Pre-harvest management of the oriental fruit fly

A. Manrakhan

Address: Citrus Research International, PO Box 28, Nelspruit 1200, South Africa.

Correspondence: A. Manrakhan. Email: aruna@cri.co.za

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Abstract

The oriental fruit fly, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae), is an important pest of commercial fruit and vegetables in various parts of Asia and Africa, in some South Pacific islands and in Hawaii. Commercial fruit and vegetables can be protected from this pest prior to harvest using multiple control tactics. This paper reviews measures being used and developed for pre-harvest management of *B. dorsalis*. An integrated use of monitoring and combinations of control tactics on an area-wide basis for the pest is discussed.

Keywords: Tephritidae, *Bactrocera dorsalis*, Integrated pest management

Review Methodology: A layout of the review article was first finalised. Over 150 peer-reviewed articles were analysed. Search terms on Google Scholar were used to track recently published articles for each section of the review. The analysis of the articles followed the order of the layout. Notes were taken from each article read and sources were cited using EndNote.

Introduction

The oriental fruit fly, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae), is a notorious pest of commercial fruit and vegetables in parts of the world where it occurs [1, 2]. As per its name, the oriental fruit fly is of Asian origin with south Asia possibly as the native range within Asia [3, 4]. *Bactrocera dorsalis* has proven to be a highly invasive pest moving out of Asia to establish itself in other parts of the world: Hawaii, various south Pacific islands and several African countries [2, 5, 6]. It is also regularly detected in North America and there were recent detections of the pest in Europe [7, 8]. *Bactrocera dorsalis* belongs to the *B. dorsalis* complex which contains a few species of economic importance [1, 9]. Three of these economically important species within the complex: *Bactrocera papayae* Drew and Hancock, *Bactrocera philippinensis* Drew and Hancock and *Bactrocera invadens* Drew, Tsuruta and White were recently synonymized with *B. dorsalis* based on the similarities in their morphology, genetics, chemical ecology and mating behaviour [10]. The notoriety of *B. dorsalis* as a pest stems from its ability to (1) utilize a broad range of hosts [1, 11, 12], (2) develop rapidly [13] and (3) disperse over large distances [14]. *Bactrocera dorsalis* is also listed as a quarantine pest in a number of countries. This poses export market access restrictions for fruit produced in regions where *B. dorsalis* is present. In fruit production regions where *B. dorsalis* occurs, high levels of fruit infestation by the pest can be recorded if the latter is not managed [15, 16]. For fruit infesting pests like *B. dorsalis*, the use of chemical control alone is not recommended due to low tolerance of insecticide residues in fruit [17]. As for other fruit pests, an integrated control with sampling as a baseline for control coupled with the application of a combination of control techniques (such as attract and kill, biological, cultural, sterile insect technique) would be essential [18]. In a European Union (EU) report on pesticide residues in food in 2017, non-compliance to maximum residue levels of some insecticides was found in some food commodities originating from within and outside of the EU [19]. The European Food Safety Authority recommended increased efficiency of systems to monitor insecticidal residue levels in food in order to protect consumers [19]. Producers of fruit destined to the EU would therefore have to resort to management options that would steer away from chemical control for pests like *B. dorsalis*. An integrated management of *B. dorsalis* with a lower reliance on chemicals would also ensure that there is no buildup of insecticidal resistance in *B. dorsalis* populations. This is in view of the demonstration of the potential of this species to develop resistance to a number of insecticides in laboratory studies with selected reared lines [20].

There are various tools available and being developed for an integrated management of *B. dorsalis* in the field before harvest and there are a number of post-harvest disinfestation treatments that have been investigated and are currently in use for this pest. Post-harvest treatments for *B. dorsalis* were recently well covered in a review by Dohino *et al.* [21]. The aim of this paper is to review the current and new tools for pre-harvest management of *B. dorsalis* in fruit production areas. This synthesis of published information could pave the way for designing integrated management programmes for *B. dorsalis* and identifies future research needs. The two important components of pre-harvest management of *B. dorsalis*: monitoring and control are covered.

Monitoring

Commercially available traps and attractants are used to monitor male and female populations of *B. dorsalis* [22]. Monitoring of *B. dorsalis* can be conducted for several purposes: (1) detection of the presence of the pest in an area, (2) delimiting the extent of spread of the pest, (3) determining the efficacy of suppression methods for the pest and (4) determining natural fluctuations of the pest for designing effective strategies of control [22].

Males of *B. dorsalis* can be effectively monitored using the attractant methyl eugenol (selected synonym being 4-allyl-1,2-dimethoxybenzene), a plant-based phenylpropanoid, abbreviated henceforth as ME [23, 24]. Tan and Nishida [25] provided a comprehensive review on the interactions of fruit flies such as *B. dorsalis* with ME. *Bactrocera dorsalis* males are highly attracted to ME which they then consume [26]. Attraction to and feeding on ME was found to increase with increasing age of *B. dorsalis* [26]. Consumption of ME improves the mating success of *B. dorsalis* since ME increases wing fanning activities during courtship and acts as a sex pheromone precursor [27–29]. Consumption of ME also reduces predation risk of *B. dorsalis* as demonstrated experimentally with the Malayan spiny gecko, *Gekko monarchus* [30].

The attraction of *B. dorsalis* to ME-baited traps and sensitivity of ME-based trapping network for the detection of *B. dorsalis* have been quantified in mark-release recapture studies [31–33]. ME-baited traps were found to attract *B. dorsalis* males from a distance of up to 500 m [34]. The estimated probability of capture of *B. dorsalis* populations by a grid of ME-baited traps varied depending on the age of the males. In mark–release–recapture studies done by Shelly *et al.* [35] using 2-week-old *B. dorsalis* males, it was estimated that a grid of two ME-baited traps per km^2 would always capture males from a population comprising of 50 individuals. In mark–release–recapture studies done by Manrakhan *et al.* [31] using 4-day-old *B. dorsalis* males, the frequency of the capture of at least one male was found to be 100% with a grid of four ME-baited traps per km^2.

ME can be dispensed either as liquid, polymeric plug and wafer for the monitoring of *B. dorsalis* [22, 32, 36–38]. In South Africa, the monitoring of *B. dorsalis* is carried out using fibre board blocks soaked in ME liquid [39]. The wafer formulation of ME was found to be significantly better than ME liquid imbibed in cotton wool and the plug formulation for the monitoring of *B. dorsalis* males [32, 37, 38]. Recently, the delivery of ME in a nanogel was investigated [40]. ME in a nanogel formulation was found to be longer lasting in the field compared to liquid ME in field trials in a guava, *Psidium guajava* L., orchard in Uttar Pradesh, India [40]. Catches of *B. dorsalis* males were also found to be influenced by the type of traps. White and yellow ME-baited bucket traps were found to attract more males than green, red or black traps baited with ME [41]. The design of a ME-baited trap was also found to influence the catches of *B. dorsalis* with bucket traps containing holes with a one-way entrance design and without toxicant being more effective than bucket traps with similar sized entrance holes with toxicant [42].

Females of *B. dorsalis* can be monitored using protein-based attractants [16, 43–46]. These protein-based attractants are usually available either as liquid protein hydrolysates or as synthetic food lures such as the three-component lure containing ammonium acetate, putrescine and trimethylamine [22]. For *B. dorsalis* females, liquid protein hydrolysates were found to be more effective than synthetic mixtures in some studies [16, 45, 46]. However, in a recent study in South Africa, the reverse was found with the three-component lure being more effective in catching *B. dorsalis* females when compared with a liquid protein hydrolysate (Torula yeast in this case) [44]. Responses of *B. dorsalis* females to protein-based baits were found to be lower than other fruit fly species like *Zeugodacus cucurbitae* (Coquillett) [47]. In trapping studies conducted in the northern areas of South Africa, catches of *B. dorsalis* females in traps baited with the three-component lure averaged around 0.01 flies per trap per day in natural areas, while male numbers of the same species in ME traps in the same environment averaged around 3.5 flies per trap per day (a 350:1 ratio of females: males). The low sensitivity of protein-baited traps for the monitoring of *B. dorsalis* females indicates the need for an improved lure for the latter. *Bactrocera dorsalis* females were found to be highly attracted to volatile components of leaves from a non-host plant commonly known as Panax (*Polyscias guilfoylei* [Bull]) [48]. Volatiles from host fruit, in particular mature fruit, were also found to be highly attractive to *B. dorsalis* females [49, 50]. Long-term and large-scale evaluations of these plant volatiles are yet to be carried out to determine their potential as monitoring tools for females. Although one of the male sex pheromone components of *B. dorsalis* (*trans*-coniferyl alcohol) has been identified as a potential attractant for con-specific females [51, 52], it is surprising that to date there have been very few assessments of the field attractiveness of this compound in time and space. *Trans*-coniferyl alcohol is one of the phenyl propanoids which are derived following the consumption of ME by *B. dorsalis* males [53]. Potential field attraction of the *B. dorsalis* male sex pheromone to *B. dorsalis* females was demonstrated by Shelly [54, 55] who used aggregations of *B. dorsalis* males placed at dusk in cups and suspended to trees and determined responses of con-specific females released from a distance of between 12 and 15 m. In one of these field studies, Shelly [55] demonstrated that males fed on ME attracted more females than those that were not. Comparative attractiveness of *B. dorsalis* to protein-based attractants, fruit volatiles and male sex pheromones should be investigated in future field trials with the objective of obtaining a better monitoring and control tool for females of this species.

Control

Baits

Control of *B. dorsalis* using insecticidal protein baits (mixtures of protein hydrolysates and insecticides) was successfully demonstrated in field trials in Hawaii in the early 1950s [56]. Protein baits target females of the species which are in search of a source of protein for reproductive maturation [57]. Steiner [56] investigated the efficacy of different concentrations of protein in luring *B. dorsalis* and found that baits with a higher amount of protein were more attractive to the species. In follow-up research by Gow [58], a promising soy meal bait combined with a bacterial culture, coded SM-14, was found for *B. dorsalis*. This bait was however not developed further in the years to come. In some earlier work on bait sprays for fruit fly control, organophosphates were found to be the most effective toxicants for use with protein baits [57]. Mixtures of protein hydrolysate and organophosphates such as malathion were subsequently effectively used to eradicate *B. dorsalis* in different areas across the world [59–61]. In the late 1990s and early 2000s, reduced risk toxicants were sought for combination with protein baits for the control of fruit flies including *B. dorsalis*. Spinosad, derived from a soil-dwelling actinomycete bacterium *Saccharopolyspora spinosa* Mertz and Yao and Phloxine B, which is a photoactive xanthene dye, were found to be good replacements for malathion in combination with protein baits for the control of *B. dorsalis* [62–64]. Phloxine B in combination with a protein hydrolysate Provesta 621 effectively reduced a *B. dorsalis* population in guava orchards in Hawaii and reduced fruit infestation by the pest [65]. High to moderate sprays of the commercially available spinosad-based bait GF-120 reduce *B. dorsalis* female numbers and fruit infestation in papaya orchards in Hawaii when combined with orchard sanitation [66]. Similarly, in trials conducted in mango, *Mangifera indica* L., orchards in Benin, a reduction of fruit infestation by *B. dorsalis* was recorded in orchards treated with GF-120 compared to untreated orchards, although male numbers of this fruit fly species in treated and untreated orchards were not significantly different [15]. However, protein bait sprays, including commercially available ones, might not be as effective in controlling *B. dorsalis* as other fruit fly pests. Piñero *et al*. [47], for instance, showed that *B. dorsalis* had a lower response to the commonly used GF-120 compared to other fruit fly species such as *Z. cucurbitae*. Female age and degree of protein starvation were found to influence the responses of *B. dorsalis* to protein baits [46, 47]. The type of protein bait also influenced the responses of *B. dorsalis* to these baits [16, 64]. Mazoferm, Torula Yeast and Provesta were found to be more attractive than the commercially available protein bait GF-120 [16, 64]. Piñero *et al*. [47] showed that the addition of ammonium acetate to GF-120 improved the responses of *B. dorsalis* females to this protein bait. The search for a better proteinaceous bait to target *B. dorsalis* females should continue.

Male annihilation technique

The male annihilation technique (MAT) involves the use of a mixture of male lure and an insecticide in order to affect high mortality of males of the target fruit fly species and subsequently suppress populations through reduced matings [67]. *Bactrocera dorsalis* was successfully eradicated from Okinawa islands in 1982 using ME-based MAT alone [68]. In other successful eradication programmes for *B. dorsalis*, MAT was integrated with other techniques: either Sterile Insect Technique (SIT) or Bait Application Technique (BAT) [60, 61, 69, 70]. In Hawaii, MAT on its own was found to reduce adult catches of *B. dorsalis* in papaya, *Carica papaya* L., orchards by almost 50% and infestation of papaya by 44% compared to a nearby untreated plot [71]. The authors further proposed that the treatment of a wider area would have possibly led to even lower adult numbers and infestation rates in the treated plots [71]. In models determining the effects of MAT on fruit fly populations, the use of ME-based MAT on its own for the control of *B. dorsalis* was deemed ineffective [72]. The simultaneous use of both MAT and SIT for *B. dorsalis*, on the other hand, would have higher suppressive effects particularly if sterile males are exposed to ME before releases [73]. In these models, the possibility of mating occurring before attraction to ME mixtures rendered the use of MAT as a sole suppression method ineffective, while the combination of MAT and SIT was considered synergistic [72, 73]. In area-wide fruit fly suppression programmes in Hawaii, the use of ME-based MAT in combination with other techniques including sterile insect releases reduced adult population levels of *B. dorsalis* and fruit infestation by the pest [74, 75].

There are various methods of deployment of ME and insecticide mixtures for the control of *B. dorsalis*. ME and insecticide mixtures can be deployed as thickened sprays or gels and they can also be impregnated in solid substrates such as wooden blocks or cotton wicks. Thickened sprays of ME and organophosphate mixture were found to attract and kill more *B. dorsalis* males than wooden blocks impregnated with a ME and organophosphate mixture in the first 2 weeks after application [76]. However, saturated wooden blocks of ME and insecticide had longer residual activity than thickened formulations containing ME and insecticide [77]. In California, Min-U-Gel (a thickener made of a fine grade of attapulgite clay) containing ME and an organophosphate has been successfully used for the eradication of *B. dorsalis* [78]. Min-U-Gel, similar to previously tested thickened ME sprays, was found to be not as long lasting in the field as saturated wooden blocks with a mixture of ME and insecticide [79]. Subsequently, a formulation consisting of ME in a Specialised Pheromone and Lure Application Technology (SPLAT) matrix and the reduced risk insecticide spinosad was shown to be promising as an attract and kill method for *B. dorsalis* males, outperforming ME-based Min-U-Gel in terms of field longevity and attractiveness [80, 81]. The ME and spinosad-based SPLAT was also found to be as toxic as the ME-based Min-U-Gel after 24 h of exposure [81].

Various densities of MAT products have been used for the eradication or suppression of *B. dorsalis* in different parts of the world. Densities of solid substrates (wooden blocks or cotton wicks) saturated with ME and a toxicant used for the eradication or suppression of *B. dorsalis* varied between 100 and 1700 blocks per km^2 with varying amounts of lure per substrate [82–85]. In South Africa, the STATIC SPINOSAD ME which consists of the SPLAT matrix with ME and spinosad is registered at 248–500 ml per ha or at 40–138 application sites per ha. In a study evaluating different MAT products for the control of *B. dorsalis* in South Africa, Manrakhan *et al.* [86] found no differences in population levels of *B. dorsalis* in areas treated with different MAT products and even in areas with different densities of ME-based MAT blocks. In Hawaii, Vargas *et al.* [87] compared two application rates of the STATIC SPINOSAD ME: 10 stations per ha versus 50 stations per ha and found the higher application rate of 50 stations per ha was more effective in suppressing *B. dorsalis*. However, more recently, Manoukis *et al.* [88, 89] demonstrated in mark–release–recapture experiments, that a lower density MAT was more effective in reducing survivorship of both females and males of *B. dorsalis*. Manoukis *et al.* [89] hypothesized that interference might be the mechanism behind reduced effectiveness of higher MAT densities for the control of *B. dorsalis*. Since different MAT products have different amounts of ME, it is important to establish the optimal density of each MAT product required for effective control of the pest.

The resistance of *B. dorsalis* populations to ME-based MAT products has been highlighted as a potential problem with the extensive use of MAT in the field. Although there is no field evidence for this, potential selection of non-responsiveness to ME in *B. dorsalis* has been demonstrated in laboratory studies [90]. ME-based MAT might also impact on non-target insect species. Two separate studies: one in Hawaii [91] and one in a number of countries in South Asia [92] reported captures of lacewings in ME-baited traps. In Hawaii, traps containing ME also inadvertently captured honey bees [93]. The attraction of honey bees to ME was demonstrated in a subsequent study by Leblanc *et al.* [94] in Hawaii with traps set out in various environments, although numbers captured were very low. The potential non-target impact of ME-based MAT should be evaluated in all regions of the world where this technique is employed for the suppression of *B. dorsalis* in order to properly determine its impact on the local insect fauna.

The use of ME-based MAT for the suppression or eradication of *B. dorsalis* in a country is subject to ME being registered for that specific purpose. In Europe and North America, ME has been regarded as being genotoxic and carcinogenic [95, 96]. At low doses of ME in foods such as those in spices and flavouring substances, ME is however considered safe for humans [97]. If ME-based MAT cannot be registered for the control of *B. dorsalis* in a region or a country where the pest is not present, the prospects for the eradication of the pest in case of an incursion could be dire. Fluorinated analogues of ME were previously synthesized in an attempt to stabilize the compound and prevent metabolic activation that would form carcinogens [98, 99]. Whilst one of the fluorinated ME analogues (one with fluorine incorporated in the side chain of the benzene ring: 4-[(2E)-3-fluoroprop-2-en-1-yl]-1,2-dimethoxybenzene abbreviated as FME) compared well with ME in terms of field attractiveness to *B. dorsalis*, other fluorinated analogues were found to be less attractive to *B. dorsalis* in the field [100, 101]. Where ME-based MAT registration is problematic, the use of FME in MAT can be explored.

Sanitation

For some commercial fruit like mango and papaya, infestation by *B. dorsalis* was found to be higher in fruit on the ground than in fruit on the tree [102, 103]. Orchard sanitation should therefore play an important role in limiting the population of this pest [102, 103]. Very few studies have however quantified the impact of orchard sanitation alone on populations of *B. dorsalis*. Liquido [104] found significantly lower fruit infestation by *B. dorsalis* in papaya orchards with sanitation than in orchards with no sanitation. Piñero *et al.* [66] also showed that the catches of *B. dorsalis* females were lower in papaya orchards with good sanitation compared to those with bad sanitation. The authors found that the addition of bait sprays reduced the correlation of female catches and level of orchard sanitation, implying that bait sprays were more important in further reducing female catches. In mango orchards in India, Verghese *et al.* [105] also showed that weekly removal of fruit in combination with regular ploughing and raking of soil for the destruction of fruit fly pupae and limited insecticidal sprays significantly reduced the infestation of mangoes.

The most effective way for the disposal of fallen fruit or fruit left over after harvest for *B. dorsalis* still remains to be quantified. The use of a tent-like structure, termed augmentorium, for trapping adult flies [106] emerging from fruit collected from the ground and after harvest has been shown to be effective for the melon fly, *Z. cucurbitaceae*. The efficacy of such a structure as an orchard sanitation practice for *B. dorsalis* should be investigated.

Biological control

Parasitoids

The first successful classical biological control programme for *B. dorsalis* was in Hawaii between the late 1940s and early 1950s and was carried out using parasitoids [107]. Among a number of fruit fly parasitoids introduced in Hawaii for fruit fly pests occurring there, three parasitoid species (Hymenoptera: Braconidae: Opiinae): *Fopius arisanus* (Sonan), *Fopius vandenboschi* (Fullaway) and *Diachasmimorpha longicaudata* (Ashmead) became successfully established and were the main ones attacking *B. dorsalis* [107, 108]. *Fopius arisanus* is an egg-pupal parasitoid. *Diachasmimorpha longicaudata* is a larval-pupa parasitoid. *Fopius vandenboschi* is an early larval parasitoid. In Hawaii, *F. arisanus* currently dominates the parasitoid guild [108]. Outside of Hawaii, in Tahiti, the releases of *F. arisanus* over a 2-year period in a classical biological control programme also successfully decreased fruit infestation by *B. dorsalis* by more than 75% on the island 4 years after the initiation of the biological control programme [109]. The parasitoid was established in all areas where it was released [109].

Indigenous parasitoids in Africa were unable to parasitize *B. dorsalis* due to its strong immune system observed in the form of egg encapsulation [110]. In the native range of *B. dorsalis* in Sri Lanka, eight parasitoid species including *F. arisanus* and *D. longicaudata* were recovered from fruit infested by *B. dorsalis* and were evaluated in laboratory tests. Parasitoids from Sri Lanka could however not be introduced into Kenya for use as biological control agents against *B. dorsalis* [110]. Instead, *F. arisanus* and *D. longicaudata* were introduced from Hawaii into Kenya [110]. *Fopius arisanus* was released in East Africa (Kenya and Tanzania), West Africa (Benin, Cameroon and Togo) and Southern Africa (Botswana, Namibia, Zambia and Zimbabwe) in order to target *B. dorsalis*. *Diachasmimorpha longicaudata* was also released in some southern African countries [110]. In Africa, *F. arisanus* was found to prefer *B. dorsalis* over indigenous *Ceratitis* species that were tested [111]. Parasitism rates of over 70% were recorded in laboratory studies for *F. arisanus* on *B. dorsalis* [111]. The establishment and spread of *F. arisanus* and its impact on *B. dorsalis* have been monitored following the releases in Benin, West Africa [112]. Field parasitism rates of up to 21% were recorded and higher parasitism rates were recorded on the indigenous bush mango, *Irvingia gabonensis* (Aubry-Lecomte ex O'Rorke) Baill compared to non-indigenous commercial fruit [112]. In Benin, *F. arisanus* was found to spread within <10 km from its point of release after about 3 years [112]. The establishment and spread of *F. arisanus* and *D. longicaudata* should continuously be monitored in various parts of Africa where the parasitoids were released. The impacts of these introduced parasitoids on fruit fly pest populations and indigenous parasitoids should be quantified.

Fungi

Research on the use of entomopathogenic fungi (EPF) for the control of *B. dorsalis* has been conducted to a large extent in Kenya at the International Centre of Insect Physiology and Ecology (icipe) [113]. In mango orchards in Kenya, soil application of a granular formulation of an isolate of *Metarhizium anisopliae* Metchnikoff Sorokin (Hypocreales: Clavicipitaceae) (Isolate icipe 20) targeting soil-borne stages of *B. dorsalis* at the onset of fruiting was found to reduce fruit infestation [114]. A combination of soil application of the granular EPF icipe 20 and protein bait sprays was more effective in reducing the catches of *B. dorsalis* and fruit infestation than either treatment used singly [114]. In a previous study on the efficacy of formulations of icipe 20 on the mortality of two *Ceratitis* species: *Ceratitis capitata* (Wiedemann) and *Ceratitis cosyra* (Walker), the granular formulation of icipe 20 was found to be more effective and more persistent in the soil than aqueous and oil/aqueous (50:50) formulations of the EPF [115]. *Metarhizium anisopliae* isolate icipe 20 was found to have no effect on the emergence of indigenous parasitoids of *Ceratitis* species in Kenya [115]. The use of EPF and parasitoids for the control of *B. dorsalis* would potentially be compatible. This however remains to be confirmed. The use of EPF in an auto-dissemination device with an attractant targeting *B. dorsalis* adults has also been investigated in Kenya [116]. Catches of *B. dorsalis* and fruit infestation were significantly reduced in mango orchards treated with traps containing ME and a *M. anisopliae* isolate: icipe 69 [116]. Further studies should however be carried out to compare the efficacy of this auto-dissemination strategy with other suppression techniques such as baiting, malathion or spinosad-based MAT and combinations thereof on *B. dorsalis*. The efficacy of EPF applied in the soil and in auto-dissemination devices will depend on various factors. In the soil, abiotic factors such as soil texture, moisture, temperature and biotic factors such as soil microbiota would affect infectivity and persistence [117]. Optimal temperatures for germination and infectivity of *M. anisopliae* isolates including icipe 20 were between 25 and 35 °C [118]. Soil temperatures lower than 20 °C could as such be problematic when EPF is used for *B. dorsalis*. Suboptimal temperatures would also influence the efficacy of EPF when used in auto-dissemination devices. Factors such as the type of attractant and horizontal transmission ability of the infected flies (via mating or aggressive encounters, e.g.) would play important roles in the efficacy of the auto-dissemination strategy [119, 120]. The mating behaviour of some fruit fly species was found to be delayed following treatment with EPF [121]. The mating rates were however unaffected following treatment of flies with EPF [121]. The effect of EPF on the mating behaviour of *B. dorsalis* is still unknown and it will be important to fill this knowledge gap before auto-dissemination of EPF is used for the control of the pest.

Nematodes

Promising isolates of entomopathogenic nematodes (EPNs) in the genus *Heterorhabditis* were found in Benin for the control of *B. dorsalis* [122]. Natural occurrence of these EPNs in mango orchards in Benin was however low [122] and as such, application of this biological control agent would have to be via artificial inoculation/augmentation in orchards. More research is required in the native and invasive range of *B. dorsalis* in order to identify effective EPN isolates and once identified, the *in vivo* and *in vitro* productions of the EPN isolates should be investigated.

Predators

The predatory weaver ant *Oecophylla longinoda* (Latreille) (Hymenoptera: Formicidae), an arboreal native ant species in Africa, was found to naturally control fruit fly infestation in mango orchards in Benin [123]. High abundance of weaver ants in mango orchards was found to reduce fruit infestation [123]. The weaver ants control *B. dorsalis* primarily by oviposition deterrence and by predation [124]. Weaver ants however reduced parasitism of *B. dorsalis* by both *F. arisanus* and *D. longicaudata* mainly by indirect predation effects (predator avoidance and reducing foraging time by parasitoids) and semiochemical-induced repellent effects [123–126]. Weaver ants and other ant species were also found to predate on soil-borne immature stages of *B. dorsalis* [127, 128]. Conservation of these natural soil-borne predators would play an important role in regulating the population of *B. dorsalis* in an area.

SIT

Control of *B. dorsalis* using sterile insect releases was initiated in the early 1960s [69, 129]. Sterilization was induced using irradiation. A white marked strain identified from a natural population in the island of Rota in the Mariana Islands was mass reared, irradiated and released to eradicate *B. dorsalis* from the Mariana Islands [69]. The strain was used for easier distinction of wild and irradiated flies. Subsequently, a translocation-based genetic sexing strain of *B. dorsalis* based on pupal colour mutants (males are brown and females are white) was developed [130] and showed promise for the control of *B. dorsalis* in pilot field tests in Thailand [131].

Transformer genes that could be targeted by RNAi to develop a male-only strain of *B. dorsalis* were recently isolated and characterized [132]. This is still a developing field and such strains are yet to be tested.

SIT targeting *B. dorsalis* in combination with other control techniques such as orchard sanitation and insecticide sprays, in particular when applied area wide, was successfully used to reduce the infestation of mangoes by this pest in Thailand between 1999 and 2000 [133, 134]. A bisexual strain of *B. dorsalis* was used in this SIT programme. In Hawaii, SIT was also integrated with other suppression techniques such as orchard sanitation, bait sprays and MAT to suppress the populations of *B. dorsalis* [74]. In continental Africa, the use of SIT against *B. dorsalis* has not yet been implemented [135]. The multitude of fruit fly species affecting commercial fruit has probably encouraged growers and national plant protection officials to opt for other suppression techniques that would not be species specific. The implementation of SIT would require production or shipment of sterile flies. Sterilization of *B. dorsalis* flies for field releases has so far been carried out by γ irradiation (using a ^{60}Co source). X-ray irradiation was found to be an alternative technology for inducing male sterility in some fruit fly species [136]. X-ray irradiators would be cheaper to transport, have fewer regulatory requirements and be more publicly acceptable than isotopic irradiators [136]. However, X-ray irradiation was found to impact on the expression of proteins, some of which are linked to pheromone signalling in males [137]. The effects of X-ray irradiation on sterility, mating competitiveness and adult life span of *B. dorsalis* should nonetheless be quantified before this type of irradiation technology is ruled out for this species. In regions where no irradiation facility exists or can be installed, methods other than irradiation for sterilization of *B. dorsalis* would possibly be favoured.

RNAi-based SIT

Tools such as RNA interference (RNAi) have been investigated for *B. dorsalis*. Li *et al.* [138] found that ingestion of dsRNA and engineered bacteria inhibited the transcript of target genes. The authors found that ingestion of dsRNA however caused the death of flies, albeit at low levels (below 40%) and reduced egg production.

The use of RNAi for sterilization of male *B. dorsalis* has recently been demonstrated [139, 140]. In greenhouse trials, releases of bacteria-fed *B. dorsalis* led to the reduction of damage in oranges [139]. The ingestion of dsRNA silenced the genes involved in spermatogenesis, impaired the quality and quantity of sperm and eventually affected fertility. Advantages with using RNAi-based SIT are that it will preclude the need for an irradiation facility and it will reduce somatic damage induced by irradiation. This field of research is still growing as researchers strive to achieve higher mortality and the production of male-only strains for releases.

Oviposition deterrents

Other suppression tools such as the use of oviposition deterrents have been explored for the control of *B. dorsalis*. However, these have not moved beyond laboratory studies. Some botanicals, for instance, have been shown to deter the oviposition of *B. dorsalis*. Extracts from seed kernels of the neem tree, *Azadirachta indica* A. Juss, (azadirachtin) were found to reduce the number of landings of *B. dorsalis* females on guava fruit and the number of eggs laid in the fruit [141]. Other plant-based oviposition deterrents identified for *B. dorsalis* are citronellal and Rhodojaponin-III [142, 143]. Whether there is a scope to explore these botanicals further depends on whether they would be subsequently allowed on commercial fruit. There are, however, commonly used agricultural products on some commercial fruit which deter oviposition for some fruit fly species and which can be tested on *B. dorsalis*. Horticultural mineral oil, used for the control of other insect pests on some fruit crops, was found to reduce the infestation of the Queensland fruit fly, *Bactrocera tryoni* (Frogatt), in mature tomato fruit, *Solanum lycopersicum* L. [144]. A kaolin-based particle used for the protection of fruit against sunburn and heat stress was found to reduce the punctures of various fruit types by *C. capitata* in laboratory studies and even reduced field infestation by the pest [145]. The development of tools such as the use of oviposition deterrents would reduce even further the risk of fruit infestation by *B. dorsalis* particularly when combined with other techniques such as biological control, baits and MAT.

Integrated and Area-Wide Management of *B. dorsalis*

An integrated approach for the management of *B. dorsalis* using monitoring and a combination of control tools is usually recommended and implemented in various regions where the pest is present [75, 146–148]. A good example of an integrated and area-wide programme for the management of *B. dorsalis* is the Hawaii Area Wide Pest Management programme (AWPM) [75] which consists of six components: population monitoring, field sanitation, protein bait, male annihilation, sterile insects and parasitoid releases. The programme was successfully demonstrated and implemented against *B. dorsalis* in papaya orchards [75]. Infestation of fully ripe papayas was shown to be threefold lower in orchards under AWPM than in untreated orchards [75]. In Africa, an integrated pest management (IPM) approach which includes at least two control components is being promoted for fruit fly pests including *B. dorsalis* [2]. The adoption of control tools within a package is, however, a function of availability and affordability. In Embu, Kenya, for instance, application of bait sprays was the least adopted component in a recommended IPM package consisting of bait sprays, MAT, sanitation and biopesticides among mango farmers due to the unavailability of protein bait spray products [149]. Orchard sanitation (in the form of burying of fallen fruit), on the other hand, was found to be the most popular component of the IPM package due to zero or minimal labour costs for the implementation of this technique [149]. Clearly, the way forward in promoting a more integrated approach would be to ensure the availability of all pest management components and to determine the cost-effectiveness of various combinations of control tools. The determination of pest populations (pest prevalence) for estimating the risk of infestation and guiding control actions should also be promoted. With *B. dorsalis* being highly polyphagous and mobile, an area-wide integrated approach [150] with monitoring and control implemented in various habitats would ultimately be more effective.

Conclusions

Since the middle of the twentieth century, monitoring and control methods have been developed for the effective management of *B. dorsalis*. There are currently a wide array of tools that can be deployed to protect the fruit from damage by this pest. Control tools exist in the form of behavioural control methods using attractants mixed with insecticides (baits and MAT), sanitation practices, biological control and SIT. There are also some novel control methods being developed such as RNAi for sterilization of *B. dorsalis*. In a number of regions where *B. dorsalis* is present, a combination of at least two control tools is being recommended and implemented. Further integration of these tools is necessary to confront the oriental fruit fly at various levels (life stages and habitats). The implementation of integrated management measures on an area-wide basis is all the more crucial for a successful battle against the oriental fruit fly.

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