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

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17

18 **Summary**

19

20 Intensive chayote cultivation in Réunion almost disappeared in the 2000s due to significant yield
21 losses from fruit flies attacking this historically important crop (*Dacus ciliatus*, *Zeugodacus cuurbitae*
22 and *Dacus demmerezi*). Since the late 2000s, the adoption of agroecological crop protection practices
23 have led to the effective management of fruit fly populations, a significant reduction in pesticide use,
24 an increase in chayote production and plantations, and the development of organic production. To
25 assist in fruit fly management, a qualitative model which simulates fruit fly damage to chayote crops,
26 known as IPSIM-chayote, was developed, providing satisfactory prediction results. It has a user-
27 friendly interface and is now available free of charge online, in three languages (French, English and
28 Spanish): <https://pvbmt-apps.cirad.fr/apps/ipsim-chayote/?lang=en>. The IPSIM-chayote modeling

29 platform can be used by farmers as a tool to simulate fruit fly damage to their crops and also as a
30 decision-making tool for their agricultural practices. The model can be used as a training resource in
31 agroecological crop protection. Public authorities and local government can use it as a tool in planning
32 and forecasting agricultural development. Finally, researchers can use it as a prediction tool and a
33 resource for the exchange of information, allowing them to review scientific knowledge or identify
34 new, relevant research areas suited to the context and challenges. IPSIM-chayote can be considered as
35 a forum for exchange and can stimulate collaborative work between individuals. It is a flexible model,
36 as it allows variables to be added. IPSIM-chayote is the first qualitative model developed for crop
37 pests in a tropical environment. It could serve as a basis for the development of other similar models
38 simulating crop pest incidence, thus contributing significantly to the development of agroecological
39 crop protection.

40

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

43

44 **1. Introduction**

45

46 *Sechium edule* (Jacq.) Swartz is a plant belonging to the Cucurbitaceae family and is native to Mexico.
47 It has been cultivated for several millennia in South America. Today, chayote is cultivated in many
48 tropical and subtropical countries (Monnerville et al., 2001) and all parts of the plant can be eaten
49 (Saade, 1996; Sharma et al., 1995). In Réunion, chayote is a popular, historically important crop,
50 where its leaves and fruits are traditionally consumed. Since the 1980s, chayote has been cultivated
51 intensively on trellises, using significant quantities of pesticides, mineral fertilizers and water
52 (Deguine et al., 2015). In the 2000s, chayote production collapsed. Cultivation declined sharply in the
53 Entre-Deux area and Cirque de Salazie, the two main traditional cultivation areas (Deguine et al.,
54 2015). The chayote sector has attributed the 50 to 90% decline in production to fruit fly damage
55 (Diptera, Tephritidae), despite repeated treatments with insecticides. In the case of fruit flies on
56 chayote crops, injuries correspond to damage since only one oviposition puncture on a fruit prevents it

57 from being sold to consumers. The incidence of punctured fruits thus directly corresponds to relative
58 yield loss in terms of number of fruits harvested per surface unit.

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

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

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

85 some crop growth models to simulate yield losses (Savary et al., 2018). In addition, these models often
86 take into account only one pest and a limited number of processes.

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

99 Based on a literature review of fruit fly models on horticultural (fruit and vegetable) crops with
100 emphasis on cucurbits, thermal time (TT), regression, mechanistic and artificial intelligence (AI)
101 models have been proposed (Inayatullah et al., 1991; Duyck and Quilici, 2002; Koyama et al., 2004;
102 Sutherst et al., 2007; Vayssières et al., 2008; Lux, 2014; Mokam et al., 2014; Sridhar et al., 2014; De
103 Villiers et al., 2016; Bana et al., 2017; Bolzan et al., 2017; Choudhary et al., 2017; Remboski et al.,
104 2018; Choudhary et al., 2019, Vanoye-Eligio et al., 2019). The literature on modeling the damage of
105 cucurbit flies is limited and no study mentions chayote. The reported modeling work only relies on
106 numerical variables from statistics, data mining, or mechanistic modeling. In addition, each study only
107 considered variables of one component of an agroecosystem only, namely the soil, weather, cropping
108 practices or field environment.

109 IPSIM (Injury Profile Simulator) is a generic modeling approach which describes the damage profile
110 on a crop relative to cropping practices and production situation (Aubertot and Robin 2013). Models
111 developed using the IPSIM approach can thus contribute to the design of cropping systems which can
112 better resist pests and are therefore less dependent on pesticides. The approach is generic; it can be

113 easily adapted to all types of pests and all crops (Robin et al., 2013; Aubertot et al., 2016; Robin et al.,
114 2016; Demesthias, 2017; Robin et al., 2018; Vedy-Zecchini, 2020), including fruit flies on chayote
115 crops in Réunion. The main hypothesis of the approach is that the damage intensity of any pest is
116 determined only by three main groups of factors: agricultural practices, the pedoclimate, and the
117 landscape. The spatial scale considered is the plot because this is the scale on which the cropping
118 system is applied, even if the same cropping system can be applied to several plots (Sébillote, 1990).
119 The temporal scale of the model depends on the biology of the pest, i.e. its level of endocyclism
120 (Aubertot and Robin, 2013). It can range from the crop cycle to several years. IPSIM models are
121 deterministic and static models. A unique feature of IPSIM is that it is able to accommodate a high
122 level of complexity within revised or even redesigned agroecosystems, as the agroecological approach
123 implies (Hill and McRae, 1995). The strength of the approach is that the predictive models obtained
124 are very close to conceptual models reflecting the available knowledge.

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

132

133 **2. Materials and methods**

134

135 *2.1. Model building process*

136

137 After reviewing the literature and acquiring expertise on the subject (Supplementary data, Section 1),
138 the IPSIM-chayote model was built using the method described on the IPSIM website
139 (www6.inra.fr/ipsim, Robin et al., 2018) and in previous studies (e.g. Robin et al., 2013). It is based on
140 the DEX method, implemented with the DEXi software (Bohanec, 2020). DEXi software can support

141 hierarchical qualitative models, such as DEXiPM (Pelzer et al., 2012) which was initially used for the
142 assessment of agroecosystems described by expert knowledge (Angevin et al., 2017). IPSIM-chayote
143 was designed in four phases which are presented in the following sections (Bohanec, 2003): (i)
144 identification and organization of attributes (main variables that may affect fruit fly damage intensity
145 and their interdependent relationships), (ii) definition of qualitative attribute scales for each attribute,
146 (iii) definition of aggregative tables that synthesize the impact of combinations of attributes to
147 determine the final intensity and (iv) calculation of the attribute weights in order to summarize the
148 influence of each attribute to the final output.

149

150 2.1.1. Identification and organization of attributes

151

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

161

162 2.1.2. Attribute scales

163

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

169 farmers); a value “unfavorable” for the development of fruit flies appears in green (as it is beneficial to
170 farmers); a “neutral” value with regard to the development of fruit flies appears in black.

171

172 2.1.3. Aggregative tables

173

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

180

181 2.1.4. Attribute weights

182

183 The influence of each input and aggregated attribute on the value of the final variable can be
184 characterized by weights. The higher the weight, the more influential the attribute (Bohanec et al.,
185 2007). The relative importance of attributes, described by weights, is automatically calculated by
186 DEXi as a function of aggregative tables using a linear regression method (Bohanec, 2020; see
187 Supplementary data, Section 2). DEXi calculates four types of weights: local and global weights,
188 normalized or not. We will consider only normalized weights since they take into account the number
189 of values within the scales. Local weights represent the influence of attributes on the associated
190 aggregated attributes. Global weights represent the influence of attributes on the final output of the
191 model.

192

193 2.2. *Description of data collection used for model evaluation*

194

195 To take into account an observed situation to assess the predictive quality of the model, it is necessary
196 to have information on the intensity of fruit fly attacks, cropping practices, the environment around the

197 plot and the climate. Depending on the nature of the information available, quantitative data were
198 converted into qualitative data to obtain variables compatible with the IPSIM framework. For
199 example, we translated quantitative data of the type "percentage of fruit punctured by fruit flies" into
200 qualitative data, ranging from "zero damage" to "very high damage". Intensity of injuries is here
201 considered as similar as intensity of damages.

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

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

225 (21 situations in winter and 22 situations in summer), we considered 30 fruits on the chayote trellis
226 and we observed the percentages of fruits with at least one fruit fly bite. We estimated the intensities
227 of damage as a function of this percentage as follows. "zero damage" class: 0%; "low damage" class:
228]0%-10%]; "medium damage" class:]10%-40%]; "high damage" class:]40%-70%]; "very high
229 damage" class:]70%-100%]. In the seven other situations, the damage intensity was characterized
230 only qualitatively at the field level according to the same ordinal scale.

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

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

245

246 *2.3. Assessment of predictive quality*

247

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

253 A confusion matrix was built to compare predictions to actual observations. We used several metrics
254 (Table 2) to measure the predictive quality of IPSIM-chayote. Accuracy is defined as the rate of
255 correct predictions for the entire dataset (Nguwi and Cho, 2010). The Cohen's quadratic weighted
256 Kappa (Agresti, 2010) can be interpreted as the proportion of variability explained by the model
257 (Fleiss and Cohen, 1973). Similar to correlation coefficients, κ coefficients range from -1 to $+1$.
258 Values of κ can be interpreted as follows: values ≤ 0 indicate no agreement; values ranging 0.01- 0.20
259 indicate none to slight agreement; values ranging 0.21 - 0.40 indicate a fair agreement; values ranging
260 0.41– 0.60 indicate a moderate agreement; values ranging 0.61 - 0.80 indicate a substantial agreement;
261 and values ranging 0.81 - 1.00 indicate an almost perfect agreement (McHugh, 2012). Kendall's τ_b
262 (Kendall, 1938) and Spearman's rank correlation coefficient ρ_s (Spearman, 1904) were also
263 calculated.

264 Six criteria for binary classification were calculated for each of the five output classes using the *one*
265 *version all approach*. Sensitivity (or recall) measures the proportion of actual positives which are
266 correctly identified (Witten et al., 2011). The specificity measures the proportion of negatives which
267 are correctly identified (Witten et al., 2011). Accuracy is calculated as the number of correct positive
268 predictions divided by the total number of positive predictions (Witten et al., 2011). F₁-score is a
269 harmonic mean of accuracy and sensitivity (Witten et al., 2011). In other words, it conveys the balance
270 between accuracy and sensitivity. The F₁ score reaches the best value, meaning perfect accuracy and
271 sensitivity, at a value of 1. The worst F₁ score, which means lowest accuracy and lowest sensitivity,
272 tends towards 0. Matthews correlation coefficient (MCC) is a special case of Pearson correlation
273 coefficient and leads to similar interpretations (Matthews, 1975). Area Under the Curve Receiver
274 Operating Characteristics (AUROC) is a performance measurement for binary classification problems
275 (Witten et al., 2011). AUROC tells how much the model is capable of distinguishing one class versus
276 all others. The higher the AUROC, the better the model.

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

280

281 2.4. Development of the user interface

282

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

291 The specifications for the user interface design were established after evaluation of the IPSIM-chayote
292 model and are presented below. The user interface had to use the initial model based on the DEX
293 method, and had to be free, open-source and accessible online from any device (smartphone, tablet or
294 computer). It also had to be intuitive to use, and be available in several languages¹.

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

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

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.

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

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

313

314 *2.5. Transfer of the model to professionals*

315

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

324 This model is also aimed at public authorities, in particular the DAAF which promotes agricultural
325 practices. This organization also works with other actors in the planning and development of
326 agricultural areas, crops and agroecological practices. In the field, knowledge transfer is carried out
327 via official or informal working meetings with partners. Face-to-face discussions are also held

328 regularly, either with transfer managers on specific points, or with farmers themselves to get their
329 feedback.

330

331 **3. Results and discussion**

332

333 *3.1. Presentation of the model*

334

335 3.1.1. Identification and organization of attributes

336

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

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

351

352 3.1.2. Definition of attribute scales

353

354 The values defining the scales were identified using the expert knowledge available for all attributes
355 and described by value scales defined words. IPSIM-chayote uses a value scale of up to five grades

356 but most often uses a three-grade value scale for the aggregated and input attributes. This scale refers
357 to the insect: the "favorable" value means that the attribute is favorable to the development of fruit
358 flies and therefore potentially detrimental to the crop and farmer. The attribute scales are described in
359 Fig. 3.

360

361 3.1.3. Definition of aggregative tables

362

363 The eight aggregated attributes of IPSIM-chayote derive from the combination of immediate
364 descendant attributes. They have been established using the expert knowledge available and are
365 summarized in Fig. 3.

366 Figure 4 shows decision rules that correspond to the aggregated "fruit fly management" attribute and
367 defines the value of this attribute for the eight possible combinations of two levels of sanitation, two
368 levels of sexual trapping, and two levels of adulticide baits. For example, if there is no sanitation, no
369 sexual trapping and no adulticide baits, the "fruit fly management" attribute will be only slightly
370 unfavorable to the development of fruit flies (the final incidence of fruit flies on chayote will
371 increase). All utility functions of the model and the seven other attribute tables are presented in the
372 Supplementary data, Section 3.

373

374 3.1.4. Attribute weights

375

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

379

380 3.2. Prediction quality analysis

381

382 The confusion matrix obtained is presented in Fig. 5. The associated statistical criteria are presented in
383 Table 4. The results of the confusion matrix were satisfying as most situations were correctly

384 predicted and errors did not exceed two classes of difference. This was confirmed by good accuracy
385 (58% of situations were perfectly predicted), and the other statistical criteria presented in Table 4. In
386 particular, IPSIM-chayote explained 79% of the dataset variability, as described by Cohen's quadratic
387 weighted Kappa. Table 5 and Fig. 6 show that individual classes were well predicted, except for the
388 "high" injury intensity class, for which performance was just slightly better than a random model.

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

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

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

412

413 3.3. IPSIM-chayote and IPSIM-chouchou974 applications

414

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

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

431

432 3.4. *Transfer to users*

433

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

437 The transfer phase took place from July 2019 to February 2020. In Réunion, training sessions were
438 organized in Saint-Pierre with agricultural technicians, DAAF officials and researchers, in Salazie
439 (with chayote producers) and in Saint-Paul (with agricultural instructors). In addition, the IPSIM-

440 chayote model is now taught in university modules at Bachelor and Master level at the University of
441 Réunion. More information on the IPSIM-chayote model is available here: [https://pvbmt-](https://pvbmt-apps.cirad.fr/apps/ipsim-chayote/?lang=en)
442 [apps.cirad.fr/apps/ipsim-chayote/?lang=en](https://pvbmt-apps.cirad.fr/apps/ipsim-chayote/?lang=en).

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

444 - Professionals, including farmers: as a tool to help simulate fly damage to their chayote crops and to
445 help them plan their agricultural practices;

446 - Transfer and training organizations (advisers, supervisors and agricultural teachers): as training
447 resource for agroecological crop protection;

448 - Public authorities: as an aid to planning and forecasting agricultural development in Réunion;

449 - Researchers: to assist in the exchange of knowledge and information or to identify new, relevant
450 research areas adapted to the context and the issues. The use of this model online by international
451 scientific bodies (for example, research schools), universities (tutorials using the model) or distance
452 learning (e.g. Massive Open Online Courses) has already been tested and is expected to be developed.

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

461

462 **4. Conclusion**

463

464 Intensive chayote cultivation in Réunion almost disappeared in the 2000s due to major damage caused
465 by fruit flies attacking this historically important crop. Since the end of the 2000s, studies have made it
466 possible to develop agroecological crop protection within a participatory framework, bringing together
467 many agricultural fields and the chayote producers playing a central role. These ethical practices have

468 made it possible to effectively manage populations of fruit flies and to greatly reduce, or eliminate,
469 insecticide treatments on chayote, without any loss of production. At the end of the 2010s, organic
470 chayote plantations outnumbered the non-organic plantations (Deguine et al., 2019). These exemplary
471 results require training and monitoring of farmers at all times, which prompted those involved to
472 design and develop a simple model to simulate fruit fly damage to chayote crops. The qualitative
473 IPSIM-chayote model was created collaboratively and is based on the IPSIM platform which is
474 available online. It gives excellent prediction results (Cohen's quadratic weighted Kappa 0.79).

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

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

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

485

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487

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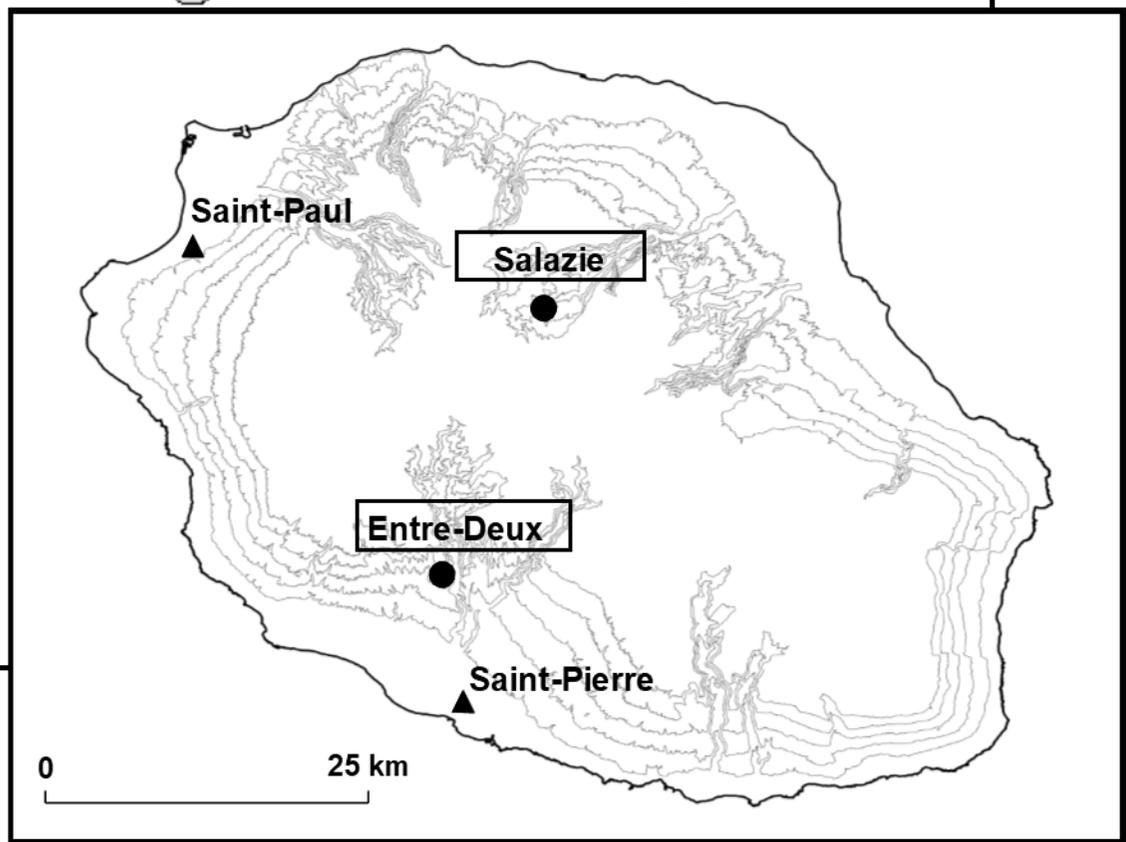
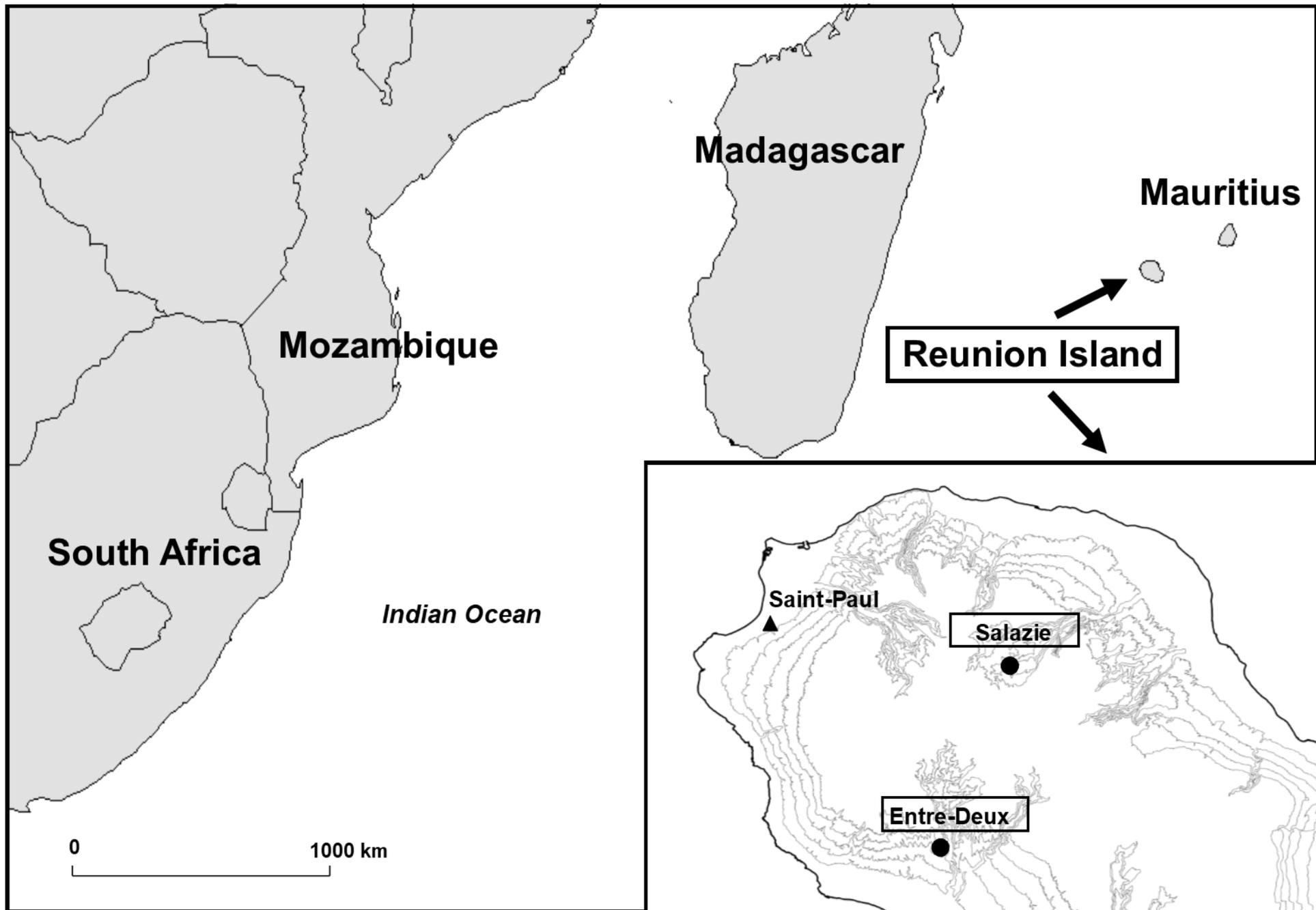
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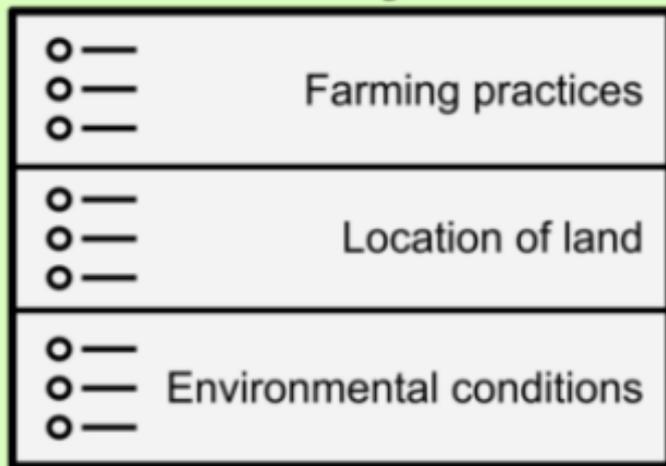
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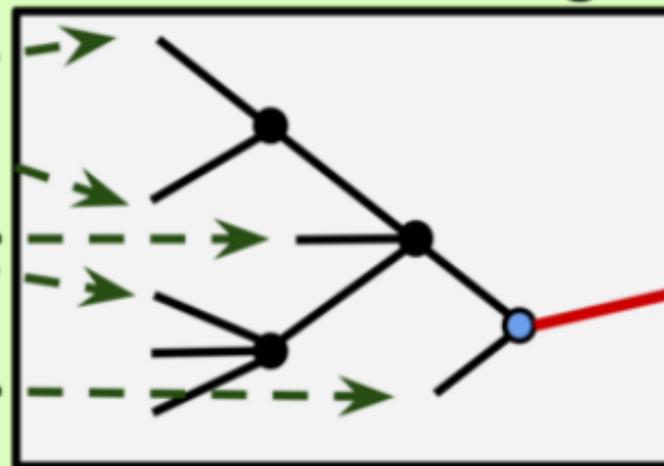
DEX method for predicting damages

User survey



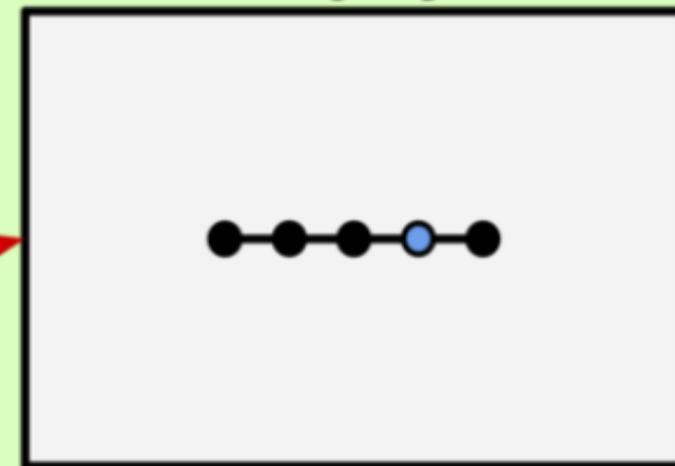
Estimation of the crop situation

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 <i>Dacus ciliatus</i>	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 crop 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 fruit fly



	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 unfavourable to fruit flies
6	no	yes	no	few unfavourable to fruit flies
7	no	no	yes	few unfavourable to fruit flies
8	no	no	no	few unfavourable to fruit flies

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



OK

Cancel

Simulated

Zero

Low

Medium

High

Very High

Total

Observed

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

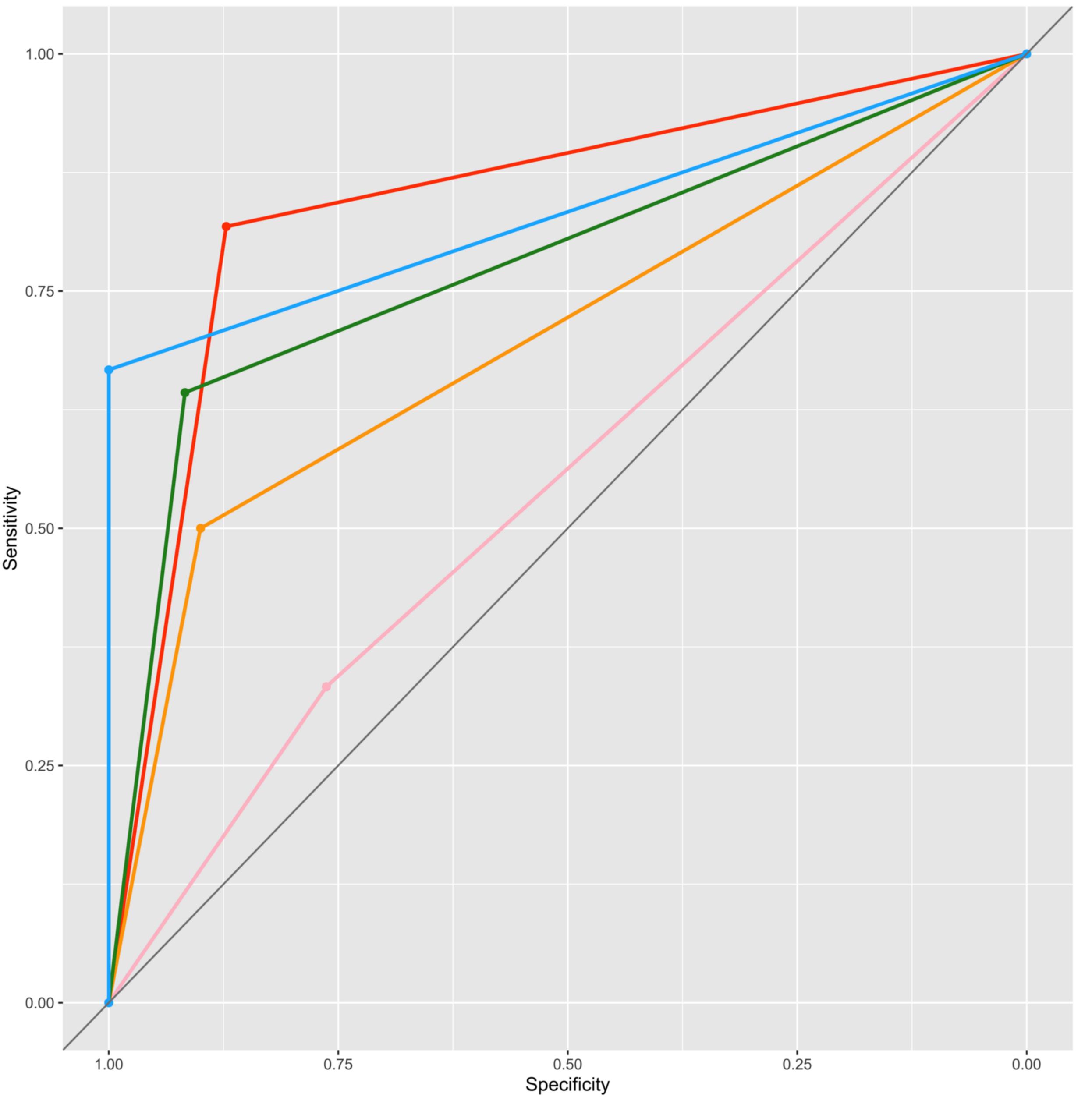
26.0

14

28.0

50

100.





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 agrochemical and agroecological
 100% agroecological

Other crops

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

- None
 Low
 Moderate to high

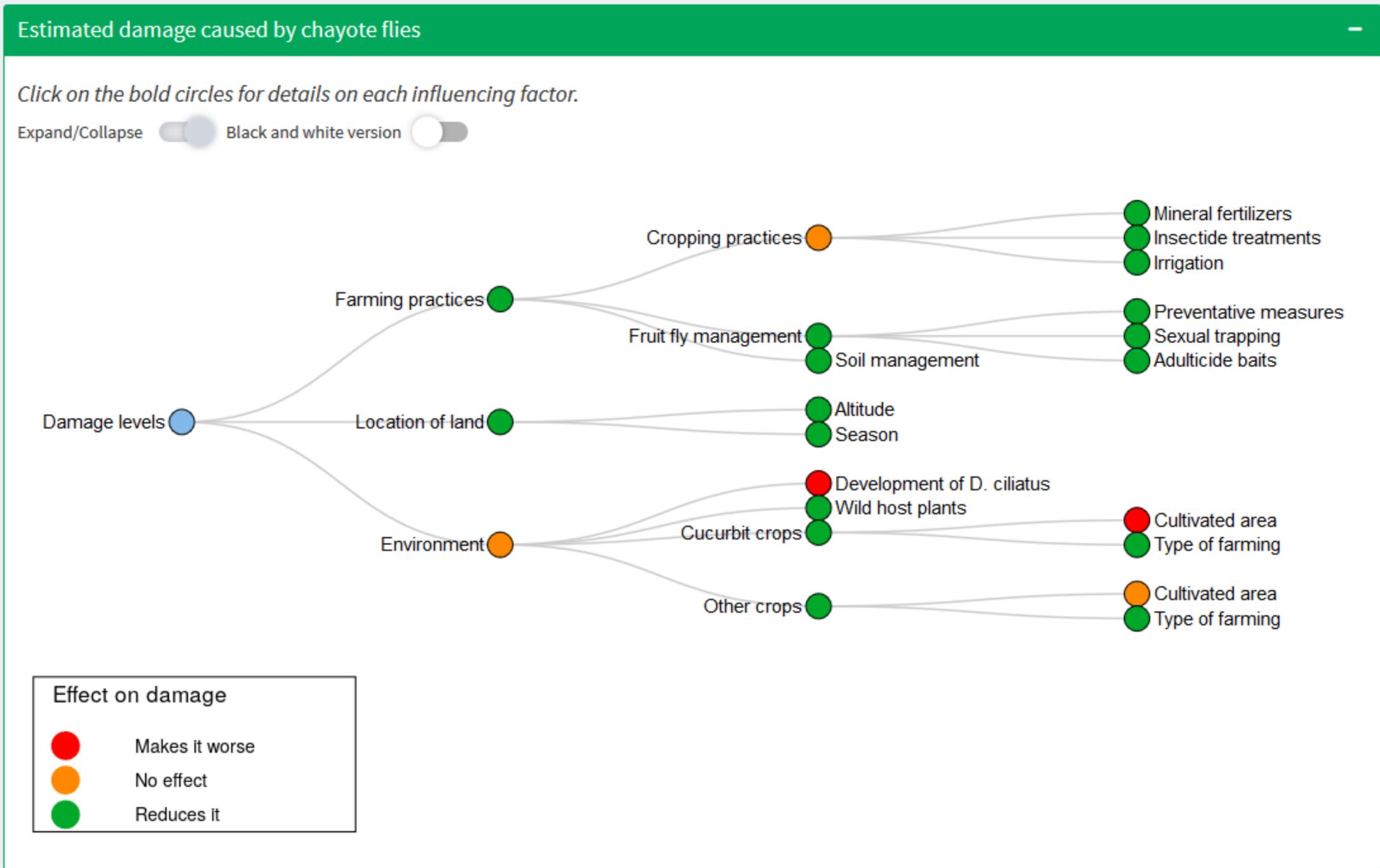
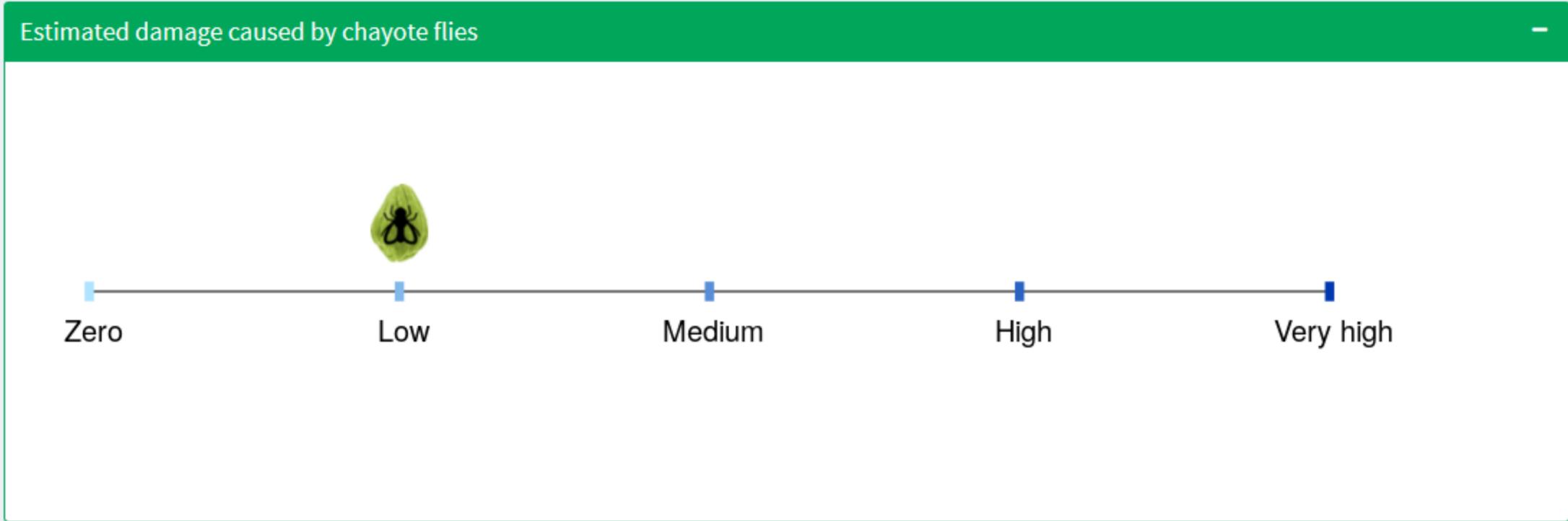
15. What type of farming is practiced there?

- 100% agrochemical
 100% agroecological

✓ Validate



- What is it ?
- Contribution and thanks
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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
	τ_b	Kendall rank correlation coefficient
	ρ_s	Spearman's rank correlation coefficient
Class	Sensitivity	Proportion of actual positives correctly predicted
	Specificity	Proportion of negatives correctly predicted
	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 <i>Dacus ciliatus</i>			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