

Fruit flies (Diptera: Tephritidae) on vegetable crops in Reunion Island (Indian Ocean): state of knowledge, control methods and prospects for management

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Fruit flies (Diptera: Tephritidae) on vegetable crops in Reunion Island (Indian Ocean): state of knowledge, control methods and prospects for management.

Abstract -- Significance of fruit flies in vegetable crops. Vegetable crops hold a key position in agricultural production in Reunion (Indian Ocean); however, many pests and diseases threaten the profitability of this agricultural sector. Fruit flies (Diptera: Tephritidae) figure among the main pests for solanaceous crops and cucurbits (cucumber, zucchini, melon, etc.). Losses of as much as 80% of tomato and 100% of cucurbit crop harvests have been frequently observed. **Inventory and distribution.** Four fruit fly species belonging to the Tephritidae family cause major damage to vegetable crops in Reunion: *Bactrocera cucurbitae* (Coquillet), *Dacus ciliatus* Loew and *D. demmerezi* (Bezzi) on Cucurbitaceae, and *Neoceratitis cyanescens* (Bezzi) on Solanaceae (primarily the tomato). Distribution of each of them is presented. **Biology and behavior.** A few studies on the biology and behavior of the four fruit flies were conducted in Reunion in the late 1990s. Their main biological characteristics are summarized. **Population control methods used in Reunion.** Various methods such as chemical control, preventive measures (sanitation), physical control, biotechnical control [colored traps, the Male Annihilation Technique (MAT) and the Bait Application Technique (BAT)], and biological control currently used in Reunion against fruit flies are reported. Other control methods such as Integrated Pest Management and the Sterile Insect Technique are not used in Reunion. **Prospects for implementing agro-ecological management of vegetable fruit flies in Reunion.** This part presents research actions implemented in fly bio-ecology, research actions into the genetic structure of populations and design of an agro-ecological management scheme for vegetable fruit flies. **Conclusions.** The control methods used independently have not been successful to effectively control tephritid populations. A more integrated approach is required, also taking into account the landscape scale and its mosaic of habitats, especially wild plants, whose role must be considered within a framework of agro-ecological management of these pest populations.

Reunion / vegetable crops / Tephritidae / *Bactrocera cucurbitae* / *Dacus ciliatus* / *Dacus demmerezi* / *Neoceratitis cyanescens* / pest control / control methods

Les mouches des fruits (Diptera : Tephritidae) sur légumes à la Réunion (océan Indien) : état des connaissances, méthodes de contrôle et perspectives de gestion.

Résumé -- Importance des mouches des fruits en cultures maraîchères. Les cultures maraîchères occupent une position clé dans la production agricole à la Réunion (océan Indien), toutefois, de nombreux ravageurs et maladies menacent la rentabilité de ce secteur agricole. Les mouches des fruits (Diptera : Tephritidae) figurent parmi les principaux ravageurs des solanacées et des cucurbitacées (concombre, courgette, melon, etc.). Des pertes de près de 80 % des récoltes de tomate et de 100 % de cucurbitacées ont été fréquemment observées. **inventaire et distribution.** Quatre espèces de mouches des fruits appartenant à la famille des Tephritidae provoquent des dommages importants aux cultures légumières à la Réunion : *Bactrocera cucurbitae* (Coquillet), *Dacus ciliatus* Loew et *D. demmerezi* (Bezzi) sur les cucurbitacées, et *Neoceratitis cyanescens* (Bezzi) sur les solanacées (principalement les tomates). La distribution de chacun d'eux est présentée. **Biologie et comportement.** Quelques études sur la biologie et le comportement des quatre mouches des fruits ont été menées à la Réunion dans les années 1990. Leurs principales caractéristiques biologiques ont été résumées. **Méthodes de contrôle des populations utilisées à la Réunion.** Diverses méthodes utilisées actuellement à la Réunion contre ces mouches des fruits sont exposées : lutte chimique, mesures préventives (assainissement), contrôle physique, contrôle biotechnique [pièges colorés, technique d'élimination des mâles (MAT) et technique d'utilisation d'appâts (BAT)] et lutte biologique. D'autres méthodes de lutte comme la lutte intégrée, et la technique des insectes stériles ne sont pas utilisées à la Réunion. **Perspectives de mise en œuvre de la gestion bio-écologique des mouches de fruits en culture maraîchère à la Réunion.** Cette partie présente les actions de recherche mises en œuvre en bio-écologie de la mouche, les actions de recherche sur la structure génétique des populations et la conception d'un système de gestion agro-écologique pour les mouches des fruits des légumes. **Conclusions.** Les méthodes utilisées indépendamment les unes des autres n'ont pas prouvé leur efficacité pour contrôler les populations de téphritides. Une approche plus intégrée est nécessaire qui prendrait en compte l'échelle du paysage et de sa mosaïque d'habitats, en particulier les plantes spontanées dont le rôle doit être considéré dans le cadre d'une gestion agro-écologique des populations de ces ravageurs.

Réunion / plante légumière / Tephritidae / *Bactrocera cucurbitae* / *Dacus ciliatus* / *Dacus demmerezi* / *Neoceratitis cyanescens* / lutte antiravageur / méthode de lutte

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1. Significance of fruit flies in vegetable crops

Vegetable crops hold a key position in agricultural production in Reunion Island (Indian Ocean) due to the number of farmers involved and the income generated by this industry. So besides sugar cane, Reunion's historical crop, vegetable production represented nearly 42 000 t in 2006, with a surface area of 1800 ha, *i.e.*, slightly less than fruit production [1]. However, many pests and diseases threaten the profitability of this agricultural sector [2], forcing farmers to resort to synthetic pesticides with all the risks that this entails for human health and the environment. Fruit flies (Diptera: Tephritidae) figure among the main pests for solanaceous crops (in particular, field-grown tomato, *Lycopersicon esculentum* Mill.) and cucurbits: cucumber (*Cucumis sativus* L.), zucchini (*Cucurbita pepo* L.), melon (*Cucumis melo* L.), etc. Losses of as much as 80% of tomato and 100% of cucurbit crop harvests have been frequently observed.

According to farmers, fruit fly damage to vegetable crops has become significantly greater since the 1990s, although the various species concerned had been reported for several decades [3]. Broad-spectrum insecticides, often unauthorized for the given crop, have been used at high doses and frequencies, without rotation of chemical families, which has probably negatively impacted on natural enemies of these pests and led to development of resistance. These practices have led to the impossibility of maintaining populations below an economic threshold. Besides poor management of this chemical control and the use of unsuitable insecticides, other hypotheses regarding changes of cropping practices could explain these proliferations: spatial expansion and, during other seasons of cultivated and wild host plants, lack of rotation and fallow, introduction of more susceptible varieties, and relaxation in the application of prophylaxis recommendations.

2. Inventory and distribution

Four fruit fly species belonging to the Tephritidae family cause major damage to

vegetable crops in Reunion: *Bactrocera cucurbitae* (Coquillet), *Dacus ciliatus* Loew and *D. demmerezi* (Bezzi) on Cucurbitaceae, and *Neoceratitis cyanescens* (Bezzi) on Solanaceae (primarily the tomato) [4, 5]. Other species specialized on fruit crops such as *Ceratitidis capitata* (Wiedemann) and *Bactrocera zonata* (Saunders) have been reported on vegetable crops, but do not cause significant damage in Reunion Island (S. Quilici, pers. comm.).

Bactrocera cucurbitae, the melon fly, has been relatively recently introduced into Reunion (identified in 1972), probably from India via Mauritius [3]. Its current distribution ranges from South Asia, whence it originates, to many Pacific Islands (including Hawaii) and, more recently, the Seychelles and Africa, where it is currently spreading [6]. Its biology is relatively well known, and the species has been much studied in India, South-East Asia and Hawaii [7]. It is a thermophilic species not commonly found at altitudes over 800 m in Reunion.

Dacus ciliatus, the Ethiopian cucurbit fly, was probably introduced from Africa whence it originated. It has been reported in Reunion since 1964 [4]. It is also present in most of the South-West Indian Ocean islands, but also in India and South-East Asia [8]. It has been much less studied than the species above. It is a eurythermal species, since it has been found in Reunion from the shore to high-altitude areas (at least 1200 m).

Dacus demmerezi, the Indian Ocean cucurbit fly, is a more stenothermal species, probably originating from the Madagascan plateau. It was first reported in Reunion in 1972 [3]; it is also present in Mauritius. Due to its limited distribution, the species has been very little studied, although this species causes sometimes major damage in high-altitude areas of Reunion Island (above 600 m). As such, it is considered to be a secondary damaging species in Mauritius, a low-altitude island (P. Sookar, pers. comm.).

Each of these three species may potentially cause entire destruction of the crop, although generally two species are found coexisting in the same location, according to the altitude and season. Relatively mild attacks have been registered on certain zucchini, cucumber and melon cultivars [4].

The tomato fruit fly, *Neoceratitis cyanescens*, has been described in Madagascar, where it is probably indigenous. It is not considered as a major pest there, though we have been unable as yet to explain this observation. The species was introduced into Reunion and then into Mauritius, where the first damage was reported in 1951 and 1958, respectively [9]. Its presence in Mayotte (Comoro Archipelago) was only reported in 1992 [4], while it was present a long time before this first mention. In Reunion Island, the distribution area of the tomato fly extends from the coast to an altitude of 1500 m, according to the availability of host plants [3]. We observed that there are no flies present at altitude during the cool season but no study has been conducted to test diapause, quiescence or migration hypotheses.

3. Biology and behavior

A few studies on the biology and behavior of these insects were conducted in Reunion Island in the late 1990s. We summarized the main biological characteristics of the four species mentioned (table 1).

The tomato fruit fly, *Neoceratitis cyanescens*, is one of the main pests of solanaceous crops, on which it stings young fruits to lay its eggs. This species is specialized on the Solanaceae family, represented by around twenty species in Reunion, but only eight are considered as host plants [10]. It causes significant damage to field-grown tomato and, to a lesser extent, to the sweet pepper (*Capsicum annuum* L.), eggplant (*Solanum melongena* L.), tree tomato [*Cyphomandra betacea* (Cav.)] and chilli pepper (*Capsicum frutescens* L.). Other wild or sub-indigenous Solanaceae such as the black nightshade (*Solanum americanum* Mill.), bug weed (*S. mauritianum* Scop.) and turkey berry (*S. torvum* Sw.) serve as breeding reservoirs. The wide distribution of these host plants on the island up to an altitude of 1500 m, as well as abundant, nearly uninterrupted fruit bearing, offer suitable conditions for the development of tomato fruit flies all year round [11].

Mating starts from the second day after emergence of the adults. At 25 °C, the

females mate very frequently, about three out of four days [12]. The pre-oviposition period lasts from 4 to 6 days. Larval development in the fruit lasts from 10 to 15 days [13]. Upon maturing, the larvae burst out of the fruit, and then pupate in the soil. As pupation lasts around ten days, the development cycle from egg to adult takes 21 to 31 days [9, 13, 14]. In response to odors released by host plants, and carried by the wind, the tomato fly females are guided to the source by successive flights [5]. After arriving at the host habitat, visual stimulation alone is sufficient to guide their landing onto the fruit [15]. Females respond strongly to a bright orange-colored sphere, which probably mimics the host fruit [15, 16]. However, the incorporation of appropriate olfactory signals enhances their search efficiency [17]. The response to stimuli is affected by the nature and structure of the habitat [17]. The response of females to a host fruit type visual signal depends on their age and their egg load, but also their nutritional condition [15]. This response is at its greatest in the afternoon, the preferred period for ovipositing [18].

Bactrocera cucurbitae, *Datus ciliatus* and *D. demmerezi* are three oligophagous species specialized mainly on the Cucurbitaceae family, the first two developing on 16 species and the latter on 13 species [4]. Of these 16 species, four are wild Cucurbitaceae - *Coccinia grandis* (L.) Voigt, *Momordica charantia* L., *Cucumis anguria* L. and *Lagenaria sphaerica* (Sonder) Naudin - which act as reservoir plants, enabling above all the reproduction of *B. cucurbitae* and *D. ciliatus* all year round, primarily on the shore with the driest wind [4]. These two species are polyvoltine at low altitude. In Reunion Island, besides Cucurbitaceae, we can report rare attacks on the tomato, wild passion fruit (*Passiflora foetida* L.) and passion fruit (*Passiflora edulis* Sims) [4]. We noted that *B. cucurbitae* attacks the tomato and papaya little or not at all (*Carica papaya* L.) in this island, whereas it causes damage to these crops in other parts: India [19], Cameroon [20], Hawaii [21] and Benin [6]. This probably results from competition for resources with *N. cyanescens* for the tomato, and with various fruit fly species (*Ceratitis* spp.) that might develop on the

Table I.
Economic importance and bioecology of fruit flies on vegetables on Reunion [4, 5].

Species	Name	Economic importance	Area of origin	Distribution area	Preferred altitude	Cultivated host plants	Wild host plants	Development time	Reproductive parameters
<i>Bactrocera cucurbitae</i>	Melon fly	High economic importance	Asia	Asia, Pacific, East and West Africa, Mauritius, Reunion, Seychelles	< 800 m	Cucurbitaceae: 16 species including <i>Cucurbita pepo</i> L., <i>Cucurbita maxima</i> Duch., <i>Cucumis sativus</i> L., <i>Cucumis melo</i> L., <i>Sechium edule</i> (Jacq.) Sw.	<i>Momordica charantia</i> L., <i>Coccinia grandis</i> (L.) Voigt, <i>Cucumis anguria</i> L., <i>Lagenaria sphaerica</i> (Sonder) Naudin.	At 25 °C: Egg to adult 26 d Ovarian maturity 11 d K = 322 degree days Development threshold = 8 °C	At 25 °C: Expectation of life at birth (e_0) = 142 d Growth reproductive rate = 218–588 eggs Mean generation time T = 47 d
<i>Dacus ciliatus</i>	Ethiopian fruit fly, Lesser pumpkin fly, cucurbit fly	Moderate economic importance	Africa	Africa (except Northern Africa), Indian Ocean islands, Asia	0–1200 m	Cucurbitaceae: 13 species	<i>Momordica charantia</i> L., <i>Coccinia grandis</i> (L.) Voigt, <i>Cucumis anguria</i> L., <i>Lagenaria sphaerica</i> (Sonder) Naudin.	At 25 °C: Egg to adult 26 d Ovarian maturity 11 d K = 323 degree days Development threshold = 11 °C	At 25 °C: Expectation of life at birth (e_0) = 123 d Growth reproductive rate = 190–310 eggs Mean generation time T = 51 d
<i>Dacus demmerezi</i>	Indian Ocean cucumber fly	Moderate economic importance	Madagascar	Madagascar, Reunion, Mauritius	> 600 m	Cucurbitaceae: 13 species	<i>Momordica charantia</i> L., <i>Coccinia grandis</i> (L.) Voigt, <i>Cucumis anguria</i> L., <i>Lagenaria sphaerica</i> (Sonder) Naudin.	At 25 °C: Egg to adult 26 d Ovarian maturity 16 d K = 355 degree days Development threshold = 9 °C	–
<i>Neoceratitis cyanescens</i>	Tomato fruit fly	High economic importance	Madagascar	Madagascar, Reunion, Mauritius, Comoros	0–1500 m	Solanaceae: <i>Lycopersicon esculentum</i> Mill., <i>Capsicum annuum</i> L., <i>Capsicum frutescens</i> L., <i>Solanum melongena</i> L., <i>Cyphomandra betacea</i> (Cav.) Sendtn.	<i>Solanum americanum</i> Mill., <i>Solanum torvum</i> Sw., <i>Solanum mauritanium</i> Scop.	At 25 °C: Egg to adult 26 d Ovarian maturity 4 d K = 433 degree days Development threshold = 11 °C	At 25 °C: Expectation of life at birth (e_0) = 40 d Growth reproductive rate = 142–225 eggs Mean generation time T = 45 d

papaya in Reunion. It could also involve a special biotype of this species, but this aspect has not been investigated.

The fruit of cultivated species is attacked by females of the three species within around ten days of fruit setting and sometimes even before the ovary has been fertilized, as it is often the case with the pumpkin and zucchini. Hence these fruits are generally punctured two days before fruit setting, the fruits of the watermelon [*Citrullus lanatus* (Thunb.)] are punctured two to six days after, and the fruits of the cucumber are punctured four to ten days after [22]. These three *Dacini* species may lay their eggs in either the vegetative part of the plant (stems) or in the floral organs (male and female flowers). These two biological characteristics relating to egg-laying may partly explain why some farmers do not identify the damage caused by these pests [4]. Furthermore, the extensive cropping systems (picking type) which are quite frequently encountered are a factor favoring development of Tephritidae populations because of (i) the absence of cropping and control practices, and (ii) the presence of “reservoir plants” through the absence of human intervention.

Study of demographic parameters of *D. ciliatus* showed a high biotic potential, which could partly explain its wide geographic distribution in Asia and Africa [23], just like *B. cucurbitae* [24]. Experiments on the behavior of *D. ciliatus* showed that the orange color was significantly more attractive to sexually mature females, and that the yellow color was significantly more attractive to sexually mature males [25]. These responses of *D. ciliatus* to visual stimuli could be used to improve trapping of this species as part of biotechnical control, as could the investigation of chemical stimuli.

The spatio-temporal distribution of these insects depends both on biotic factors (specific bio-ecological characteristics, host fruit availability, presence of other competing species, etc.) and abiotic factors (temperature, humidity, wind, etc.). Populations are particularly high during the southern summer (December to March) both in terms of spatial distribution and density. Consequently, their economic impact on crops is considerable during this period.

4. Population control methods used in Reunion Island

In Reunion Island, control of fruit flies is still largely based on the use of insecticides. Research issues have gradually turned towards alternative methods, taking inspiration from work already conducted on orchard fruit flies in the island, or on vegetable fruit flies worldwide. We summarized the various methods currently used against these flies in Reunion Island (*table II*).

4.1. Chemical control

Until now, farmers have applied foliar insecticides directly onto plots in order to control either adults present in the crop directly via contact or inhalation, or adults arriving at the plot subsequently via a residual or repellent effect. Overall, farmers have reported the effectiveness of these sprayings, although they have not been proved by field experiments in the island. These applications have no effect on larvae survival, which are protected inside the fruits. Laboratory studies have demonstrated the efficacy of several active ingredients on imagoes [26, 27], but transposing this to the field did not necessarily give the same results.

The frequent and repeated use of various insecticides belonging to three main chemical families (organophosphates, carbamates and pyrethroids), has perhaps led to resistance, which could partly explain the increase in damage observed over the past few years, but no studies have been conducted on this issue in Reunion. Furthermore, these insecticide sprayings probably reduce populations of natural enemies (predators, parasitoids, etc.), as a natural pest control.

Observations of daytime activities of some fruit fly species demonstrated that only females entered the plot to lay eggs, whereas males or immature females remained located in the immediate surroundings of fields (*e.g.*, hedges) to feed, mate or rest [4, 5]. Hence treatments applied to the field will at best only affect part of the adult population.

4.2. Preventive measures (sanitation)

Unsellable fruits, especially those housing larvae, left on the ground or on plants, are

Table II.
Control methods used against vegetable fruit flies in Reunion.

Methods	Efficacy	Actual use by farmers in Reunion Island	Drawbacks	Propositions
Chemical control	Not validated or proven in the field	Often used	Cost, dangerous, some products are not registered	Reduction of pesticide use
Prophylaxis (gathering of stung fruits)	Shown in Hawaii	Not used	Man-power cost; uncommon practice	Farmers' training
Physical control (mosquito net)	Yes	Rarely used	Net costs; only applicable for sheltered cucurbits	Collective buying of nets; conduct trials on other crops (tomato)
Yellow sticky traps	Not enough	Rarely used	A bit applicable Useful insect capture	-
Male Annihilation Technique (MAT)	Efficient in collective control	Moderately used	Attractants for only two species	Development of new sexual attractants
Bait Application Technique (BAT)	Not enough	Rarely used	Unavailability of effective and registered products	Development of new products (success bait...)
Biological control	Not enough because natural beneficial populations are low	Not used	Mass rearing techniques and production costs of beneficials for great releases	Production of parasitoids in augmentorium; management of environment to favor beneficials; release of new parasitoid species.

a major reservoir for the next generation [28]. Elimination of these fruits should be systematic so as to reduce subsequent infestations. It is also recommended to destroy crop residues after harvest. However, these principles are still little implemented by farmers in Reunion, above all for issues of custom and labor costs.

The absence of host plants (cultivated or not) during a period in principle offers little benefit on a single farm in view of the flies' high mobility capacities and their lifetime of several months. However, these periods exist at high altitude during the Southern winter (June to September), but we soon observe recolonization of the crops when the temperature increases, although we cannot say whether these are overwintering populations (very likely for *D. demmerezi* in view of its distribution primarily at high altitude), or migrants from lower altitude. Eliminating uncultivated host plants around the edges of plots, such as the wild bitter melon, does not seem to have much effect on infestation. Indeed, most Cucurbitaceous plots located in areas where they are not normally grown (big sugar cane cropping regions) but with bitter melons (*Mormodica charantia*) present around the edges, have always had very little infestation (pers. obs.). It would also seem that the permanent presence of suitable crops in a production area maintains the high population levels observed. For the tomato fruit fly, the importance of bug weed (*Solanum mauritianum*) as a source of infestation needs to be studied. Conversely, these indigenous plants may have a positive role, acting as auxiliary reservoirs (banker plants). Trials conducted in Hawaii demonstrated that implementing preventive measures in a production region reduced populations on their own by over 60% (E. Harris, pers. commun.), which emphasizes the usefulness of these practices on the scale of a whole production area, rather than on a single plot or farm.

4.3. Physical control

Mechanical protection of crops via nets or screens to prevent insect egg-laying is a solution already employed on some crops such as cabbage [29], and could be a way

forward against flies. However, using agro-textile nets has often proven problematic under tropical conditions due to the plant being subjected to big temperature and humidity rises, causing poor plant development or development of diseases (pers. obs.). Furthermore, these nets prevent flower pollination, which is essential in most Cucurbitaceous plants, especially as fruit fly egg-laying starts even before the female flowers open [4]. Finally, the cost of these nets remains prohibitive in Reunion Island, as well as the labor required to handle them. However, mini-tunnel systems communicating with hives have been tested with success in Senegal [30, 31]. Practices of individual fruit bagging using nets are sometimes employed in some countries with low labor costs [32]. In Guinea, straw protection of very young pumpkin and zucchini fruits has yielded beneficial results, significantly reducing infestations (J.-F. Vayssières, pers. obs.).

Observations, followed by a trial by the *Fédération Départementale des Groupements de Défense contre les Organismes Nuisibles* (FDGDON, St Paul, La Reunion), demonstrated that cucurbit flies do not enter open plastic tunnels housing cucumber crops, the openings of which are closed off by bird nets (mesh size around 3 cm, black). The phenomenon has not currently been explained; the net may disrupt the flight behavior of the flies, preventing them from entering in spite of the large mesh size. Another case concerns open tomato crop shelters (without nets over the openings) with which all farmers observed very little tomato fly damage, although major attacks can be observed on neighboring open field crops. Although no studies have been conducted to date on this aspect, the behavior of *N. cyanescens* may be affected by the transparent plastic film, as it modifies the light spectrum [33]. This phenomenon is already known for other insects in greenhouses, where UV filtering through certain plastic films impairs movement or egg-laying [34].

4.4. Biotechnical control

Biotechnical control is defined as the use of stimuli or visual and chemical agents that

affect the behavior or development of the target insect [35]. This involves using techniques that will act on the insects' behavior via visual or olfactory stimuli, and guide them to an attractive source, trapping or killing them, thereby enabling a count (monitoring) or elimination (mass trapping). Improving biotechnical control must be based on better knowledge of the bio-ecology and behavior of the species.

4.4.1. Colored traps

It has long been known that fruit flies are attracted by the color yellow. It is possible to use panels of this color, or bottles of oil covered with glue, and set them up within or around the crops (a traditional method used by some farmers in Reunion Island). Tests have been conducted on chayote [*Sechium edule* (Jacq.)], a cucurbit crop locally grown on vines, which demonstrated better attractiveness with yellow bottles put under the vine than those above it. Other more specific colors, as well as the shape of the glue-coated traps, have been tested [4, 5, 16, 17]. These types of visual traps, intended rather for tracking the development of populations, are not very practical as besides the drawbacks due to the glue we have found a lack of selectivity in the yellow traps, as many predator and pollinator insect species are also attracted. In addition, we have not observed a significant population or damage decrease by setting traps in a single plot in our trials.

4.4.2. Male Annihilation Technique (MAT)

A few chemical substances, known as parapheromones, have the property of strongly attracting the males of some fruit fly species in the same way as sexual pheromones. Consequently, these products can be used in trapping systems. Several types of traps, based on the "Tephritrap[®]" used in fruit orchards, have been tested locally. These were most often dry traps containing a parapheromone-soaked capsule or plate, with an added vapor action insecticide (dichlorvos, malathion).

Two vegetable fruit fly species present in Reunion, *B. cucurbitae* and *D. demmerezi*,

are attracted by a known parapheromone, the cuelure. Comparative tests have been conducted with various diffusers: the one supplied locally by the FDGDON, comprising a wooden cube impregnated with cuelure and malathion, currently appears to be the most useful in terms of effectiveness, cost and availability in Reunion. As malathion in the long term may be withdrawn from the market, other active ingredients such as spinosad could replace it [36].

In vegetable producing areas, these traps can capture a very high number of males (sometimes hundreds per trap per week), which reflects the high population levels. However, this method cannot significantly reduce populations and damage when the traps are set up inside or around a single plot as the adults probably move to an entire area (reinfestation via migrations). In addition, uncaptured males are capable of fertilizing a number of females (polygyny), and the females also have the ability to live for several months. Hence this method used alone may be insufficient [37]. This constraint has also been observed with the use of sexual pheromones [38] which may, on the other hand, give good results as, for example, with forest moths such as *Lymantria dispar* (L.) [39], provided that the populations are low density and the infested area isolated.

Therefore, it would be necessary to apply a combined control method to an entire production area. A campaign against flies attacking chayote was conducted by the FDGDON using cuelure traps in an isolated production area located at an average altitude of 400 m in the South of the island. After several months of trapping, the quantity of trapped *B. cucurbitae* males had greatly decreased as *D. demmerezi* was barely present at this altitude. However, fruit damage did not decrease and the rearing of larvae taken from the fruit primarily produced *D. ciliatus*, a species not attracted by cuelure. Hence, generalized trapping led to the replacement of an initially dominant species by another less competitive species.

4.4.3. Bait Application Technique (BAT)

Fruit flies need water, carbohydrates and proteins to ensure their survival, but also for egg maturation. The foraging behavior

for these nutrients can be exploited by attracting the flies with products providing them with these substances. Numerous products containing proteins or yeasts, or even plant-derived substances, have been used as attractants worldwide [40–44] used either in traps or mixed with an insecticide for spot treatments on crops.

These attractants can be used with two methods. First, McPhail-type liquid traps are used, in which the flies are attracted and drowned. Yet this device attracts few individuals compared to the parapheromone traps and so remains insufficient for significantly reducing populations, although the specificity is lower and the attraction applies to both sexes. Furthermore, there do not always seem to be correlations between the number of individuals trapped and the level of damage, but we have a lack of data. Nonetheless, these traps are good indicators of the species presence and their changes over time.

Spot sprayings, long since successfully used in fruit orchards [45], consist of applying to some plants or plant parts a food attractant acting as a lure, mixed with an insecticide. Several protein or yeast-based food attractants were tested in large outdoor cages with laboratory-reared flies. This type of attractant was tested in liquid form in McPhail-type traps. The products tested (Nulure[®], Solbait[®], Hym lure[®], Corn Steep water[®], Pinnacle[®], Torula[®] and various yeasts including brewing waste derivatives) were all more effective than the Buminal[®] control, the only food attractant for fruit flies sold in France [46, 47]. However, authorization for their use is classified as minor usage in Reunion, which has not yet been defined, and they cannot yet be put on the market. Improvements in effectiveness by reducing the pH or increasing the concentration have also been observed to a certain degree, but using additives (borax, ammonium acetate) or using enzymes (papain) had no positive effect [48, 49], unlike the findings with other fruit fly species. Though the methodology has been gradually refined to eliminate some biases [50], we have not tested the effectiveness or repellent effect of only a few insecticides intended for mixing with attractants.

These experiments in field cages are, however, fairly remote from the reality of spot treatments, where small quantities of products are applied to the leaves in the form of drops, which will dry more or less quickly. Hence a new protocol for comparative tests in large cages has been proposed using dry traps containing an insecticide plate, a piece of maize leaf mounted on a wet piece of cotton, onto which a drop of a given volume of attractant is placed. The results proved to be contradictory depending on the replicates. Trials have started to this end to explain the variability of the responses observed, which appears to be related to the position of the traps in the cage relative to the sun, the time of fly activity, the temperature and the attraction by the maize leaf, wet piece of cotton and yellow color of the insecticide plate.

Field tests conducted in collaboration with several local partners (FDGDON, Plant Protection Service) provided an opportunity for testing a new product, GF 120 (= SYNEIS APPAT[®]), a mixture of a food attractant and a natural insecticide, spinosad, applied in spot spraying to the crop or border plants favorable to flies, such as maize. Indeed, studies in Reunion into fly behavior have demonstrated that the applications would gain effectiveness if applied around the edges of the plot [18], as it is done in West Africa [6]. These tests have not, however, demonstrated the effectiveness of GF 120 under the conditions of Reunion, even if the doses, concentrations or application frequency are increased, whereas it appears to be effective in other parts of the world [51]. Laboratory tests have confirmed its toxicity against several fly species [52] and we have observed it for ourselves in large outdoor cages, as in Mauritius [53]. Furthermore, studies on *B. cucurbitae* have demonstrated that the age of the flies, exposure time and product concentration had an effect on attractiveness and mortality [54].

A hypothesis may be drawn up regarding this lack of effectiveness in the field. As flies are highly mobile insects, it is highly likely that they are constantly arriving from surrounding host crops, where populations may be high. Furthermore, we do not know the remanence of attractants, and their rapid

breakdown could also explain the phenomenon. It is also possible that the females have time to lay even before being eliminated by spot sprayings. However, according to manufacturer sources, GF 120 would be effective in fruit crops when applied to hundreds of hectares of single crop land, in an environment with few natural areas or little wild land. This situation is therefore different to that in Reunion where vegetable crop plots are piecemeal, and surrounded by a variety of habitats. Furthermore, tests conducted in Reunion [50] and the USA [55] have demonstrated that flies with protein-sufficient diets are much less attracted by attractants containing protein, such as GF 120, for example. Hence it is highly possible that flies can easily find protein sources in a local context rich in food resources (plant exudates, excrement, maize pollen, fruits, etc.).

4.5. Biological control

Fruit flies have a number of natural enemies, which generally attack the eggs or larvae. However, these stages are more or less protected by the fruits hosting them, except when the larvae emerge from the fruit to pupate in the soil. They can then fall prey to various predators (including ants) and parasitoids. The eggs inserted under the fruit skin can also be parasited fairly easily by oophagous species, whereas only larvae near the edges of the fruit can be reached by other parasitoids. Adults may also be captured by various organisms (spiders, for example), but this aspect has still been little studied.

Several entomophagous species have been listed across the world, but their effectiveness is not always sufficient in economic terms. Only a few species are recognized as beneficial and have been introduced to various countries, and some of them to Reunion in the past few years, but not all are acclimated or are still at too low a level to have a useful action [56].

Psytalia fletcheri (Silvestri) (Hymenoptera: Braconidae) is the most used parasitoid worldwide for controlling *B. cucurbitae* [57]. Its introduction into Reunion in 1995

and its installation have been a success [58], but the level of parasitism observed in the past few years is still low in crops (< 5%), including on plots without insecticides [4]. However, it is possible that the levels obtained from larvae in the fruit underestimate the real parasitism rate because some larvae could be parasited when they emerge from the fruit before pupation in the soil. Furthermore, we have not studied the effectiveness of this parasitoid against *D. demmerezi* and *D. ciliatus*, although it is known that this hymenopterous insect can parasite them in the laboratory [56]. The main *P. fletcheri* reservoir in Reunion appears to be the wild bitter melon (*Mor-modica charantia*), which primarily hosts *B. cucurbitae* [4].

On the other hand, the effectiveness of this species has been demonstrated in Hawaii provided that pre-reared individuals are released in mass (over 60,000 individuals·ha⁻¹ per week) [59], which poses the problem of cost. A complementary technique aimed at increasing parasitoid populations consists of putting sting fruits in a cage (with larvae therefore partly parasited), the mesh of which enables emergent parasitoids to escape but prevents the flies from passing through. This technique used in Hawaii is known as the “augmentation” (E. Harris, pers. commun.).

A fruit fly egg parasitoid, *Fopius arisanus* (Sonan) (Hymenoptera: Braconidae), has been recently imported to the island to control *Bactrocera zonata*, but a study has demonstrated that it cannot complete its cycle on *B. cucurbitae* and that it develops little on the three other species concerned [60].

In the cases of *D. ciliatus*, *D. demmerezi* and *N. cyanescens*, the parasitoids are much less known, and further research would need to be conducted in their areas of origin, which are assumed to be in Africa and Madagascar. Some parasitoid species have been recently mentioned on *D. ciliatus* in Egypt [61]. In Reunion, very little data exists on parasitoids of *N. cyanescens*: the ones mentioned are *Psytalia* near *distinguenda* (Granger) and *Ps. insignipennis* (Granger), but this parasitism seems to be occasional [5].

5. Other control methods not used in Reunion

5.1. Integrated Pest Management

Integrated Pest Management (IPM), developed since the 1970s in the Northern countries, has generally aimed to harmonize organic control with rational chemical control in a curative approach, with rather disappointing results in most situations [62]. Furthermore, there are no insecticides specific to fruit flies. Hence, as with other pests, fly control has until now been almost exclusively based on chemicals, where the insecticides used may subsequently end up on the fruits, in the soil and in the water tables, not to mention the adverse effects on useful fauna (entomophagous species, pollinators, etc.). For example, an experimental tomato plot managed without chemical sprayings in the South of the island exhibited major fruit damage due half to *N. cyanescens* and half to tomato fruitworm noctuid moth *Helicoverpa armigera* (Hubner), which does not normally cause damage in Reunion, probably controlled by broad-spectrum treatments applied against *N. cyanescens*.

Finally, we need to take into account all of the pests of the crops concerned, since their overall management may be difficult in some cases following the cessation of broad-spectrum insecticide applications.

5.2. Sterile Insect Technique

Also known as genetic control, the principle of the Sterile Insect Technique (SIT) consists of releasing very great quantities of males pre-sterilized by ionizing rays. They then compete with the wild males and mate with the females, which will lay sterile eggs. This method, which may form part of IPM, does, however, assume that the sterile males are much greater in number than the wild males and that their fitness for mating is unaltered. This technique has completely eradicated species such as *B. cucurbitae* on some Pacific islands [63, 64]. However, it poses several drawbacks, particularly in the context of Reunion. Firstly, the mass rearing of millions of individuals would need to be

controlled over several years, which presupposes setting up a production factory. In the case of flies attacking vegetables in Reunion, the techniques and experience are known for just one species, *B. cucurbitae*, and it would be necessary to launch studies to develop large-scale rearing of three other species, especially since mass rearing of *N. cyanescens* and above all of *D. ciliatus* has always been problematic in the laboratory. There is also the added problem of the females' mating capacity throughout their lifetime with several males: for example, the *N. cyanescens* females mate nearly every day [5]. Moreover, following eradication of some species in other lands, species displacement phenomena through elimination of the competition have been observed [65]. Consequently, SIT should be applied simultaneously to the three species present on Cucurbitaceae in Reunion. Hence, for economic reasons and due to the relatively small crop surface areas concerned, it appears unlikely that this method will be implemented. It could possibly be profitable at a regional level, but not all lands are affected by the same species.

6. Prospects for implementing agro-ecological management of vegetable fruit flies in Reunion

6.1. Approach and references

The structure of landscape as a mosaic of habitats affects the spatio-temporal dynamic of insect populations. Landscape management may contribute to maintaining insect populations at non-harmful levels, by promoting faunistic balances and preserving biodiversity. This approach is based on agro-ecological pest management [66] and can be applied in particular in the form of management of their habitats or those of their natural enemies and of pollinators on expanded time, space and management scales [67]. Enhancement of beneficial fauna may be achieved through increasing plant diversity, whether cultivated (rotations, mosaics, intercropping, etc.) or uncultivated (borders, hedges, fallows, natural environments, etc.). This biodiversity also ensures better resilience of agro-systems [68].

Planting service plants around plots has several objectives depending on the species: a trap or repellent effect for pests (“push-pull”), or acting as a reservoir for beneficials (functional biodiversity). Regarding trap plants, the initial observations seem to indicate that the wild bitter melon (*Mor-modica charantia*) is more attractive to *B. cucurbitae* females than the zucchini, which therefore appears to be protected, but the opposite clearly applies to *D. ciliatus*. Similarly, with traps placed in large field cages, we have found that bitter melon leaves were clearly more attractive to *B. cucurbitae* females than the same weight of zucchini leaves. The importance of this sub-indigenous plant as a parasitoid reservoir, however, is still limited as levels of parasitism remain low (< 10%) (P. Ryckewaert, unpublished).

Observations have shown that vegetable fruit flies could gather on certain field border plants on which they feed [69], mate [4] and rest [18]. Hence grasses such as maize, sorghum or sugar cane often act as shelter plants for these flies. Maize seems particularly favorable to these insects, which probably find water, exudates and pollen [4, 70], or even aphid honeydew or other nutrients. Therefore, it appears more logical to place traps or apply spot treatments to this type of plant rather than to the crop [51, 71, 72]. Finally, these plants may also promote development of beneficials, or host them.

The approach initiated in Reunion is consistent with the agro-ecological approach described above, the conceptual bases of which were summarized by Deguine *et al.* [73]. It is also completely consistent with the guidelines adopted in some countries for vegetable fruit fly control based on a large-scale management approach (Area-Wide Pest Management) [74]. In Hawaii, a program of this type was initiated in 2000 on several hundred hectares, on several crops (cucurbits, papayas, etc.) and on several fruit fly species including *B. cucurbitae*, a species present in Reunion [75]. Besides the fact that Hawaii and Reunion exhibit numerous similarities, particularly in terms of agriculture and climate, the situation on this island in 2008 may be compared to that of Hawaii in 2000: significant fruit and vegeta-

ble fly damage in horticultural systems; a certain skepticism on the part of some protagonists, primarily the farmers, already disappointed by previous proposals; a common, shared and conscious desire on the part of stakeholders in the project [76]. Seven years of findings are now available to evaluate its effectiveness, both in technical terms [72, 77, 78] and economic terms [79]. Four years after its initiation, the profits generated exceeded the annual costs of its application. This program is currently considered in the United States as a model for success in IPM, and one of the keys to this success is due to the efficient coordination between the different protagonists in the program [80]. Furthermore, it has been subject to adaptations that have been successful in other countries, such as Japan [81] and Taiwan [82]. Other initiatives are being launched based on this model, such as on Mauritius, with the support of the International Atomic Energy Agency.

6.2. Research actions implemented in fly bio-ecology

Among the research actions to be developed, those relating to acquisition of knowledge of fly bio-ecology are the first to intensify. While *B. cucurbitae* is a fly whose biology has been well studied in the world, the same does not apply to the three other species found in Reunion (*D. ciliatus*, *D. demerzezi* and *N. cyanescens*). The aim of the studies should be to establish the main bio-ecological characteristics of these flies, and will cover the circadian rhythm, particularly the flies' movements between cultivated plants (Cucurbitaceae, Solanaceae) and uncultivated plants (primarily borders). Similarly, studies into the main natural enemies need to be conducted, both on predators (ants, ground beetles, rove beetles) and on parasitoids (including *Psytalia fletcheri*). Tri-trophic interactions (pests, natural enemies, plants) will be a key object of study in this approach.

6.3. Research actions into genetic structure of populations

A work program is being initiated at the International Center for Agricultural Research for Development (CIRAD, Reunion) to analyze via micro-satellite markers the genetic

variability of vegetable fruit fly populations, by the following parameters: host plants (wild *vs.* cultivated), altitude gradient [(0 to 1200) m] and seasonal temperatures (winter-summer). This work will enable one to specify the importance of reservoir plants and shelter plants in the reproduction of fruit flies, and gain a better knowledge of dispersal, seasonal migration and practical details of the winter season transition. The year 2008 was devoted to starting sampling on 25 sites (*B. cucurbitae* and *D. demmerezi*), tool construction (*D. demmerezi*, *D. ciliatus* and *N. cyanescens*) and developing DNA extraction. The program will continue these preliminary activities on the four fly species concerned.

6.4. Design of an agro-ecological management scheme for vegetable fruit flies

Thereafter, it will be a matter of developing and evaluating a technical management package for fly populations, based on an agro-ecological approach. The design of this package is based on existing foreign experience, especially from Hawaii, while taking into account the particularities of Reunion (socio-economic characteristics of agriculture, biological characteristics of the flies present, etc.). The technical consistency of this package is an essential preliminary step. The foundation of the package is based on the following techniques: monitoring, trap plants and using new products (assisted push-pull), the Male Annihilation Technique (MAT), biological control and agro-ecological practices.

7. Conclusions

The control methods tested hitherto in Reunion against vegetable fruit flies have proven to be greatly insufficient in limiting damage to the crops concerned. The absence of paraperomones for all species, genuinely effective food attractants which are approved and have sufficiently long-lasting action, the existence of short crop cycles repeated all year round without no-host plant zones, the ability of the flies to

live for several months and move around easily, the presence of high population levels probably resulting from an imbalance, the presence of scattered plots, and the difficulty in implementing preventive measures may explain the failures observed up until now.

Fly population control should be implemented at production area level, with collective and coordinated resources, to promote a new agro-ecological balance centered on the role of functional plants, habitat management and development of natural beneficials, on a landscape scale. Other alternative methods (MAT, BAT, etc.) may be used as complements. These environmentally friendly techniques can therefore be included under Organic Agriculture and IPM approaches.

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Las moscas de las frutas (Diptera: Tephritidae) en verduras en la Reunión (océano Índico): estado de los conocimientos, métodos de control y perspectivas de gestión.

Resumen -- Importancia de las moscas de las frutas en cultivos de hortalizas. Los cultivos de hortalizas ocupan una posición determinante en la producción agrícola en la Reunión (océano Índico). No obstante, existen numerosas plagas así como enfermedades, que suponen una amenaza para la rentabilidad de este sector agrícola. Las moscas de las frutas (Diptera: Tephritidae) se clasifican entre las plagas principales de las solanáceas y de las cucurbitáceas (pepino, calabacín, melón, etc.). Se observaron frecuentemente pérdidas de cerca del 80 % de las cosechas de tomate y del 100 % de cucurbitáceas. **Inventario y distribución.** Cuatro especies de moscas de las frutas pertenecientes a la familia de los Tephritidae provocan importantes daños en los cultivos de verduras en la Reunión: *Bactrocera cucurbitae* (Coquillett), *Dacus ciliatus* Loew y *D. demmerezi* (Bezzi) en los cucurbitáceos, y *Neoceratitis cyanescens* (Bezzi) en las solanáceas (principalmente los tomates). La distribución de cada uno de ellos está presentada. **Biología y comportamiento.** En la Reunión en los años 1990 se realizaron ciertos estudios sobre la biología así como sobre el comportamiento de las cuatro moscas de las frutas. Se resumieron sus principales características biológicas. **Métodos de control de las poblaciones empleadas en la Reunión.** Se exponen diversos métodos empleados actualmente en la Reunión contra estas moscas de las frutas: lucha química, medidas preventivas (saneamiento), control físico, control biotécnico [color de las trampas, técnica de anihilación del macho (MAT), así como técnica de empleo de cebos (BAT)], y lucha biológica. En la Reunión no se emplean otros métodos de lucha como la lucha antiparasitaria integrada o la técnica del insecto estéril. **Perspectivas de puesta en marcha de la gestión agro-ecológica de las moscas de las frutas en cultivo de hortaliza en la Reunión.** Esta parte presenta tanto las acciones de investigación puestas en marcha en bio-ecología de la mosca, como las acciones de investigación en la estructura genética de las poblaciones, o incluso la concepción de un sistema de gestión agro-ecológico para las moscas de las frutas de las verduras. **Conclusiones.** Los métodos empleados independientemente unos de otros no demostraron su eficacia para el control de las poblaciones de las Tephritidae. Se necesita un acercamiento más íntegro, que tome en cuenta la escala del paisaje y de su mosaico de hábitats, en concreto las plantas espontáneas, cuyo papel debe considerarse en el marco de una gestión agro-ecológica de las poblaciones de estas plagas.

Reunión / hortalizas (plantas) / Tephritidae / *Bactrocera cucurbitae* / *Dacus ciliatus* / *Dacus demmerezi* / *Neoceratitis cyanescens* / control de plagas / métodos de control