any scale, a value "favorable" for the development of fruit flies appears in red (as it is detrimental to farmers); a value “unfavorable" for the development of fruit flies appears in green (as it is beneficial to farmers); a “neutral” value with regard to the development of fruit flies appears in black.

2.1.3. Aggregative tables

The aggregative tables are based on scientific and technical knowledge. They summarize the influence of attribute interactions at all levels. The aggregation is performed via sets of qualitative “if-then” decision rules. In DEXi, the rules corresponding to each aggregated attribute are gathered in tabular form that corresponds to aggregative tables, initially called “utility functions”. The software then performs a bottom-up aggregation from input attributes toward the root of the model, i.e. the intensity of fruit fly damages on chayote.

2.1.4. Attribute weights

The influence of each input and aggregated attribute on the value of the final variable can be characterized by weights. The higher the weight, the more influential the attribute (Bohanec et al., 2007). The relative importance of attributes, described by weights, is automatically calculated by DEXi as a function of aggregative tables using a linear regression method (Bohanec, 2020; see Supplementary data, Section 2). DEXi calculates four types of weights: local and global weights, normalized or not. We will consider only normalized weights since they take into account the number of values within the scales. Local weights represent the influence of attributes on the associated aggregated attributes. Global weights represent the influence of attributes on the final output of the model.

2.2. Description of data collection used for model evaluation

To take into account an observed situation to assess the predictive quality of the model, it is necessary to have information on the intensity of fruit fly attacks, cropping practices, the environment around the plot and the climate. Depending on the nature of the information available, quantitative data were converted into qualitative data to obtain variables compatible with the IPSIM framework. For example, we translated quantitative data of the type "percentage of fruit punctured by fruit flies" into qualitative data, ranging from "zero damage" to "very high damage". Intensity of injuries is here considered as similar as intensity of damages.

The data collection and the dataset used to evaluate the model came from three sources: surveys carried out with chayote producers during field visits; bioecological studies on chayote flies by CIRAD (Centre for International Cooperation in Agronomic Research for Development) and tests conducted by FDGDON (Departmental Federation of Defence Groups against Harmful Organisms). The observation data, used to assess the predictive quality of IPSIM-chayote, were collected on two sites from 2007 to 2011: the town of Salazie, and the town of Entre-Deux where chayote trellis plantations are still present (Fig. 1). In total, 86 locations were studied. By removing locations with incomplete or missing data, 50 locations were finally used to evaluate the model.

Field surveys in chayote production areas were conducted by CIRAD, the VIVEA cooperative and the Réunion Chamber of Agriculture. They observed 39 locations (35 in the municipality of Salazie and four in Entre-Deux). Of these 39 locations, 21 used agrochemicals, 10 used agroecological methods and eight used a combination of both methods. Twenty locations had a growing period in the summer and 19 in the winter. In addition, CIRAD's bioecological studies were carried as part of various end-of-study internships, for students at the University of Réunion and the François Rabelais University in Tours (Gilles, 2008; Aubry et al., 2009; François, 2009). These studies, independent from the Gamour project (Gamour is a R&D project that ran from 2009 to 2011 and studied the effectiveness of agroecological cucurbit fly management (Deguine et al., 2015)), were conducted in Salazie and Entre-Deux. They focused on the bioecology, the spatio-temporal dynamics and the incidence of fruit flies on chayote crops. Seven independent locations were selected (two in Salazie and five in Entre-Deux), four with growing seasons in the summer and three in the winter. Finally, the tests conducted by the FDGFON in Salazie made it possible to select four independent locations: two used agrochemical practices, two agroecological practices, two with growing seasons in the winter and two in the summer. We estimated the intensities of damage in two different ways. In the majority of situations

(21 situations in winter and 22 situations in summer), we considered 30 fruits on the chayote trellis and we observed the percentages of fruits with at least one fruit fly bite. We estimated the intensities of damage as a function of this percentage as follows. "zero damage" class: 0%; "low damage" class:]0%-10%]; "medium damage" class:]10%-40%]; "high damage" class:]40%-70%]; "very high damage" class:]70%-100%]. In the seven other situations, the damage intensity was characterized only qualitatively at the field level according to the same ordinal scale.

In a context where the chayote production areas and the number of chayote producers are relatively limited, the independence of the observations on the same plot needs to be ensured (for example when monitoring the temporal dynamics of fruit fly populations over seasons and years). To this end, data independence tests on data from the same plot were carried out by calculating the correlation levels obtained for different time intervals. It was shown that for time intervals of at least six months, there was no longer any correlation between the counts made on the same plot. We therefore considered two periods per plot: summer production and winter production.

The 50 independent locations selected were diversified in terms of their cropping practices, in particular phytosanitary practices, geographical location and surrounding landscape (Table 1). As for cropping practices; 23 fields had prophylactic measures (i.e. sanitation using augmentorium (Deguine et al., 2011)); 22 sexual trapping; 16 adulticide baits; 31 soil cover; 50 irrigation; 5 low, 34 intermediate, and 11 high fertilization respectively; 23 low, 12 intermediate, and 15 high use of insecticides. In addition, the observed intensities of fruit fly damage were fairly evenly distributed across the IPSIM-chayote rating scale used in the model (Table 1).

2.3. Assessment of predictive quality

The evaluation stage compared observed and simulated classes of fruit fly injuries using independent datasets including a large number of various production situations and crop management options (Aubertot and Robin, 2013). In order to assess its predictive quality, IPSIM-chayote was used with the dataset described in the preceding section. It is important to state that this dataset was not used to fine-tune the model and constitutes an independent dataset for its evaluation.

A confusion matrix was built to compare predictions to actual observations. We used several metrics (Table 2) to measure the predictive quality of IPSIM-chayote. Accuracy is defined as the rate of correct predictions for the entire dataset (Nguwi and Cho, 2010). The Cohen's quadratic weighted Kappa (Agresti, 2010) can be interpreted as the proportion of variability explained by the model (Fleiss and Cohen, 1973). Similar to correlation coefficients, κ coefficients range from −1 to +1. Values of κ can be interpreted as follows: values ≤ 0 indicate no agreement; values ranging 0.01- 0.20 indicate none to slight agreement; values ranging 0.21 - 0.40 indicate a fair agreement; values ranging 0.41– 0.60 indicate a moderate agreement; values ranging 0.61 - 0.80 indicate a substantial agreement; and values ranging 0.81 - 1.00 indicate an almost perfect agreement (McHugh, 2012). Kendall's τ_b (Kendall, 1938) and Spearman's rank correlation coefficient ρ_S (Spearman, 1904) were also calculated.

Six criteria for binary classification were calculated for each of the five output classes using the *one version all approach*. Sensitivity (or recall) measures the proportion of actual positives which are correctly identified (Witten et al., 2011). The specificity measures the proportion of negatives which are correctly identified (Witten et al., 2011). Accuracy is calculated as the number of correct positive predictions divided by the total number of positive predictions (Witten et al., 2011). F_1-score is a harmonic mean of accuracy and sensitivity (Witten et al., 2011). In other words, it conveys the balance between accuracy and sensitivity. The F_1 score reaches the best value, meaning perfect accuracy and sensitivity, at a value of 1. The worst F_1 score, which means lowest accuracy and lowest sensitivity, tends towards 0. Matthews correlation coefficient (MCC) is a special case of Pearson correlation coefficient and leads to similar interpretations (Matthews, 1975). Area Under the Curve Receiver Operating Characteristics (AUROC) is a performance measurement for binary classification problems (Witten et al., 2011). AUROC tells how much the model is capable of distinguishing one class versus all others. The higher the AUROC, the better the model.

All calculations were performed using Mathematica 10.1.0.0 (Wolfram Research Inc., 2015), except for the ROC (Receiver Operating Characteristics) analysis which was performed with the pROC package of the R software (Robin et al., 2011).

2.4. Development of the user interface

A new user interface was created which is more user-friendly than the one of the DEXi software, which is not aimed at end-users such as farmers. This new interface is specific to users and for a specific purpose. It allows the authors to transfer and share the IPSIM-chayote damage prediction model. Figure 2 presents the conceptual model of the user interface. This interface will allow researchers, technicians and agricultural advisers to interact with the model more easily, and facilitates the exchange of current knowledge on the effect of agroecological practices on chayote fruit damage, to allow farmers to understand and predict fruit fly damage on their own plots. It aims to give confidence to decision-makers to engage in developing agroecological strategies for chayote crops.

The specifications for the user interface design were established after evaluation of the IPSIM-chayote model and are presented below. The user interface had to use the initial model based on the DEX method, and had to be free, open-source and accessible online from any device (smartphone, tablet or computer). It also had to be intuitive to use, and be available in several languages[1].

For statistical and information technology purposes, the application must be compatible with the R programming language (R Core Team, 2019), which is free and widely used by the scientific community today.

To meet these specifications, Shiny was chosen (Chang et al., 2019). Shiny allows variables (inputs) to be modified and the results (outputs) of the model, coded in R, to be interactively and dynamically obtained through a user-friendly interface. It is a communication tool widely used by the R-user

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[1] The application is licensed under CC-BY-NC-SA (https://creativecommons.org/licenses/by-nc-sa/4.0/), which means that each user is free to share, copy, distribute, transmit, adapt and modify it under the following conditions: i) for any commercial use, the authorization of the authors must be secured; ii) if modifications are made, these must be clearly indicated. If there are modifications, the user must distribute the new version under the same CC-BY-NC-SA license. In addition, data entered by users should not be saved. They should only be used to produce predictions.

community. In addition, we used ggplot2 (Wickham, 2016) and collapsible Tree (Khan, 2018) R packages for graphics.

The user interface was created collaboratively. Potential users were invited to help contribute to and adapt the interface during its design phase. Fifteen meetings between CIRAD, DAAF (Directorate of Food, Agriculture and Forestry), the Chamber of Agriculture, ARIFEL (Association Réunionese Interprofessional Fruits et Legumes - Interprofessional Réunion Association of Fruits and Vegetables) and chayote producer associations were organized in Salazie and Saint-Pierre between March and August 2019. This made it possible to develop the content and ergonomics of the user interface from the expectations of its future users. Thus, the wording of the questionnaire and the ergonomics of the user interface were adapted to the requests in a collegial manner (Kaeri et al., 2020). In addition, at the request of several users, the graphs in the "results" part of the user interface were adapted for people with color blindness.

2.5. Transfer of the model to professionals

The development of the model and its evaluation by users were carried out in close collaboration with the managers and technicians of the Réunion Chamber of Agriculture, as well as technicians from professional organizations or ARIFEL. The transfer of technology to farmers and assistance in monitoring in the field are at the forefront of the transfer of the IPSIM-chayote model to farmers. The aim is to educate these personnel in the use of the IPSIM-chayote model, so that they can then train the farmers to use the model themselves. By training farmers, the educators transfer the model to them at the same time. These training courses can take place on any device: computers, smartphones, or tablets.

This model is also aimed at public authorities, in particular the DAAF which promotes agricultural practices. This organization also works with other actors in the planning and development of agricultural areas, crops and agroecological practices. In the field, knowledge transfer is carried out via official or informal working meetings with partners. Face-to-face discussions are also held regularly, either with transfer managers on specific points, or with farmers themselves to get their feedback.

3. Results and discussion

3.1. Presentation of the model

3.1.1. Identification and organization of attributes

The structure of IPSIM-chayote model is described in Fig. 3. It has 23 attributes, of which 15 are input and 8 aggregated. The 15 input attributes are: sanitation (prophylaxis measure), sexual trapping, adulticide baits, fertilizers, insecticide treatments, irrigation, vegetal cover on the soil, altitude, season, favorable altitudinal space for *Dacus ciliatus*, abundance of wild host plants around the plot, importance of cucurbit crops, cucurbit crop management, importance of other crops, and other crop management practices. The eight aggregated attributes are: fruit fly management, crop management, characteristics of cucurbit crops in the vicinity, characteristics of crops other than cucurbits (level 2), farming practices, location of land, environment (level 1) and estimated damage (final level).

These attributes are organized in a hierarchical tree presenting the known relationships between attributes. The input attributes are represented by the terminal leaves in the tree, the aggregated attributes are represented by the nodes and the final attribute, i.e. the final intensity of fruit fly injury on chayote (proportion of injured fruits), is represented by the trunk. These attributes are arranged into three main groups (sub-trees) of mutually interrelated attributes: cropping practices, field location and environment.

3.1.2. Definition of attribute scales

The values defining the scales were identified using the expert knowledge available for all attributes and described by value scales defined words. IPSIM-chayote uses a value scale of up to five grades but most often uses a three-grade value scale for the aggregated and input attributes. This scale refers to the insect: the "favorable" value means that the attribute is favorable to the development of fruit flies and therefore potentially detrimental to the crop and farmer. The attribute scales are described in Fig. 3.

3.1.3. Definition of aggregative tables

The eight aggregated attributes of IPSIM-chayote derive from the combination of immediate descendant attributes. They have been established using the expert knowledge available and are summarized in Fig. 3.
Figure 4 shows decision rules that correspond to the aggregated "fruit fly management" attribute and defines the value of this attribute for the eight possible combinations of two levels of sanitation, two levels of sexual trapping, and two levels of adulticide baits. For example, if there is no sanitation, no sexual trapping and no adulticide baits, the "fruit fly management" attribute will be only slightly unfavorable to the development of fruit flies (the final incidence of fruit flies on chayote will increase). All utility functions of the model and the seven other attribute tables are presented in the Supplementary data, Section 3.

3.1.4. Attribute weights

Table 3 summarises the weights of each of the model's 23 attributes and provides an overview of its structure. For example, the aggregated attribute "characteristics of cucurbit crops in the vicinity" is determined at 20% by "importance of cucurbit crops" and at 80% by "cucurbit crop management".

3.2. Prediction quality analysis

The confusion matrix obtained is presented in Fig. 5. The associated statistical criteria are presented in Table 4. The results of the confusion matrix were satisfying as most situations were correctly predicted and errors did not exceed two classes of difference. This was confirmed by good accuracy (58% of situations were perfectly predicted), and the other statistical criteria presented in Table 4. In particular, IPSIM-chayote explained 79% of the dataset variability, as described by Cohen's quadratic weighted Kappa. Table 5 and Fig. 6 show that individual classes were well predicted, except for the "high" injury intensity class, for which performance was just slightly better than a random model.

IPSIM-chayote is the first IPSIM-type model made for crop pests on a tropical crop. Most of the other IPSIM models relate to temperate crops and pathogens (Robin et al., 2013; Aubertot et al., 2016; Robin et al., 2016; Demesthias, 2017; Robin et al., 2018; Vedy-Zecchini, 2020). The model presents a close, almost perfect agreement with observations (κ_{QW} = 0.79; McHugh, 2012) and makes it possible to accurately predict the intensity of fruit fly damage to chayote crops. This is of key interest for producers, agricultural technicians and teachers, researchers, students, public authorities. This type of model has multiple uses: a prediction and decision-making tool, an educational resource for agroecological crop protection, a resource for scientific investigation and exchange and a planning and forecasting tool to assist in agricultural development. The use and transfer of IPSIM-chayote has been facilitated by the simple, ergonomic user interface which is available in three languages and can be used on any computer, tablet or smartphone, free of charge.

The IPSIM-chayote model can be used to create other models, but it also has some limitations. Fruit flies are the main chayote pests and chayote cultivation is comparable to a perennial crop, which is easier to model than an annual crop; moreover, chayote cultivation is clustered in a production basin, and agroecological practices are easier to apply in this context than agrochemical practices: they require fewer field interventions (e.g. fewer treatments or no treatments) and require less work and time. The IPSIM-chayote model should facilitate the creation of similar models for perennial crops such as mango, for the reasons mentioned above, even if there is a wider range of pests for mango than for chayote.

Aggregative rules in IPSIM aggregative tables can be considered as equivalent to parameters (Aubertot and Robin, 2013). An algorithm could therefore be developed to improve the predictive quality of IPSIM models. In particular, a "Leave-One-Out" cross-validation technique (Moore, 2001) could be used to avoid any potential spatio-temporal correlation (Wallach et al., 2001).

3.3. IPSIM-chayote and IPSIM-chouchou974 applications

The application is available in three languages: English and Spanish (IPSIM-chayote) and French (IPSIM-chouchou974). It is publicly available via the UMR PVBMT (CIRAD) website: https://pvbmt-apps.cirad.fr/apps/ipsim-chayote/?lang=en. The source code of the application is freely available at https://gitlab.com/cirad-apps/ipsim-chayote.

The design and development of the IPSIM-chayote application aims to make the model more accessible and intuitive, so that it meets its multiple purposes. IPSIM visualization is a critical element of qualitative modeling. IPSIM models have been designed and used with the DEXi software (Bohanec, 2020), a desktop application which only runs on Microsoft Windows platforms. In order to address the portability issue of DEXi, we developed a user-friendly graphical application of IPSIM-chayote through Shiny. This R package allows the user to create interactive web applications, by converting R code to HTML, which are hosted from the cloud or on a physical server (Beeley, 2016). Explanations on how to use the user interface can be found in the Supplementary data, Section 4. In addition, examples of use for specific situations are also given in the Supplementary data, Section 5. Figures 7 and 8 represent screenshots corresponding to a situation of agroecological management of chayote flies. A contrasting situation (agrochemical management of chayote flies) is also presented in the Supplementary data, Section 5.

3.4. Transfer to users

The primary aim during the development of the model was to make it accessible to a wide range of users. All groups of users were consulted in the design phase of the IPSIM-chayote model, as well as during the transfer phase.

The transfer phase took place from July 2019 to February 2020. In Réunion, training sessions were organized in Saint-Pierre with agricultural technicians, DAAF officials and researchers, in Salazie (with chayote producers) and in Saint-Paul (with agricultural instructors). In addition, the IPSIM-chayote model is now taught in university modules at Bachelor and Master level at the University of Réunion. More information on the IPSIM-chayote model is available here: https://pvbmt-apps.cirad.fr/apps/ipsim-chayote/?lang=en.

In Réunion, agricultural sector stakeholders are now able to use the model for a variety of purposes:

- Professionals, including farmers: as a tool to help simulate fly damage to their chayote crops and to help them plan their agricultural practices;
- Transfer and training organizations (advisers, supervisors and agricultural teachers): as training resource for agroecological crop protection;
- Public authorities: as an aid to planning and forecasting agricultural development in Réunion;
- Researchers: to assist in the exchange of knowledge and information or to identify new, relevant research areas adapted to the context and the issues. The use of this model online by international scientific bodies (for example, research schools), universities (tutorials using the model) or distance learning (e.g. Massive Open Online Courses) has already been tested and is expected to be developed.

The knowledge gained developing the IPSIM-chayote model can be transferred to other qualitative IPSIM-type models. An IPSIM-mango model is planned. Mango cultivation has been the subject of numerous studies in recent years which have made it possible to develop agroecological practices to protect orchards (Deguine et al., 2018) and to acquire detailed knowledge of orchard biodiversity and food webs (Jacquot et al., 2017 and 2019). This innovative model will take into account not only the impact of fruit flies, but also all mango tree pests (insects and mites, phytopathogenic fungi and bacteria), as well as interactions with the main natural enemies which have been identified in mango orchards (parasitoids and predators).

4. Conclusion

Intensive chayote cultivation in Réunion almost disappeared in the 2000s due to major damage caused by fruit flies attacking this historically important crop. Since the end of the 2000s, studies have made it possible to develop agroecological crop protection within a participatory framework, bringing together many agricultural fields and the chayote producers playing a central role. These ethical practices have made it possible to effectively manage populations of fruit flies and to greatly reduce, or eliminate, insecticide treatments on chayote, without any loss of production. At the end of the 2010s, organic chayote plantations outnumbered the non-organic plantations (Deguine et al., 2019). These exemplary results require training and monitoring of farmers at all times, which prompted those involved to design and develop a simple model to simulate fruit fly damage to chayote crops. The qualitative IPSIM-chayote model was created collaboratively and is based on the IPSIM platform which is available online. It gives excellent prediction results (Cohen's quadratic weighted Kappa 0.79).

The model has an intuitive, ergonomic user interface and it is scalable as it allows variables to be added if the context changes and predictive quality can be improved with mathematical algorithms available soon.

In addition, IPSIM-chayote is a resource for information exchange and promotes interactions between individuals for collaborative work. IPSIM-chayote is of interest to many stakeholders: farmers, government officials, agricultural advisers and trainers and researchers.

IPSIM-chayote is the first qualitative model developed for insect pests on a tropical crop. It will serve as the basis for the development of other IPSIM-type models which simulate the injury intensity of crop pests in Réunion and other neighbouring Indian Ocean countries, thus making a significant contribution to the development of agroecological crop protection.

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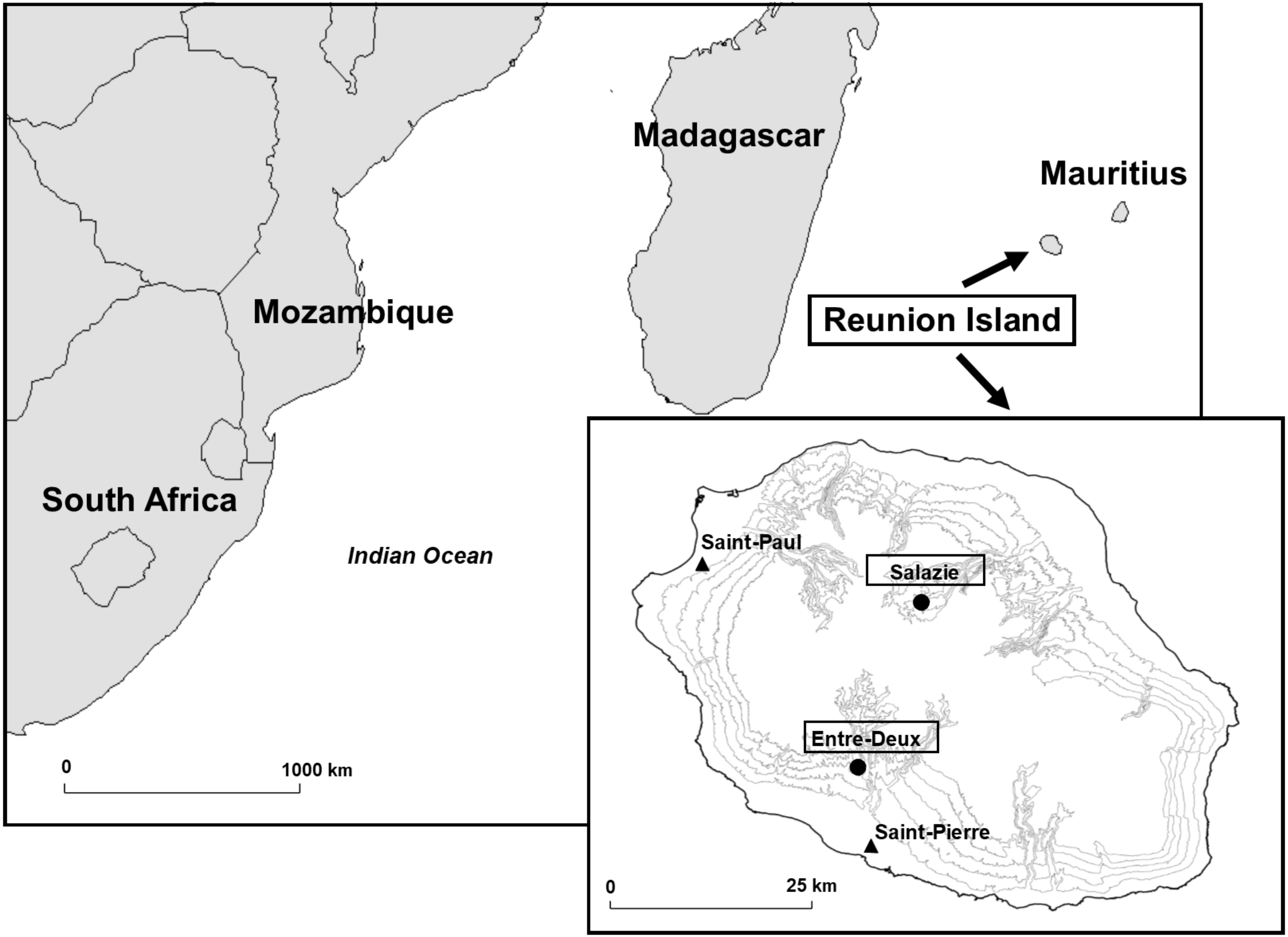
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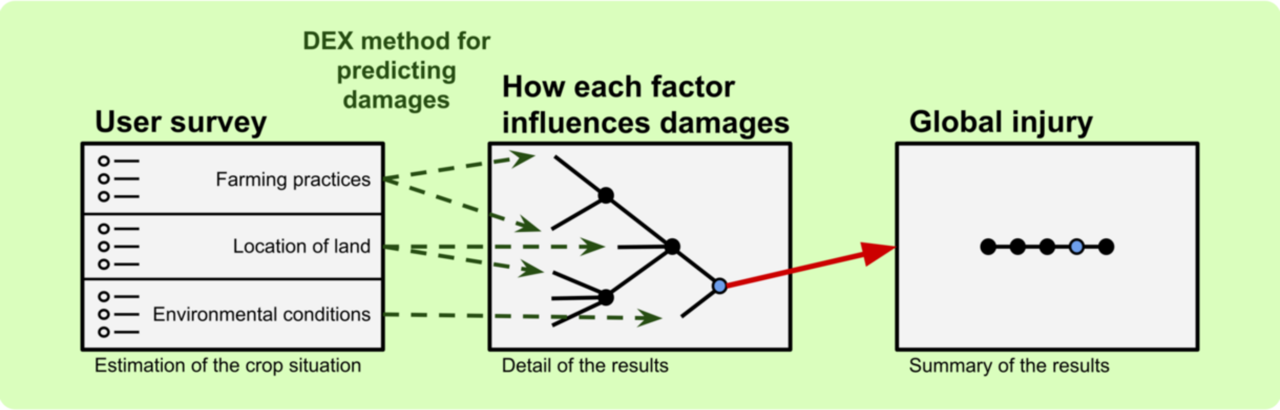

DEX method for predicting damages
User survey
Farming practices
Location of land
Environmental conditions
Estimation of the crop situation
How each factor influences damages
Detail of the results
Global injury
Summary of the results

Attribute	Scale
Estimated damage	**very high**; **high**; **medium**; ***low***; ***zero***
├─**Farming practices**	***favorable to management***; neutral; **unfavorable to management**
│ ├─**Fruit fly management**	***very unfavorable to fruit flies***; **few unfavorable to fruit flies**
│ │ ├─Sanitation	***yes***; **no**
│ │ ├─Sexual trapping	***yes***; **no**
│ │ └─Adulticide baits	***yes***; **no**
│ ├─**Crop management**	**very favorable to fruit flies**; **favorable to fruit flies**
│ │ ├─Fertilizers	**higher than recommendation**; as recommended; few or nothing
│ │ ├─Insecticide treatments	**null**; **medium**; **many**
│ │ └─Irrigation	**in excess**; ***as recommended***
│ └─Vegetal cover on the soil	**no**; ***yes***
├─**Location of land**	**very favorable to fruit flies**; ***meanly favorable to fruit flies***
│ ├─Altitude	**low**; ***medium***
│ └─Season	**summer**; ***winter***
└─**Environment**	**very favorable to fruit flies**; **favorable to fruit flies**; ***unfavorable to fruit flies***
├─Favorable altitudinal space for Dacus ciliatus	**yes**; ***no***
├─Abundance of wild host plants around the plot	**high**; ***low***; ***null***
├─**Characteristics of cucurbit crops in the vicinity**	***unfavorable to fruit fly populations***; without effects; **favorable to fruit fly populations**
│ ├─Importance of cucurbit crops	null; low; **high**
│ └─Cucurbit crop management	***agroecological crop protection everywhere***; agroecological crop protection mixed with agrochemical cro protection; **agrochemical crop protection everywhere**
└─**Characteristics of crops other than cucurbits**	**unfavorable to beneficials**; without effects on beneficials; ***favorable to beneficials***
├─Importance of other crops	null; low; meanly to high
└─Other crop management	***agroecological crop protection***; **chemical crop protection**

Decision rules Fruit fly management

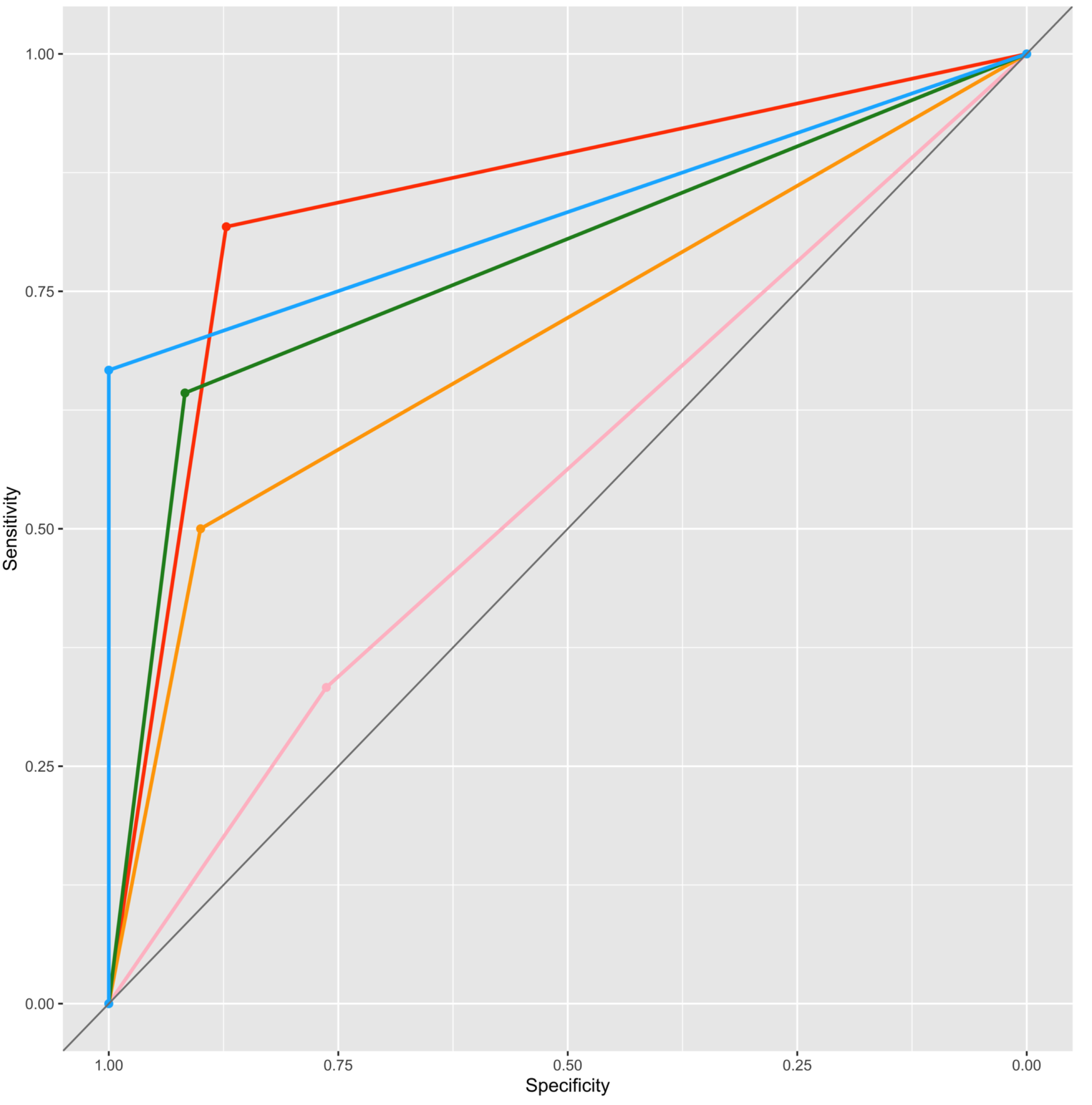
very unfavourable to frui

	Sanitation	Sexual trapping	Adulticide baits	Fruit fly management
1	yes	yes	yes	**very unfavourable to fruit flies**
2	yes	yes	no	**very unfavourable to fruit flies**
3	yes	no	yes	**very unfavourable to fruit flies**
4	yes	no	no	**very unfavourable to fruit flies**
5	no	yes	yes	**few unfavorable to fruit flies**
6	no	yes	no	**few unfavorable to fruit flies**
7	no	no	yes	**few unfavorable to fruit flies**
8	no	no	no	**few unfavorable to fruit flies**

Rules: 8/8 (100,00%), determined: 100,00% [very unfavourable to fruit flies:4,few u

OK Cancel

Observed \ Simulated	Zero	Low	Medium	High	Very High	Total
Zero	2 *4.00*	1 *2.00*	0 *0*	0 *0*	0 *0*	3 *6.00*
Low	0 *0*	9 *18.0*	2 *4.00*	3 *6.00*	0 *0*	14 *28.0*
Medium	0 *0*	1 *2.00*	5 *10.0*	4 *8.00*	0 *0*	10 *20.0*
High	0 *0*	1 *2.00*	2 *4.00*	4 *8.00*	5 *10.0*	12 *24.0*
Very High	0 *0*	0 *0*	0 *0*	2 *4.00*	9 *18.0*	11 *22.0*
Total	2 *4.00*	12 *24.0*	9 *18.0*	13 *26.0*	14 *28.0*	50 *100.*


1.00
0.75
0.50
0.25
0.00
Sensitivity
1.00
0.75
0.50
0.25
0.00
Specificity

IPSIM-chouchou974 ≡

- What is it ?
- Contribution and thanks
- How does it work ?
- Your data
- Your results
- To learn more
- Contact us

Farming practices

Crop and phytosanitary practices

1. How much mineral fertilizer do you use on your land?

- ● Less than the recommended levels
- ○ The recommended levels
- ○ More than the recommended levels

2. Do you use insecticides on your plot?

- ● Little or none
- ○ Moderate amounts
- ○ Frequently

3. Is the irrigation of your land:

- ● Suitable
- ○ Unsuitable (not enough or too much)

Fruit fly management

4. Do you take preventive measures against fruit flies?

○ No ● Yes

5. Do you use sexual trapping techniques for monitoring?

○ No ● Yes

6. Do you use adulticide baits?

○ No ● Yes

Soil management

7. Do you maintain a permanent vegetation cover on your land?

○ No ● Yes

Location of land

Altitude

8. What altitude is your land at?

- ○ Less than 600 meters
- ● More than 600 meters

Season

9. What is the growing season:

○ Hot season (summer) ● Other

Environmental conditions

Dacus ciliatus development

10. Is your land located in a known *Dacus ciliatus* zone?

○ No ● Yes

Wild host plants

11. What is the abundance of wild host plants on your land?

- ● Zero
- ○ Low
- ○ High

Cucurbit crops

12. What proportion of your land does chayote account for?

- ○ None
- ○ Low
- ● Moderate to high

13. What type of farming do you practice?

- ○ 100% agrochemical
- ○ Mix of agrochemichal and agroecological
- ● 100% agroecological

Other crops

14. What proportion of the surrounding land do other crops account for?

- ○ None
- ○ Low
- ● Moderate to high

15. What type of farming is practiced there?

- ○ 100% agrochemical
- ● 100% agroecological

✔ Validate

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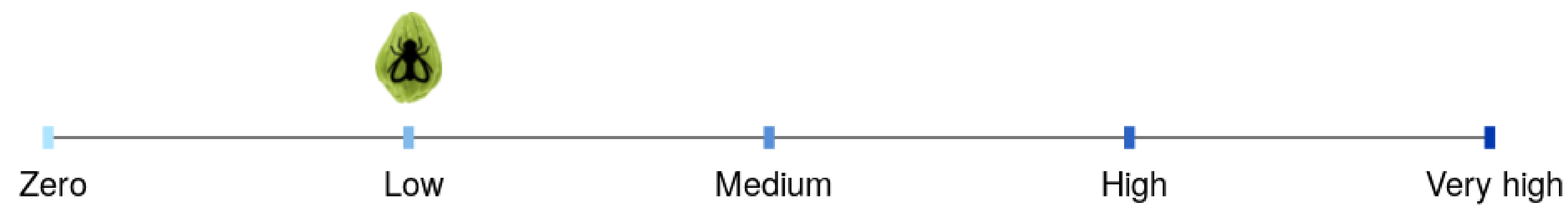
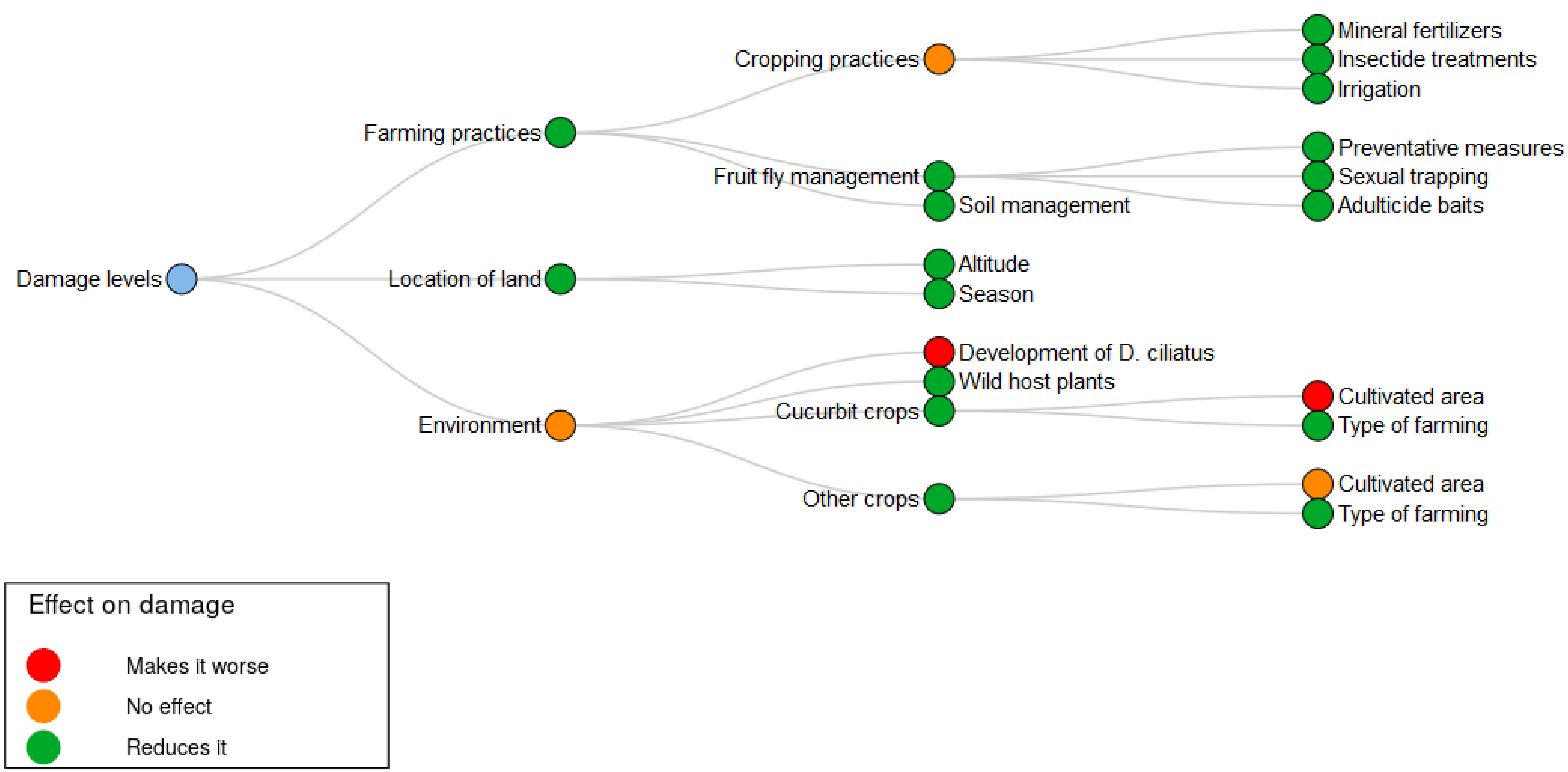
Estimated damage caused by chayote flies



Estimated damage caused by chayote flies

Click on the bold circles for details on each influencing factor.

Expand/Collapse Black and white version



Location and field		Season			Abundance of wild host plants in the surroundings		Importance of cucurbit crops			Cropping practices for other cucurbit crops		Importance of other crops		Intensity of damages				
Municipality	Area	No fields	Summer	Winter	Low	High	None	Low	High	Agrochemical	Agroecological	Low	Medium-high	Zero	Low	Medium	High	Very high
Mare à Poule d'eau	Salazie	9	5	4	9	0	0	9	0	9	0	9	0	0	0	2	6	1
Entre-Deux village	Entre-Deux	9	5	4	5	4	5	4	0	0	9	0	9	0	4	1	0	4
Mare à Citrons	Salazie	4	2	2	4	0	0	0	4	0	4	4	0	0	0	1	2	1
Hell Bourg	Salazie	8	4	4	8	0	0	8	0	0	8	8	0	2	4	0	2	0
Salazie village	Salazie	8	4	4	8	0	0	8	0	8	0	8	0	1	2	2	2	1
Bois de pommes	Salazie	10	5	5	10	0	0	10	0	10	0	10	0	0	4	3	0	3
Ilet à Vidot	Salazie	2	1	1	2	0	0	2	0	2	0	2	0	0	0	1	0	1
Total or mode		50	26	24	46	4	5	41	4	29	21	41	9	3	14	10	12	11

Scope	Criterion	Meaning
General	Accuracy	Rate of correct predictions for the entire dataset
	kQW	Cohen’s quadratic weighted Kappa
	τb	Kendall rank correlation coefficient
	ρS	Spearman’s rank correlation coefficient
Class	Sensitivity	Proportion of actual positives correctly predicted
	Specificity	Proportion of negatives correctly precicted
	Precision	Number of correct positive predictions/Number of positive predictions
	F1 score	Harmonic mean of precision and sensitivity
	MCC	Matthews Correlation Coefficient
	AUROC	Area Under the Receiver Operating Characteristics

Attributes	Local normalized weights			Global normalized weights		
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
Estimated damage						
Farming practices	32			32		
Fruit fly management		100			32	
Sanitation			100			32
Sexual trapping			0			0
Adulticide baits			0			0
Crop management		0			0	
Fertilizers			100			0
Insecticide treatments			0			0
Irrigation			0			0
Vegetal cover on the soil			0			0
Location of land	24			24		
Altitude			0			0
Season			100			24
Environment	45			45		
Favorable altitudinal space for *Dacus ciliatus*			60			27
Abundance of wild host plants around the plot			27			12
Characteristics of cucurbit crops in the vicinity		13			6	
Importance of cucurbit crops			20			1
Cucurbit crop management			80			5
Characteristics of crops other than cucurbits		0			0	
Importance of other crops			0			0
Other crop management			100			0

Accuracy	k_{QW}	τ_b	ρ_S
0.580	0.790	0.717	0.801

Damage intensity	Sensitivity	Specificity	Precision	F1 score	MCC	AUC ROC
Zero	0.667	1.000	1.000	0.800	0.801	0.822
Low	0.643	0.917	0.750	0.692	0.589	0.780
Medium	0.500	0.900	0.556	0.526	0.416	0.772
High	0.333	0.763	0.308	0.320	0.094	0.703
Very high	0.818	0.872	0.643	0.720	0.637	0.758