Journal of Pest Science
https://doi.org/10.1007/s10340-018-1044-3

REVIEW

Palmageddon: the wasting of ornamental palms by invasive palm weevils, *Rhynchophorus* spp.

Ivan Milosavljević[1] · Hamadttu A. F. El-Shafie[2] · Jose Romeno Faleiro[3] · Christina D. Hoddle[1] · Michael Lewis[1,4] · Mark S. Hoddle[1,4]

Received: 4 January 2018 / Revised: 29 August 2018 / Accepted: 14 September 2018

Abstract
Urban areas landscaped with ornamental palms, especially Canary Islands date palms (*Phoenix canariensis*), are particularly vulnerable to incursion by invasive palm weevils, *Rhynchophorus* spp. (Coleoptera: Curculionidae). Metropolitan palmscapes are often resource rich in terms of palm species diversity and density, and these areas typically have numerous conduits (e.g., air, road, or sea transportation hubs) that assist with international and regional trade and tourism which can facilitate accidental or deliberate weevil introductions. Once established in urban areas, *Rhynchophorus* populations may be hard to suppress, from where they can expand their range and threaten agricultural commodities or native palms in wilderness areas. Here, we review current knowledge about relationships between *Rhynchophorus* invasions and urban environments. Further research areas should be addressed to improve forecasts of invasion risks and to complement management options for detection and control. We propose that greater attention be paid to quarantine restrictions on live palm movements and pro-active early detection and monitoring programs in areas deemed to be at high risk of invasion and establishment. In response to an incursion, we advocate the deployment of containment and eradication campaigns in urban zones when populations are small and highly localized.

Keywords Ornamental palms · Palm weevils · Invasive pest management · Monitoring · Biological control

Key message

- The identity and impact of *Rhynchophorus* spp. attacking palms in urban areas, which often serve as invasion bridgeheads prior to incursions into agricultural areas, are reviewed.
- Increased attention to exclusionary quarantines, incursion monitoring, and eradication to prevent establishment and spread of *Rhynchophorus* spp. is needed.
- Future management strategies could exploit new technological developments for insect surveillance, genetic modification of palm hosts, and new association biological control.

Communicated by N. Meurisse.

Special Issue on Invasive Pests of Forests and Urban Trees.

✉ Ivan Milosavljević
ivanm@ucr.edu

1 Department of Entomology, University of California Riverside, 900 University Ave., Riverside, CA 92521, USA

2 Date Palm Research Center of Excellence (DPRC), King Faisal University, B.O. 55031, Al-Ahsa 31982, Saudi Arabia

3 Salcette, Goa 403 720, India

4 Center of Invasive Species Research, University of California Riverside, 900 University Ave., Riverside, CA 92521, USA

Introduction

Palm weevils (*Rhynchophorus* spp.: Coleoptera: Curculionidae), especially the highly invasive and tremendously destructive red palm weevil, *R. ferrugineus* (Olivier), have global notoriety because they are devastating pests of palm trees (Faleiro 2006). The larva is the most damaging life stage, and heavy larval feeding in the apical meristem causes economic damage as it can cause frond disfigurement and palm death (Idris et al. 2015). Larval tunneling creates entry points for other damaging insect pests and diseases (e.g., fungal pathogens) (Downer et al. 2009; Dembilio and Jaques

2015; Kontodimas et al. 2017). Pest severity is exacerbated because feeding larvae are concealed, and this makes early detection and control difficult. Consequently, failure to detect internal infestations when they are small and damage is limited can delay the onset of remedial pesticide applications, thereby increasing the possibility that palms will be killed as feeding damage increases (Hoddle et al. 2013).

There are approximately 10 *Rhynchophorus* spp. (Wattanpongsiri 1966), and they tend to be problematic within their respective native ranges (Murphy and Briscoe 1999). *Rhynchophorus ferrugineus*, native to the Indian sub-continent (i.e., India, Sri Lanka) and parts of Southeast Asia (i.e., northern Thailand, Vietnam, Cambodia, and the northern Philippines), has demonstrated high invasion capacity and is problematic in a range of habitats that encompass agricultural settings [e.g., edible dates (*Phoenix dactylifera*) and coconut (*Cocos nucifera*)] to urban palmscapes [e.g., those dominated by Canary Islands date palms (*P. canariensis*)] (Wattanpongsiri 1966; Murphy and Briscoe 1999). This pest has successfully invaded parts of East Asia, the Middle East, Mediterranean Basin, and the Caribbean [see Fiaboe et al. (2012)] for a comprehensive list of countries and dates of first detection). In addition to *R. ferrugineus*, other *Rhynchophorus* species have invasion potential. For example, *R. palmarum* (L.), native to Mexico, Central and South America, has established in California USA (Hoddle and Hoddle 2017), and *R. vulneratus* (Panzer), native to Indonesia, was found then subsequently eradicated from California (Hoddle et al. 2016).

The economic importance of *Rhynchophorus* spp. attacking agricultural palm crops is exemplified by the adverse impacts *R. ferrugineus* has on date production (Faleiro 2006; El-Sabea et al. 2009; Giblin-Davis et al. 2013; Idris et al. 2015; Al-Dosary et al. 2016; Yasin et al. 2017). Review of this agri-centric literature is beyond the scope of this article. Instead, we discuss here the current knowledge of the biology, ecology, and management of *Rhynchophorus* spp. attacking palms in urban areas which often serve as invasion bridgeheads prior to incursions into agricultural areas. We also identify research areas that could advance our understanding of *Rhynchophorus* spp. and their management in urban landscape plantings of ornamental palms.

The biology and ecology of *Rhynchophorus* species

Biogeography of *Rhynchophorus* species

The genus *Rhynchophorus* naturally has a pan-tropical distribution (Wattanapongsiri 1966). However, three species, *R. ferrugineus*, *R. vulneratus*, and *R. palmarum* (Fig. 1), have established outside of their native ranges in distinctly non-tropical areas such as the xeric deserts of the Middle East (*R. ferrugineus*) and areas with Mediterranean climates [e.g., California (i.e., *R. palmarum* and *R. vulneratus*) and Mediterranean Europe and North Africa (i.e., *R. ferrugineus*)] (Giblin-Davis 2001; Fiaboe et al. 2012; Rugman-Jones et al. 2013; Hoddle et al., 2016; Hoddle and Hoddle 2017). International and regional trade in live palms (Idris et al. 2015), possible smuggling of live weevils (Hoddle 2015), and potentially long distance dispersal following accidental introduction into new areas (Hoddle et al. 2015; Hoddle and Hoddle 2016) has resulted in establishment and spread in countries outside of the native range.

Taxonomic identification of *Rhynchophorus* species

Most *Rhynchophorus* spp. can be identified using structural characters (Wattanpongsiri 1966; Zhang et al. 2002; Abe et al. 2009; Giblin-Davis et al. 2013). However, high levels of polymorphism, especially with respect to color (Fig. 2), have created confusion around the taxonomic identification of some species like *R. ferrugineus* and *R. vulneratus* which are native to the same general area [i.e., Southeast Asia; (Rugman-Jones et al. 2013)]. Both species are attracted to the same aggregation pheromone. Additionally, in some instances, the generally black-colored *R. palmarum* has a small percentage of the population that exhibits coloration typical of some *R. ferrugineus* and *R. vulneratus* (Löhr et al. 2015). Molecular analyses can help resolve uncertainties pertaining to species identities and for invasive species, potential area of origin (Rugman-Jones et al. 2013, 2017).

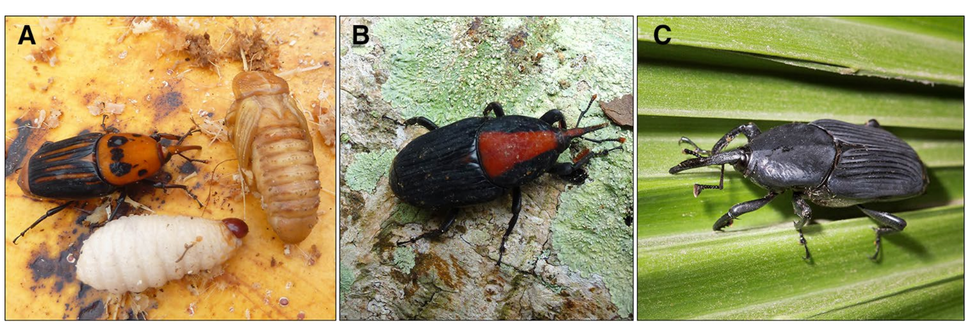

Fig. 1 Three *Rhynchophorus* species, **a** *R. ferrugineus* adult, larva, and pupa extracted from a pupal cocoon, **b** *R. vulneratus,* and **c** *R. palmarum* have exhibited significant invasion potential having successfully established breeding populations outside of their native ranges. (Color figure online)

Fig. 2 Color polymorphism of adult specimens currently classified as red palm weevil, *Rhynchophorus ferrugineus*. Genetic analyses confirm that specimens with similar color morphologies represent two species: *R. ferrugineus* and *R. vulneratus*. (Color figure online)

Host plant preferences

Rhynchophorus spp. are oligophagous and can reproduce on a diverse variety of palm species (Arecales: Arecaceae) (Wattanpongsiri 1966). For example, *R. ferrugineus, R. vulneratus,* and *R. palmarum* have been recorded reproducing on over 30, 12, and 10 arecaceous hosts, respectively (Arango and Rizo 1977; Restrepo et al. 1982; Griffith 1987; Sánchez and Cerda 1993; Giblin-Davis 1993; Murphy and Briscoe 1999; Giblin-Davis 1993, 2001; Alpizar et al. 2002; EPPO 2008). Sugar cane, *Saccharum officinarum* (Poales: Poaceae) may support larval development in the field (e.g., *R. palmarum*) (Magalhães et al. 2008; Löhr et al. 2015) and laboratory colonies (e.g., *R. ferrugineus*) (Dembilio and Jaques 2015). Adult weevils may feed but not reproduce on the fruit of non-palm hosts [e.g., *R. palmarum* on avocado fruit (*Persea americana*)] (EPPO 2008). With respect to *R. ferrugineus*, this weevil shows clear preferences for some palm species over others, and it has been shown defensive antixenotic and antibiotic mechanisms may influence host selection (Barranco et al. 2000; Dembilio et al. 2009). In the native range, *C. nucifera* are highly preferred (Faleiro 2006), and in Malaysia, *R. ferrugineus* is considered an invasive pest of coconut plantations (Azmi et al. 2013; Chong et al. 2015). In the invaded areas of Mediterranean Europe (e.g., Italy, Spain, Greece, France), North Africa (e.g., Tunisia), and parts of East Asia (e.g., Japan, China, and Taiwan), *R. ferrugineus* has exhibited a clear preference for non-native ornamental *P. canariensis* palms, whereas in the Middle East, it is a major pest of ornamental and commercial fruit-producing *P. dactylifera* (Kontodimas et al. 2006; El-Juhany 2010; Melita et al. 2017).

Life cycle and feeding behavior

All *Rhynchophorus* spp. have similar reproductive and developmental biologies and most of what is known has been described from life history studies on *R. ferrugineus* (Wattanpongsiri 1966; Jaya et al. 2000) and *R. palmarum* (Wilson 1963; Hagley 1965; Sánchez et al. 1993). Mating times are variable and females may copulate with multiple partners throughout their lifetime (Hagley 1965; Sánchez et al. 1993). Adult life span is typically a few months in duration, irrespective of sex, and the sex ratio of free-ranging populations, irrespective of weevil species, is 1:1 (male/female) (Ramachandran 1998; Hunsberger et al. 2000; Li et al. 2010). *Rhynchophorus* spp. are multivoltine and can complete multiple generations within the same palm host

(Esteban-Durán et al. 1998; Salama et al. 2002; Dembilio and Jaques 2015).

When ovipositing, female weevils chew holes into palm tissue where eggs are subsequently deposited. Females can oviposit multiple times over several weeks (Hagley 1965; Faleiro 2006). There is preference variation in oviposition sites selected by females, and this may be influenced by palm species and pre-existing damage (e.g., pruning wounds). For example, *R. ferrugineus* will lay eggs in wounds, cracks, and crevices in the palm trunk from the collar region near the roots (e.g., *P. dactylifera*), or at the base of frond petioles and axils near the crown of the palm (e.g., *P. canariensis*) (Kalshoven 1981; Abraham et al. 1998).

Under optimal conditions *Rhynchophorus* spp. are highly fecund. Females lay on average 200 and 245 eggs for *R. ferrugineus* and *R. palmarum*, respectively. Their longevity is 1–3 months (Hagley 1965; Wattanpongsiri 1966). Most eggs are fertile [> 75% hatch; (Kaakeh 2005)] and, depending on temperature, eggs hatch within 3–4 days (at 21–32 °C) (Dembilio and Jaques 2015). The number of immature stages and larval growth rate appears to be variable within and across species, and may be affected by the quality and quantity of the food source, temperature, or sex (Kaakeh 2005; Dembilio and Jacas 2012). *Rhynchophorus* spp. usually have 4–7 larval instars; however, in some instances, up to ten instars have been recorded before the pupal stage is reached (Wattanpongsiri 1966; EPPO 2005, 2008). After completing larval development, larvae pupate inside cylindrical cocoons spun from palm fibers (Fig. 3). Pupation sites are selected within the palm trunk or in concealed places such as tunnels excavated by pre-pupal larvae at the base of palm fronds. Pupation lasts approximately 3–4 weeks (Hagley 1965). It has been estimated that egg to adult emergence may take three to 4 months, mediated by the quality and quantity of the food source, sex, and the prevailing temperature (Kaakeh 2005; Idris et al. 2015; Jaya et al. 2000).

Rhynchophorus spp. larvae feed internally on soft tissue, especially meristematic tissue (i.e., palm heart), which, when severe enough, can kill the palm as it can no longer continue growing (Fig. 4) (Faleiro 2006). Larval feeding produces a wet, warm, fermenting "mash" inside the palm which has a distinctive odor. Bacterial communities have been identified within the "mash" produced at *Rhynchophorus* spp. feeding (Butera et al. 2012; Abe et al. 2010). These bacteria may support weevil larvae development by providing them with externally digested palm material. Interestingly, field observations have found no correlation between developmental and other life history parameters of *Rhynchophorus* spp. and external climatic conditions (Rahalkar et al. 1972; Avand-Faghih 1996). This may suggest that weevil development times are reasonably consistent in tropical regions where the prevailing climate is similar year round, and in invaded areas where year round climatic conditions may be more extreme [e.g., very hot summers and cold winters in date production areas of Al Ghowaybah, Saudi Arabia (Hoddle et al. 2013)]. The potential adverse effects of extreme temperatures may be moderated within the protective confines of the palm

Fig. 3 Life cycle of *Rhynchophorus palmarum.* From left to right: adult weevil, larva, cocoon, and pupa. (Color figure online)

Fig. 4 Feeding damage caused by *Rhynchophorus* spp.: **a** dropped *Phoenix canariensis* crown and **b** fronds of *P. canariensis* damaged by *R. palmarum* feeding in Tijuana, Mexico; **c** *Phoenix canariensis* in Tunis, Tunisia destroyed by *R. ferrugineus*. (Color figure online)

trunk (Dembilio and Jacas 2012), and notably in winter by the increase in temperature inside the palm associated with microbial activity at feeding sites (Giblin-Davis 2001).

Dispersal and habitat selection

Rhynchophorus spp. are strong fliers and can detect their host plants and breeding sites (i.e., palms that are already infested or weakened by other stresses) at distances over 900 m (Leefmans 1920; Griffith 1987; Weissling and Giblin-Davis 1993; Weissling et al. 1994; Abbas et al. 2006). Fermentation products (e.g., acetoin, organic acid derivatives, and ethyl esters) increase the attractiveness of infested palms to palm weevils (Guarino et al. 2011; Tagliavia et al. 2014). Flight mill studies suggest more than half of field captured *R. ferrugineus* and *R. vulneratus* can fly > 10 km per day (Hoddle et al. 2015, Hoddle and Hoddle 2016). A small percentage of *R. vulneratus* females can fly 50–80 km in 24 h (Hoddle and Hoddle 2016). The distribution of flight distances can be insightful. The flight distances of *R. vulneratus*, for example, are leptokurtic, and the heavy tails of these flight distribution data suggest heterogeneous dispersal capabilities between individuals within a population (Hoddle and Hoddle 2016). This could have significant impacts on invasion speeds and distances between incipient populations on the leading edges of the invasion wave (Hoddle and Hoddle 2016). Flight distance estimates from flight mill studies should be viewed with caution as it is unknown as to whether or not weevils undertake long distance flights in nature, especially when host palms may be abundant and in close proximity to each other. However, flight mill data can provide useful insights for comparative analyzes. For example, several factors may affect the flight propensity and distances flown by *Rhynchophorus* spp. including season (i.e., time of year), humidity and temperature, sex (i.e., males vs. females), and possibly age (Ávalos et al. 2014, 2016; Hoddle et al. 2015).

In comparison with flight mill studies, realistic assessments of flight distances may come from field trapping studies. Field observations have found adult *R. palmarum* can travel up to 1.6 km in 24 h, irrespective of sex (Griffith 1987; Sánchez et al. 1993). Mark-release-recapture studies in date plantations suggest that *R. ferrugineus* can fly at least 7 km over 3–5 days from a release point (Abbas et al. 2006). As with flight mill studies, field estimates of flight capabilities need to be viewed with caution. For example, distances from release points to points of capture probably do not accurately measure distances flown to capture points as weevil flight is seldom linear, and is very often highly circuitous and serpentine (both horizontally and vertically), even in areas devoid of foliage and competing sinks (M. Hoddle pers. obs.). Additional shortcomings with mark-recapture studies include, the limited number of traps that can be deployed, the distances over which sufficient numbers of traps can be set for recaptures [especially long distances (5–10 km) from release points], the number of marked weevils released, and inherently low recapture rates following releases (M. Hoddle pers. obs.).

Rhynchophorus spp. adults exhibit diurnal and nocturnal flight behaviors, and flight activity patterns may be species and population specific. For example, in India, Sri Lanka, and the Philippines (all part of the native range of *R. ferrugineus*) pheromone trap captures of *R. ferrugineus* adults were highest between 6 p.m. and 8 a.m. (Faleiro and Satarkar 2003; Faleiro 2006), with > 78% of weevils being caught in this time interval. Conversely, for invasive populations of *R. ferrugineus* in Saudi Arabia, Italy, and Greece, and native populations in Vietnam, and for native populations of *R palmarum* in Venezuela, flight activity either on flight mills or recorded as pheromone trap captures at field sites suggest flight activity is restricted primarily to daylight hours (Hagley 1965; Aldryhim and Al Ayedh 2015; Fanini et al. 2014).

Weevil-induced palm mortality

The threat posed to palms in the invaded regions by *R. palmarum* may be significantly greater because of its ability to vector a plant pathogenic nematode, the red ring nematode, *Bursaphelenchus* (*Rhadinaphelenchus*) *cocophilus* (Cobb 1919) (Aphelenchida: Parasitaphelenchidae), the causal agent of a lethal malady of palms known as red ring disease (Bain and Fedon 1951; Hagley 1962; Griffith 1968; Blair 1970; Oehlschlager et al. 1995; Ye et al. 2007; Magalhães et al. 2008). In the Neotropics (i.e., Central and South America, the Caribbean, and parts of southern Mexico), commercially cultivated palms and closely related landscape arecaceous plants are affected by the *R. palmarum*–*B. cocophilus* complex (Griffith and Koshy 1990). Tolerance to red ring disease is not known.

Characteristic symptoms associated with red ring disease are bronze discoloration of older leaves and premature senescence of young leaves, irreversible wilt, and premature death of palm trees (Griffith 1987; Oehlschlager et al. 2002). Once infected with *B. cocophilus*, trees may remain asymptomatic for up to 2 months making *B. cocophilus* extremely difficult to detect in the early stages of disease development (Giblin-Davis 2001). This process of attraction to nematode-infected trees and subsequent dispersal promotes the spread of nematodes which amplifies disease incidence (Giblin-Davis et al. 1996). *Bursaphelenchus cocophilus* has not been reported from Southeast Asia, India, Africa, or North America (Giblin-Davis 1993; Murphy and Briscoe 1999). *Bursaphelenchus cocophilus* is not specific to *R. palmarum,* and it can be spread by other weevil species [e.g., *Dynamis borassi* (subfamily Rhynchophorinae) and *Metamasius* *hemipterus* (subfamily Dryophthorinae)] infesting palms in the native range of *R. palmarum*. Should *B. cocophilus* become sympatric with other *Rhynchophorus* spp., it could possibly be transmitted by them (Gerber and Giblin-Davis 1990a, b; Gerber et al. 1990; Giblin-Davis 1991, 1993; Mora et al. 1994). In addition to acting as vectors of plant pathogens, *Rhynchophorus* spp. can indirectly damage palms by creating feeding wounds that facilitate entry by pathogens (Gerber and Giblin-Davis 1990a, b; Giblin-Davis 2001; Esparza-Díaz et al. 2013).

The economic impact of *Rhynchophorus* invasions

Rhynchophorus spp. are a significant threat to ornamental palm producers. California's ornamental palm industry, for example, contributes over $70 million to the regional economy each year, and potential economic damage in California from *R. palmarum* is predicted to be substantial (Hoddle and Hoddle 2017). Weevil-induced palm mortality can be measured in costs to property owners and communities (Löhr 2013; Löhr et al. 2015). These costs include expenses for removal of dead palms, lowered property values, degradation of recreational areas and urban wildlife habitat, and potentially, expenses prophylactic pesticide applications to protect palms from weevils. In the USA, the replacement cost of a 10–20-m tree has been estimated to be $1600–3200 (US) per tree (Blombery and Rodd 1983), which may be increased further depending on site access. Large mature *P. canariensis* (> 1 m in diameter, > 50 years) are generally preferred by *Rhynchophorus* spp. (M. Hoddle and I. Milosavljević, pers. obs.) and should be considered a priority for protection, especially if these palms have significant heritage and economic value (see Fig. 4).

Rhynchophorus ferrugineus and *R. vulneratus* are key pests in coconut producing regions of Southeast Asia. In this area, *C. nucifera* dominates the rural, periurban, and urban landscape and cultivation makes significant contributions to the local economy (Markrose 2008; FAOstat 2016). Coconut is extensively used for food and drink, in religious ceremonies, it provides health products, and the trunk and fronds are used as timber and thatch. Detailed economic data on the impact of these weevils on *C. nucifera* in urban areas are not available. In India, the removal costs for avenue *C. nucifera* have been estimated to be $80–100 (US) per tree (J.R. Faleiro pers. obs.). *Phoenix dactylifera* is the preferred landscaping palm species in North Africa and the Arabian Peninsula (Al-Mana and Ahmad 2010; Al-Yahyai and Khan 2015). Ornamental *P. dactylifera* vulnerable to attack by *R. ferrugineus* are also planted extensively in Southern Europe and the USA (e.g., Arizona, California, Nevada, and Florida) (Chao and Krueger 2007). This species is commonly planted around schools, shopping malls, restaurants, public parks, and median strips of streets and highways (Sayan 2001). Ornamental *P. dactylifera* are multi-purpose providing landscape beautification, shade, and small-scale commercial fruit production for local consumption (Howard and Giblin-Davis 2008; Uddin et al. 2009; Al-Yahyai and Khan 2015).

Management: current practices and future needs

Management of introduction pathways

Pathway risk assessments have been conducted to identify potential routes of movement and areas with suitable climates for weevil establishment, population growth, and spread (Ju et al. 2008; Feng and Liu 2010; Fiaboe et al. 2012; Ge et al. 2015). Transport hubs (e.g., airports or container ports) often act as key points of entry for exotic pests (Giblin-Davis et al. 2013; Milosavljević et al. 2017). For example, weevils may be moved as hitch hikers in shipping containers (Hulme 2009; Meurisse et al. 2018) or concealed in live palms, especially *C. nucifera*, *P. dactylifera*, and *P. canariensis* (Faleiro 2006). Transport of infested palms has resulted in *Rhynchophorus* spp. moving long distances into new countries or new regions within infested countries (Fig. 5) (Al-Dosary et al. 2016).

To manage this invasion pathway, the US Department of Agriculture (USDA) has proactively developed guidelines for managing incursions of *R. ferrugineus* in advance of detection in the USA (Bertone et al. 2010). Notably, importations of live palms into the USA are banned, including all *Phoenix* spp. with the specific goal of preventing accidental

Fig. 5 *Rhynchophorus* spp. can be inadvertently moved long distances when humans transport live palms (e.g., *Phoenix dactylifera*) infested with weevils. (Color figure online)

introductions of *Rhynchophorus* spp. and *B. cocophilus* (USDA-APHIS 2010a, b). Strict border security practices to exclude *Rhynchophorus* spp. are justifiable based on estimates of economic and environmental damage which will result should successful establishment and spread occur (Dembilio and Jaques 2015).

Another potential introduction pathway is the deliberate smuggling of *Rhynchophorus* spp. into a new area in an attempt to establish populations that could be harvested for human consumption. This hypothesis has been proposed for the introduction of *R. vulneratus* in Southern California, possibly from Indonesia where they are either harvested from the wild or commercially farmed (Hoddle 2015). *Rhynchophorus* larvae and pupae are a delicacy in a number of other tropical countries in Africa, Asia, and South America (DeFoliart 1993,1999; Cerda et al. 2001; Choo et al. 2009).

Early detection and monitoring

Rhynchophorus-infested palm trees are usually detected by observing conspicuous symptoms such as tunnels on the trunk and at the bases of fronds, oozing of brown liquid, frass, and fermenting odors. Visual detection of infestations is not always cost-effective (Soroker et al. 2013), and this approach may be limited to detecting small populations. Traps loaded with commercially available sex pheromones and fermenting bait are now commonly used for early detection and monitoring of adult weevils (Hallett et al. 1993; Jaffé et al. 1993; Weissling and Giblin-Davis 1993; Weissling et al. 1994; Perez et al. 1994, 1996; Giblin-Davis et al. 1994, 1996; Hallett et al. 2004; Giblin-Davis et al. 2013; Vacas et al. 2013, 2014). Interestingly, there appears to be no significant repellency or inhibition when lures for different species are used in combination (USDA-APHIS 2014). This is beneficial as traps used in California for incursion monitoring of *R. palmarum* can also incorporate a lure to enable early detection of *R. ferrugineus*.

Monitoring of dispersing adult weevils may benefit from changes in trapping methods such as the use of "smart" (i.e., traps that wirelessly relay weevil catch data in near real time to a smart device or office computer via the cloud) and "dry" traps (i.e., traps that lack fermenting bait and preservative which significantly reduces setup and maintenance costs) (Potamitis and Rigakis 2015; Potamitis et al. 2017; Al-Saroj et al. 2017). Detection of weevil feeding activity could be based on the detection of the chemical volatiles associated with infested plants by trained dogs (Nakash et al. 2000; Potamitis et al. 2009; Suma et al. 2014). Mechanical volatile-based detection may also have potential for early detection if organic compounds released in response to weevil infestations have unique chemical signatures that can be cheaply detected and identified by field-deployed devices (Choi and Verpoorte 2014). Equipment that identifies acoustic signatures unique to feeding palm weevils has been developed and field tested (Mankin et al. 2016; Potamitis et al. 2009; Poland and Rassati 2018).

With respect to early detection and monitoring, ground access remains a logistical challenge. For instance, native and weedy plants may form impenetrable thickets to palms for visual inspection of weevil infestations in wilderness areas. Low-cost drones outfitted with high-resolution cameras can be programmed to fly specific routes over areas needing investigation, and photographic aerial surveillance is a powerful and cheap way to digitally record palm health over large areas. Sequential photo-surveillance permits quantification of mortality rates and patterns of spread (Cohen et al. 2012; Hogan et al. 2017) (Figs. 6, 7).

Insecticides, cultural control, and emerging methods for population suppression

Insecticide applications are, at present, the most effective method for protecting palms from attack by palm weevils. Effective chemistries are varied. Organophosphates, carbamates, neonicotinoids, and phenylpyrazoles, for instance, can be sprayed onto foliage, used as crown or soil drenches, or injected into trunks or soil at the base of the trunk. Specimens with high historical, cultural, or ornamental significance, can be outfitted with irrigation piping that is attached to the trunk and used to periodically deliver prophylactic pesticide applications into the crown of the palm (Hodel et al. 2016). An alternative strategy for using pesticides that could be used in a highly targeted manner while simultaneously reducing environmental exposure is "attract-and-kill" (El-Shafie et al. 2011; Mafra-Neto et al. 2013). The "attract-and-kill" technique has high levels of utility in urban

Fig. 6 Periurban wilderness areas drive *Rhynchophorus palmarum* invasions in urban Southern California. *Phoenix canariensis* infested with *R. palmarum* (red arrows) are the source of weevils migrating into surrounding urban areas. (Color figure online)

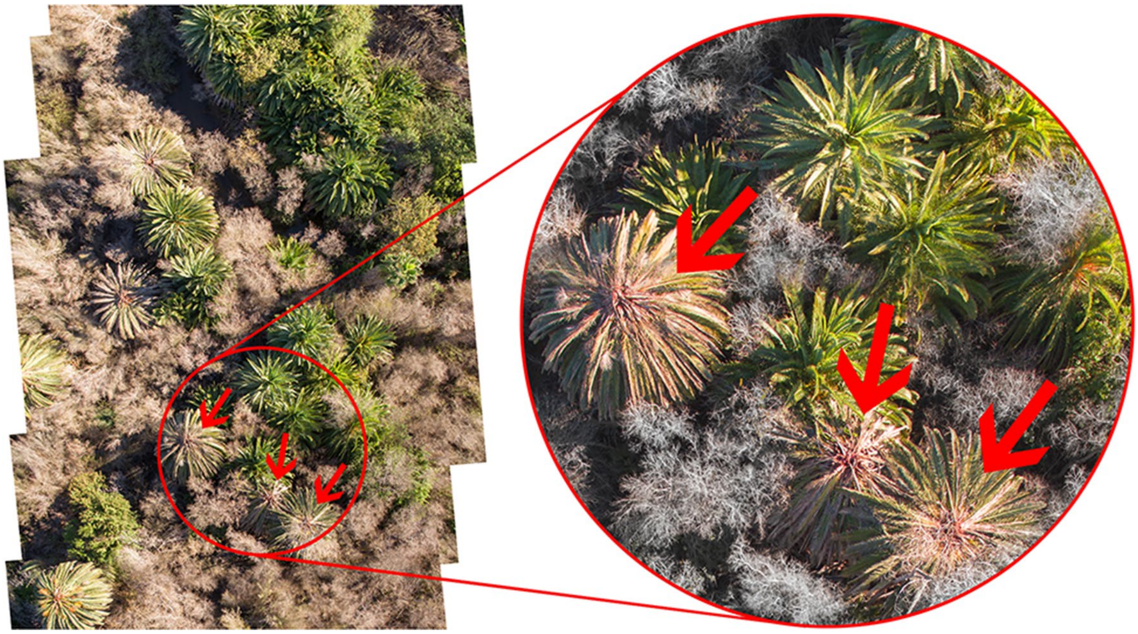

Fig. 7 Low-cost drones outfitted with high-resolution cameras can be programmed to fly specific routes over wilderness areas needing surveillance for palm weevil activity (red arrows). (Color figure online)

settings for *Rhynchophorus* spp., as pheromone and pesticide are combined in an inert matrix and applied to lamp posts, power poles, fences, and sides of buildings within and around areas of concern. This approach may reduce the need for high-volume pesticide applications over large areas, but is still in development. When used together, attract-and-kill and repellants could be used in "push–pull" management programs for *Rhynchophorus* spp. which may greatly lower insecticide use for managing palm weevils in urban areas (Guarino et al. 2013; Dembilio and Jaques 2015).

Cultural control practices that can be used for managing palm weevils in urban areas include the rapid removal (i.e., felling) and destruction (i.e., grinding infested parts of trunks and chipping fronds, or burial) of infested material (Dembilio and Jaques 2015). With respect to the removal of infested *P. canariensis*, removal costs could be reduced by removing just the infected top of the palm [i.e., the crown and small section of undamaged trunk immediately below the crown and all fronds (see Fig. 4c)], and spraying with contact insecticides the cut face of the remaining section to kill weevils attracted to it.

Diversification of the number of palm species used in urban plantings is another strategy for mitigating damage from *Rhynchophorus* spp. invasions. *Phoenix canariensis*, which are often extensively planted in urban areas, are extremely vulnerable to attack. Replacement of weevil-killed palms or planting of new palmscapes in urban areas with species of palms that are much less preferred than *P. canariensis* but exhibit similar aesthetics and environmental tolerances should be considered. Other factors such as palm age [e.g., *P. dactylifera* < 20 yrs of age) are more vulnerable to attack by *R. ferrugineus* than older palms. Therefore, younger palms need greater management to reduce mortality from weevil attacks (Shar et al. 2012)]. Two environmental factors which affect weevil survivorship are humidity and soil temperature (Sallam et al. 2012). Optimization of spacing between palms to reduce humidity and increase insolation of soilcan reduce infestation severity (Sallam et al. 2012; Al-Dosary et al. 2016). Novel methods for controlling *Rhynchophorus* spp. include sterile insect technique, gene silencing, and palm genome editing (Rahalkar et al. 1977; Krishnakumar and Maheshwari 2004; Niblett and Bailey 2012; Mazza et al. 2016; Sattar et al. 2017).

Biological control

Various fungi, viruses, bacteria, and nematodes have been identified as pathogenic to *Rhynchophorus* eggs, larvae, pupae, or adults (see Mazza et al. 2014 for more details). Isolates of the entomopathogenic fungus, *Beauveria bassiana*, have been tested in the field and can kill larvae and adult *R. ferrugineus* (Sewify et al. 2009; El-Sufty et al. 2009; Dembilio et al. 2010a; Güerri-Agulló et al. 2010; Llácer et al. 2013) with adult populations suffering ~ 90% mortality. Entomopathogenic nematodes (i.e., *Steinernema carpocapsae* and *Heterorhabditis bacteriophora*), exhibit pathogenicity under laboratory conditions toward *R. ferrugineus* larvae, pupae, and adults (Abbas et al. 2001; Atakan et al. 2009;

Saleh et al. 2011; Triggiani and Tarasco 2011; Manachini et al. 2013). Field trials performed so far have showed limited efficacy (Mazza et al. 2014), but these can be enhanced with co-applications of systemic neonicotinoid pesticides (e.g., imidacloprid) (Dembilio et al. 2010b).

Classical biological control, the deliberate introduction of natural enemies from the native range of invasive *Rhynchophorus* spp., into the invaded area has to our knowledge never been attempted. A promising candidate group of parasitoids are the tachinid flies, *Paratheresia menezesi* and *Billaea rhynchophorae*, which attack *R. palmarum* larvae in Brazil (Moura et al. 1993, 2006). In natural conditions, these two species also attack larvae of other large species of palm weevils [e.g., *Rhinostomus barbirostris* (subfamily Dryophthorinae)] that are sympatric with *R. palmarum* (Guimarães 1977). Additional knowledge on their reproductive, developmental and behavioral biology would be required to fully understand their host specificity and potential utility for classical biological control (Löhr et al. 2015) or new association biological control (Hokkanen and Pimentel 1984) targeting *Rhynchophorus* spp. Other studies report that sarcophagid flies, *Sarcophaga fuscicauda*, scoliid wasps, *Scolia errattica*, and the predatory histerid beetle, *Oxysternus maximus*, may have potential to suppress invasive *Rhynchophorus* populations (Iyer 1940; Wattanpongsiri 1966; Löhr 2013).

Eradication

Rhynchophorus ferrugineus has been successfully eradicated from the Canary Islands (and potentially Mauritania), and *R. vulneratus* from Southern California, respectively (FAO 2017a, b; Hoddle et al. 2016). The critical first step in an eradication program is a rapid response when populations are small and localized. For example, *R. vulneratus* was eradicated from a small (23 square km area) and relatively isolated residential (23,250 inhabitants) area of Laguna Beach (California, the USA) at a cost of ~ $1 million (US) (Hoddle et al. 2016).

Sustained public (i.e., access to infested palms on private land) and institutional support (i.e., funding) are critical elements of a successful eradication program (Hoddle et al. 2016), as the available levels of expertise, technical resources, funding and societal support determine effective management options. Control programs do not necessarily have to eliminate all individual weevils, but rather a reduction of the local populations to levels at which stochastic factors, such as inclement weather will make them vulnerable to extinction [i.e., exploiting the Allee effect (Liebhold and Tobin 2008; Suckling et al. 2012)].

Eradication programs are expensive (see, e.g., Hoddle et al. 2016 for economic details on the eradication of *R. vulneratus* in California) and require several consecutive years of monitoring, pesticide treatments, and trapping. Following eradication attempts, monitoring may be required for an additional consecutive 3 years to conclusively demonstrate long-term program outcomes in accordance with internationally set standards.

Conclusions

Palm weevil infestations affect the aesthetics of infested urban palmscapes and uncontrolled urban populations threaten agricultural (e.g., date plantations) and natural areas (e.g., palm oases). Accidental introduction of *Rhynchophorus* spp. into new areas has resulted in establishment and spread of these notorious palm pests in distinctly non-native habitats. Initial incursion detections are often in urban areas where weevils preferentially infest *P. canariensis* which is extremely vulnerable to attack and an excellent developmental host. Urban areas provide challenges for managing weevil infestations as infested palms are often on private land which may complicate control programs. Inappropriate management planning, poor coordination between stakeholders, and public resistance to implementation of controls can adversely affect incursion management programs. Despite these difficulties, urban infestations can be dealt with effectively. Eradication is possible and success is largely predicated on strong long-term (i.e., > 3 years) public and institutional support of the management program (Hoddle et al. 2016). Failure to rapidly curb initial weevil establishment results in increasing size of area infested and rapid population growth, which jeopardize the success of eradication and containment programs.

Author contributions

IM and MSH organized and wrote the review. HAFE and JRF contributed in the "The economic impact of invasions" section. CDH and ML provided materials on weevil flight and use of drones, respectively. All authors reviewed, provided constructive comments, and approved the manuscript.

Acknowledgements This publication was supported by the US Department of Agriculture's (USDA) Agricultural Marketing Service through Grant 17-0275-044-SC. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the USDA.

Funding This publication was supported by the US Department of Agriculture's (USDA) Agricultural Marketing Service through Grant 17-0275-044-SC. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the USDA.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

References

Abbas MST, Saleh MME, Akil AM (2001) Laboratory and field evaluation of the pathogenicity of entomopathogenic nematodes to the red palm weevil, *Rhynchophorus ferrugineus* (Oliv.) (Col.: Curculionidae). J Pest Sci 74:167–168

Abbas MST, Hanounik SB, Shahdad AS, Ai-Bagham SA (2006) Aggregation pheromone traps, a major component of IPM strategy for the red palm weevil, *Rhynchophorus ferrugineus* in date palms (Coleoptera: Curculionidae). J Pest Sci 79:69–73

Abe F, Hata K, Sone K (2009) Life history of the red palm weevil, *Rhynchophorus ferrugineus* (Coleoptera: Dryophtoridae), in Southern Japan. Fla Entomol 92:421–425

Abe F, Ohkusu M, Kubo T, Kawamoto S, Sone K, Hata K (2010) Isolation of yeasts from palm tissues damaged by the red palm weevil and their possible effect on the weevil overwintering. Mycoscience 51:215–223

Abraham VA, Al Shuaibi MA, Faleiro JR, Abozuhairah RA, Vidyasagar PSPV (1998) An integrated management approach for red palm weevil, *Rhynchophorus ferrugineus* Oliv., a key pest of date palm in the Middle East. J Agric Mar Sci 3:77–84

Al-Dosary NMN, Al-Dobai S, Faleiro JR (2016) Review on the management of red palm weevil *Rhynchophorus ferrugineus* Olivier in date palm *Phoenix dactylifera* L. Emir J Food Agric 28:34

Aldryhim YN, Al Ayedh HY (2015) Diel flight activity patterns of the red palm weevil (Coleoptera: Curculionidae) as monitored by smart traps. Fla Entomol 98:1019–1024

Al-Mana FA, Ahmad YA (2010) Case study on the trunk's deformity of date palm trees used in street landscape in Riyadh, Saudi Arabia. Am-Euras J Agric Environ Sci 8:67–72

Alpizar D, Fallas M, Oehlschlager AC, Gonzalez LM, Chinchilla CM, Bulgarelli J (2002) Pheromone mass trapping of the west Indian sugarcane weevil and the American palm weevil (Coleoptera: Curculionidae) in palmito palm. Fla Entomol 85:426–430

Al-Saroj S, Al-Abdallah E, Al-Shawaf AM, Al-Dandan AM, Al-Abdullah I, Al-Shagag A, Al-Fehaid Y, Abdallah AB, Faleiro JR (2017) Efficacy of bait free pheromone trap (Electrap™) for management of red palm weevil, *Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Curculionidae). Pest Manag Hort Ecosyst 23:55–59

Al-Yahyai R, Khan MM (2015) Date palm status and perspective in Oman. In: Al-Khayri JM, Jain SM, Johnson DV (eds) Date palm genetic resources and utilization, vol 2. Asia and Europe. Springer, Dordrecht, pp 207–240

Arango G, Rizo D (1977) Some considerations on the behaviour of *Rhynchophorus palmarum* and *Metamasius hemipterus* on sugarcane. Rev Colomb Entomol 3:23–28

Atakan E, Elekçioğlu H, Gözel U, Günes Ç, Yüksel O (2009) First report of *Heterorhabditis bacteriophora* (Poinar, 1975) (Nematoda: Heterorhabditidae) isolated from the red palm weevil, *Rhyncophorus ferrugineus* (Oliver, 1970) (Coleoptera: Curculionidae) in Turkey. Bull OEPP 39:189–193

Ávalos JA, Martí-Campoy A, Soto A (2014) Study of the flying ability of *Rhynchophorus ferrugineus* (Coleoptera: Dryophthoridae) adults using a computer-monitored flight mill. Bull Entomol Res 104:462–470

Ávalos JA, Balasch S, Soto A (2016) Flight behaviour and dispersal of *Rhynchophorus ferrugineus* (Coleoptera: Dryophthoridae) adults using mark-release-recapture method. Bull Entomol Res 106:606–614

Avand-Faghih A (1996) The biology of red palm weevil, *Rhynchophorus ferrugineus* Oliv. (Coleoptera: Curculionidae) in Saravan region (Sistan and Balouchistan Province, Iran). Appl Entomol Phytopathol 63:16–18

Azmi WA, Chik Z, Razak ARA, Ghani NIA (2013) A new invasive coconut pest in Malaysia: the red palm weevil (Curculionidae: *Rhynchophorus ferrugineus*). Planter 89:97–110

Bain F, Fedon C (1951) Investigations on red ring of coconut. Agron Trop 1:103–130

Barranco P, de la Peña JA, Martín MM, Cabello T (2000) Host rank for *Rhynchophorus ferrugineus* (Olivier, 1790) (Coleoptera: Curculionidae) and host diameter. Bol Sanid Veg Plagas 26:73–78

Bertone C, Defeo V, Michalak PS, Roda A (2010) USDA new pest response guidelines: Red palm weevil *Rhynchophorus ferrugineus*. Animal & Plant Health Inspection Service, USDA, p 131. https://pestlens.info/. Accessed 5 Aug 2018

Blair G (1970) Studies on red ring disease of coconut palm. Oléagineux 25:19–22

Blombery A, Rodd T (1983) An informative, practical guide to palms of the world: their cultivation, care and landscape use. Angus and Robertson Ltd., London

Butera G, Ferraro C, Colazza S, Alonzo G, Quatrini P (2012) The culturable bacterial community of frass produced by larvae of *Rhynchophorus ferrugineus* Olivier (Coleoptera: Curculionidae) in the Canary island date palm. Lett Appl Microbiol 54:530–536

Cerda H, Martinez R, Briceno N, Pizzoferrato L, Manzi P, Ponzetta MT, Marin O, Paoletti MG (2001) Palm worm: (*Rhynchophorus palmarum*) traditional food in Amazonas, Venezuela-nutritional composition, small scale production and tourist palatability. Ecol Food Nutr 40:13–32

Chao CC, Krueger RR (2007) The date palm (*Phoenix dactylifera* L.): overview of biology, uses, and cultivation. HortScience 45:1077–1082

Choi YH, Verpoorte R (2014) Metabolomics: what you see is what you extract. Phytochem Anal 25:289–290

Chong JL, H'ng TM, Azmi WA, Amansuria NH (2015) Genetic variation and invasion history of the invasive red palm weevil (*Rhynchophorus ferrugineus* [Olivier]) in Terengganu. Int J Agric For Plant 1:34–42

Choo J, Zent EL, Simpson BB (2009) The importance of traditional ecological knowledge for palm weevil cultivation in the Venezuelan Amazon. J Ethnobiol 29:113–128

Cohen Y, Alchanatis V, Prigojin A, Levi A, Soroker V, Cohen Y (2012) Use of aerial thermal imaging to estimate water status of palm trees. Precis Agric 13:123–140

DeFoliart GR (1993) Hypothesizing about palm weevil and palm rhinoceros beetle larvae as traditional cuisine, tropical waste recycling, and pest and disease control on coconut and other palms: can they be integrated? Principes 37:42–47

DeFoliart GR (1999) Insects as food: why the Western attitude is important. Annu Rev Entomol 44:21–50

Dembilio Ó, Jacas JA (2012) Bio-ecology and integrated management of the red palm weevil, *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae), in the region of Valencia (Spain). Hell Plant Prot J 5:1–12

Dembilio Ó, Jaques JA (2015) Biology and management of Red palm weevil. In: Wakil W, Faleiro JR, Miller TA (eds) Sustainable pest management in date palm: current status and emerging challenges. Springer, Basel, pp 13–36

Dembilio Ó, Jacas JA, Llácer E (2009) Are the palms *Washingtonia filifera* and *Chamaerops humilis* suitable hosts for the red palm weevil, *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae)? J Appl Entomol 133:565–567

Dembilio Ó, Quesada-Moraga E, SantiagoÁlvarez C, Jacas JA (2010a) Potential of an indigenous strain of the entomopathogenic fungus *Beauveria bassiana* as a biological control agent against the red palm weevil, *Rhynchophorus ferrugineus*. J Invertebr Pathol 104:214–221

Dembilio Ó, Llácer E, Martínez de Altube MDM, Jacas JA (2010b) Field efficacy of imidacloprid and *Steinernema carpocapsae* in a chitosan formulation against the red palm weevil *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae) in *Phoenix canariensis*. Pest Manag Sci 66:365–370

Downer AJ, Uchida JY, Hodel DR, Elliott ML (2009) Lethal palm diseases common in the United States. Horttechnology 19:710–716

El-Juhany LI (2010) Degradation of date palm trees and date production in Arab countries: causes and potential rehabilitation. Aust J Basic Appl Sci 4:3998–4010

El-Sabea AMR, Faleiro JR, Abo El Saad MM (2009) The threat of red palm weevil *Rhynchophorus ferrugineus* to date plantations of the Gulf region of the Middle East: an economic perspective. Outlook Pest Manag 20:131–134

El-Shafie HAF, Faleiro JR, Al-Abbad AH, Stoltman L, Mafra-Neto A (2011) Bait-free attract and kill technology (Hook™ RPW) to suppress red palm weevil, *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae) in date palm. Fla Entomol 94:774–778

El-Sufty R, Al-Awash SA, Al Bgham S, Shahdad AS, Al Bathra AH (2009) Pathogenicity of the fungus *Beauveria bassiana* (Bals.) Vuill to the red palm weevil, *Rhynchophorus ferrugineus* (Oliv.) (Col.: Curculionidae) under laboratory and field conditions. Egypt J Biol Pest Control 19:81–85

Esparza-Díaz G, Olguin A, Carta LK, Skantar AM, Villanueva RT (2013) Detection of *Rhynchophorus palmarum* (Coleoptera: Curculionidae) and identification of associated nematodes in South Texas. Fla Entomol 96:1513–1521

Esteban-Durán J, Yela JL, Beitia-Crespo F, Jiménez-Álvarez A (1998) Biología del curculiónido ferruginoso de las palmeras *Rhynchophorus ferrugineus* (Olivier) en laboratorio y campo: Ciclo en cautividad, peculiaridades biológicas en su zona de introducciónen España y métodos biológicos de detección y posible control (Coleoptera: Curculionidae: Rhynchophorinae). Bol Sanid Veg Plagas 24:737–748

European and Mediterranean Plant Protection Organization (EPPO) (2005) Data sheets on quarantine pests: *Rhynchophorus palmarum*. OEPP Bull 35:468–471

European and Mediterranean Plant Protection Organization (EPPO) (2008) Data sheets on quarantine pests: *Rhynchophorus ferrugineus*. OEPP Bull 38:55–59

Faleiro JR (2006) A review on the issues and management of red palm weevil *Rhynchophorus ferrugineus* (Coleoptera: Rhynchophoridae) in coconut and date palm during the last one hundred years. Int J Trop Insect Sci 26:135–154

Faleiro JR, Satarkar VR (2003) Diurnal activity of red palm weevil *Rhynchophorus ferrugineus* (Olivier) in coconut plantation. Insect Environ 9:63–64

Fanini L, Longo S, Cervo R, Roversi PF, Mazza G (2014) Daily activity and non-random occurrence of captures in the Asian palm weevils. Ethol Ecol Evol 26:195–203

FAOstat (2016) FAO statistical databases. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/faostat/en/#home. Accessed 5 Aug 2018

Feng Y, Liu H (2010) Potential suitability analysis of *Rhychophorus ferrugineus* (Olvier) in China based on Maxtent and GIS. J Huazhong Agric Univ 29:552–556

Fiaboe KKM, Peterson AT, Kairo MTK, Roda AL (2012) Predicting the potential worldwide distribution of the red palm weevil *Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Curculionidae) using ecological niche modeling. Fla Entomol 95:659–673

Food and Agriculture Organization of the United Nations (FAO) (2017a) Current situation of Red palm weevil in the NENA region: current situation of management practices, challenges/weaknesses and available research and technologies for its improvement. Scientific Consultation and High-Level Meeting on Red Palm Weevil Management, Rome. http://www.fao.org/3/a-ms664e.pdf. Accessed 5 Aug 2018

Food and Agriculture Organization of the United Nations (FAO) (2017b) Innovative participatory approach to control Red palm weevil on date palms in Mauritania. Food Chain Crisis, Emergency Prevention System Information Sheets. http://www.fao.org/3/I8323EN/i8323en.pdf. Accessed 5 Aug 2018

Ge X, He S, Wang T, Yan W, Zong S (2015) Potential distribution predicted for *Rhynchophorus ferrugineus* in China under different climate warming scenarios. PloS One 10:e0141111. https://doi.org/10.1371/journal.pone.0141111

Gerber K, Giblin-Davis RM (1990a) Association of the red ring nematode, *Rhadinaphelenchus cocophilus*, and other nematode species with *Rhynchophorus palmarum* (Coleoptera: Curculionidae). J Nematol 22:143–149

Gerber K, Giblin-Davis RM (1990b) *Teratorhabditis palmarum* n. sp. (Nemata: Rhabditidae), an associate of *Rhynchophorus palmarum* and *R. cruentatus* (Coleoptera: Curculionidae). J Nematol 22:337–347

Gerber K, Giblin-Davies RM, Escobar-Goyes J (1990) Association of red ring nematode, *Rhadinaphelenchus cocophilus*, with weevils from Ecuador and Trinidad. Nematropica 20:39–49

Giblin-Davis RM (1991) The potential for introduction and establishment of the red ring nematode in Florida. Principes 35:147–153

Giblin-Davis RM (1993) Interactions of nematodes with insects. In: Khan MW (ed) Nematode interactions. Springer, Dordrecht, pp 302–344

Giblin-Davis RM (2001) Borers of palms. In: Howard FW, Moore D, Giblin-Davis RM, Abad RG (eds) Insects on palms. Commonwealth Agricultural Bureau (CAB) International, London, pp 267–304

Giblin-Davis RM, Weissling TJ, Oehlschlager AC, Gonzalez LM (1994) Field response of *Rhynchophorus cruentatus* (F.) (Coleoptera: Curculionidae) to its aggregation pheromone and fermenting plant volatiles. Fla Entomol 77:164–177

Giblin-Davis RM, Oehlschlager AC, Perez AL, Gries G, Gries R, Weissling TJ, Chinchilla CM, Peña JE, Hallett RH, Pierce HD Jr, Gonzalez LM (1996) Chemical and behavioral ecology of palm weevils (Curculionidae: Rhynchophorinae). Fla Entomol 79:153–167

Giblin-Davis RM, Faleiro JR, Jacas JA, Peña JE, Vidyasagar PSPV (2013) Biology and management of the red palm weevil, *Rhynchophorus ferrugineus*. In: Peña JE (ed) Potential invasive pests of agricultural crops. Commonwealth Agricultural Bureau (CAB) International, London, pp 1–34

Griffith R (1968) The relationship between the red ring nematode and the palm weevil. J Agric Soc Trin Tob 68:342–356

Griffith R (1987) Red ring disease of coconut palm. Plant Dis 71:192–196

Griffith R, Koshy PK (1990) Nematode parasites of coconut and other palms. In: Luc M, Sikora RA, Bridge J (eds) Plant parasitic nematodes in subtropical and tropical agriculture. CABI, Wallingford, pp 363–385

Guarino S, Bue PL, Peri E, Colazza S (2011) Responses of *Rhynchophorus ferrugineus* adults to selected synthetic palm esters: electroantennographic studies and trap catches in an urban environment. Pest Manag Sci 67:77–81

Guarino S, Peri E, Bue PL, Germanà MP, Colazza S, Anshelevich L, Ravid U, Soroker V (2013) Assessment of synthetic chemicals for disruption of *Rhynchophorus ferrugineus* response to attractant-baited traps in an urban environment. Phytoparasitica 41:79–88

Güerri-Agulló B, Gómez-Vidal S, Asensio L, Barranco P, Lopez-Llorca LV (2010) Infection of the red palm weevil (*Rhynchophorus ferrugineus*) by the entomopathogenic fungus *Beauveria bassiana*: a SEM study. Microsc Res Tech 73:714–725

Guimarães JH (1977) A revision of the genus *Paratheresia* Townsend (Diptera: Tachinidae, Theresiini). Pap Avulsos Zool 30:267–288

Hagley EAC (1962) The palm weevil, *Rhynchophorus palmarum* L., a probable vector of red ring disease of coconuts. Nature 193:499

Hagley EAC (1965) On the life history and habits of the palm weevil, *Rhynchophorus palmarium*. Ann Entomol Soc Am 58:22–28

Hallett RH, Gries G, Borden JH, Czyzewska E, Oehlschlager AC, Pierce HD Jr, Angerilli NPD, Rauf A (1993) Aggregation pheromones of two Asian palm weevils, *Rhynchophorus ferrugineus* and *R. vulneratus*. Naturwissenschaften 80:328–331

Hallett RH, Crespi BJ, Borden JH (2004) Synonymy of *Rhynchophorus ferrugineus* (Olivier) 1790 and *R. vulneratus* (Panzer) 1798 (Coleoptera, Curculionidae, Rhynchophorinae). J Nat Hist 38:2863–2882

Hoddle MS (2015) Red palm weevils—food or foe? Palms 59:21–31

Hoddle MS, Hoddle CD (2016) How far can the palm weevil, *Rhynchophorus vulneratus* (Coleoptera: Curculionidae), fly? J Econ Entomol 109:629–636

Hoddle MS, Hoddle CD (2017) Palmageddon: the invasion of California by the South American palm Weevil is underway. CAPCA Advis 20:40–44 http://westernipm.org/index.cfm/center-projects/signature-programs/invasive-species/south-american-palm-weevil/201704-capca-adviser-hoddle-pdf. Accessed 5 Aug 2018

Hoddle MS, Al-Abbad AH, El-Shafie HAF, Faleiro JR, Sallam AA, Hoddle CD (2013) Assessing the impact of areawide pheromone trapping, pesticide applications, and eradication of infested date palms for *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae) management in Al Ghowaybah, Saudi Arabia. Crop Prot 53:152–160

Hoddle MS, Hoddle CD, Faleiro JR, El-Shafie HAF, Jeske DR, Sallam AA (2015) How far can the Red palm weevil (Coleoptera: Curculionidae) Fly? Computerized flight mill studies with field-captured weevils. J Econ Entomol 108:2599–2609

Hoddle MS, Hoddle CD, Alzubaidy M, Kabashima J, Nisson J, Millar J, Dimson M (2016) The palm weevil *Rhynchophorus vulneratus* is eradicated from Laguna Beach. Calif Agric 71:23–29

Hodel DR, Marika MA, Ohara LM (2016) The South American palm weevil: a new threat to palms in California and the Southwest. Palm Arbor 3:1–27 https://cisr.ucr.edu/pdf/south_american_palm_weevil_hodel.pdf. Accessed 5 Aug 2018

Hogan S, Kelly M, Stark B, Chen Y (2017) Unmanned aerial systems for agriculture and natural resources. Calif Agric 71:5–14

Hokkanen HM, Pimentel D (1984) New approach for selecting biological control agents. Can Entomol 116:1109–1121

Howard FW, Giblin-Davis RM (2008) Palm insects. In: Capinera JL (ed) Encyclopedia of entomologist, vol 16. Springer, New York, pp 2721–2726

Hulme PE (2009) Trade, transport and trouble: managing invasive species pathways in an era of globalization. J Appl Ecol 46:10–18

Hunsberger AG, Giblin-Davis RM, Weissling TJ (2000) Symptoms and population dynamics of *Rhynchophorus cruentatus* (Coleoptera: Curculionidae) in Canary Island date palms. Fla Entomol 83:290–303

Idris AM, Miller TA, Durvasula R, Fedoroff N (2015) Bridging the knowledge gaps for development of basic components of Red palm weevil IPM. In: Wakil W, Faleiro JR, Miller TA (eds) Sustainable pest management in date palm: current status and emerging challenges. Springer, Basel, pp 37–62

Iyer CSV (1940) Two interesting and unrecorded enemies of the palm beetle, *Rhynchophorus ferrugineus*. Indian J Entomol 2:98

Jaffé K, Sánchez P, Cerda H, Hernández JV, Jaffé R, Urdaneta N, Guerra G, Martínez R, Miras B (1993) Chemical ecology of *Rhynchophorus palmarum*: attraction to host plants and to a male-produced aggregation pheromone. J Chem Ecol 19:1703–1720

Jaya S, Suresh T, Sobhitha-Rani RS, Sreekumar S (2000) Evidence of seven larval instars in the red palm weevil, *Rhynchophorus ferrugineus* Olivier reared on sugarcane. J Entomol Res 24:27–31

Ju RT, Li YZ, Wang F, Du YZ, Zhang DS (2008) Prediction of suitable distributions of red palm weevil *Rhyncophorus ferrugineus* Fabricius (Coleoptera: Curculionidae) in China with analysis of bio-climatic matching. Sci Agric Sin 41:2318–2324

Kaakeh W (2005) Longevity, fecundity, and fertility of the red palm weevil, *Rhynchophorus ferrugineus* Olivier (Coleoptera: Curculionidae) on natural and artificial diets. Emir J Agric Sci 17:23–33

Kalshoven LGE (1981) Pests of crops in Indonesia. P.T. Ichtiar Baru, Van Hoeve, Jakarta

Kontodimas DC, Milonas PG, Vassiliou V, Thymakis N, Economou D (2006) The occurrence of *Rhynchophorus ferrugineus* in Greece and Cyprus and the risk against the native Greek palm tree *Phoenix theophrasti*. Entomol Hell 16:11–15

Kontodimas D, Soroker V, Pontikakos C, Suma P, Beaudoin-Ollivier L, Karamaouna F, Riolo P (2017) Visual identification and characterization of *Rhynchophorus ferrugineus* and *Paysandisia archon* infestation. In: Soroker V, Colazza S (eds) Handbook of major palm pests: biology and management. Wiley, Chichester, pp 187–208

Krishnakumar R, Maheshwari P (2004) Preliminary studies of gamma irradiation on the development of red palm weevil, *Rhynchophorus ferrugineus* (Oliv.). Insect Environ 9:175–177

Leefmans S (1920) De palmsnuitkever (*Rhynchophorus ferrugineus* Olivier). Meded Inst Plziekt Buitenzorg 43:1–90

Li L, Qin WQ, Ma ZL, Yan W, Huang SC, Peng ZQ (2010) Effect of temperature on the population growth of *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae) on sugarcane. Environ Entomol 39:999–1003

Liebhold AM, Tobin PC (2008) Population ecology of insect invasions and their management. Ann Rev Entomol 53:387–408

Llácer E, Santiago-Álvarez C, Jacas JA (2013) Could sterile males be used to vector a microbiological control agent? The case of *Rhynchophorus ferrugineus* and *Beauveria bassiana*. Bull Entomol Res 103:241–250

Löhr B (2013) Rediscovering forgotten opportunities. Biocontrol News Inf 34:19N–26N. https://webpages.scu.edu/ftp/kwarner/Warmer_BNI_News.pdf. Accessed 5 Aug 2018

Löhr B, Vásquez-Ordóñez AA, Lopez-Lavalle LAB (2015) *Rhynchophorus palmarum* in disguise: undescribed polymorphism in the "black" palm weevil. PloS one 10:e0143210

Mafra-Neto A, de Lame FM, Fettig CJ, Munson AS, Perring TM, Stelinski LL, Stoltman LL, Mafra LE, Borges R, Vargas RI (2013) Manipulation of insect behavior with specialized pheromone and lure application technology (SPLAT®). In: Beck JJ, Coats JR, Duke SO, Koivunen ME (eds) Pest management with natural products. American Chemical Society, Washington, pp 31–58

Magalhães JAS, de MoraesNeto AHA, Miguens FC (2008) Nematodes of *Rhynchophorus palmarum*, L. (Coleoptera: Curculionidae), vector of the Red ring disease in coconut plantations from the north of the Rio de Janeiro State. J Parasitol Res 102:1281–1287

Manachini B, Schillaci D, Arizza V (2013) Biological responses of *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae) to *Steinernema carpocapsae* (Nematoda: Steinernematidae). J Econ Entomol 106:582–1589

Mankin RW, Al-Ayedh HY, Aldryhim Y, Rohde B (2016) Acoustic detection of *Rhynchophorus ferrugineus* (Coleoptera: Dryophthoridae) and *Oryctes elegans* (Coleoptera: Scarabaeidae) in *Phoenix dactylifera* (Arecales: Arecacae) trees and offshoots in Saudi Arabian orchards. J Econ Entomol 109:622–628

Markrose VT (2008) Coconuts in India. Coconut Development Board, Kerala, India. https://www.bgci.org/education/1685/. Accessed 5 Aug 2018

Mazza G, Francardi V, Simoni S, Benvenuti C, Cervo R, Faleiro JR, Llácer E, Longo S, Nannelli R, Tarasco E, Roversi PF (2014) An overview on the natural enemies of *Rhynchophorus* palm weevils, with focus on *R. ferrugineus*. Biol Control 77:83–92

Mazza G, Inghilesi AF, Stasolla G, Cini A, Cervo R, Benvenuti C, Francardi V, Cristofaro M, Arnone S, Roversi PF (2016) Sterile *Rhynchophorus ferrugineus* males efficiently impair reproduction while maintaining their sexual competitiveness in a social context. J Pest Sci 89:459–468

Melita O, Gkounti V, Kontodimas D, Papachristos D, Karamaouna F (2017) Can high pest pressure of the red palm weevil *Rhynchophorus ferrugineus* beat the defense of *Phoenix theophrasti*? Hell Plant Prot J 10:46–50

Meurisse N, Rassati D, Hurley BP, Brockerhoff EG, Haack RA (2018) Common pathways by which non-native forest insects move internationally and domestically. J Pest Sci. https://doi.org/10.1007/s10340-018-0990-0

Milosavljević I, Schall KA, Hoddle CD, Morgan DJW, Hoddle MS (2017) Biocontrol program targets Asian citrus psyllid in California's urban areas. Calif Agric 71:169–177

Mora LS, Calvache HH, Avila M (1994) Diseminación de rhadinaphelenchus cocophilus (Cobb) Goodey: agente causal del anillo rojo-hojacorta de la palma de aceite en San Carlos de Guaroa (Meta). Rev Palmas 15:15–27 https://publicaciones.fedepalma.org/index.php/palmas/article/ view/419/419.pdf. Accessed 5 Aug 2018

Moura JIL, Mariau D, Delabie JHC (1993) Efficacy of *Paratheresia menezesi* Townsend (Diptera: Tachinidae) for natural biological control of *Rhynchophorus palmarum* L. (Coleoptera: Curculionidae). Oléagineux 48:219–223

Moura JIL, Toma R, Sgrillo RB, Delabie JHC (2006) Natural efficiency of parasitism by *Billaea rhynchophorae* (Blanchard) (Diptera: Tachinidae) for the control of *Rhynchophorus palmarum* (L.) (Coleoptera: Curculionidae). Neotrop Entomol 35:273–274

Murphy ST, Briscoe BR (1999) The red palm weevil as an alien invasive: biology and the prospects for biological control as a component of IPM. Biocontrol News Inf 20:35–46

Nakash J, Osem Y, Kehat M (2000) A suggestion to use dogs for detecting red palm weevil (*Rhynchophorus ferrugineus*) infestation in date palms in Israel. Phytoparasitica 28:153–155

Niblett CL, Bailey AM (2012) Potential applications of gene silencing or RNA interference (RNAi) to control disease and insect pests of date palm. Emir J Food Agric 24:462–469

Oehlschlager AC, McDonald RS, Chinchilla CM, Patschke SN (1995) Influence of a pheromone-based mass-trapping system on the distribution of *Rhynchophorus palmarum* (Coleoptera: Curculionidae) in oil palm. Environ Entomol 24:1005–1012

Oehlschlager AC, Chinchilla C, Castillo G, Gonzalez L (2002) Control of red ring disease by mass trapping of *Rhynchophorus palmarum* (Coleoptera: Curculionidae). Fla Entomol 85:507–513

Perez AL, Gries G, Gries R, Giblin-Davis RM, Oehlschlager AC (1994) Pheromone chirality of African palm weevil, *Rhynchophorus phoenicis* (F.) and palmetto weevil, *Rhynchophorus cruentatus* (F.) (Coleoptera: Curculionidae). J Chem Ecol 20:2653–2671

Perez AL, Hallett RH, Gries R, Gries G, Oehlschlager AC, Borden JH (1996) Pheromone chirality of Asian palm weevils, *Rhynchophorus ferrugineus* (Oliv.) and *R. vulneratus* (Panz.) (Coleoptera: Curculionidae). J Chem Ecol 22:357–368

Poland TM, Rassati D (2018) Improved biosecurity surveillance of non-native forest insects—a review of current methods. J Pest Sci. https://doi.org/10.1007/s10340-018-1004-y

Potamitis I, Rigakis I (2015) Smart traps for automatic remote monitoring of *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae). PeerJ PrePrints 3:e1337v1. https://doi.org/10.7287/peerj.preprints.1337v1

Potamitis I, Ganchev T, Kontodimas D (2009) On automatic bioacoustic detection of pests: the cases of *Rhynchophorus ferrugineus* and *Sitophilus oryzae*. J Econ Entomol 102:1681–1690

Potamitis I, Eliopoulos P, Rigakis I (2017) Automated remote insect surveillance at a global scale and the Internet of Things 2. Robotics 6:19. https://doi.org/10.3390/robotics6030019

Rahalkar GW, Harwalkar MR, Rananavare HO (1972) Development of red palm weevil, *Rhynchophorus ferrugineus* Oliv. on sugarcane. Indian J Entomol 34:213–215

Rahalkar GW, Harwalkar MR, Rananvare HD, Kurian C, Abrham VA, Abdulla Koya KM (1977) Peliminary field studies on the control of the red palm weevil, *Rhynchophorus ferrugineus* using radio sterilized males. J Nucl Agric Biol 6:65–68

Ramachandran CP (1998) The red palm weevil *Rhynchophorus ferrugineus* F.: a review and future strategies. Indian Coc J 29:104–106

Restrepo GL, Rivera AF, Raigosa BJ (1982) Ciclo de vida, habitos y morfometria de *Metamasius hemipterus* Olivier y *Rhynchophorus palmarum* L. (Coleoptera: Curculionidae) en Carla de azucar (*Saccharum oflicinarum* L.). Acta Agron Colomb 32:33–44

Rugman-Jones PF, Hoddle CD, Hoddle MS, Stouthamer R (2013) The lesser of two weevils: molecular-genetics of pest palm weevil populations confirm *Rhynchophorus vulneratus* (Panzer 1798) as a valid species distinct from *R. ferrugineus* (Olivier 1790), and reveal the global extent of both. PloS one 8:e78379

Rugman-Jones PF, Kharrat S, Hoddle MS, Stouthamer R (2017) The invasion of Tunisia by *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae): crossing an ocean or crossing a sea? Fla Entomol 100:262–265

Salama HS, Hamdy MK, Magd El-Din M (2002) The thermal constant for timing the emergence of the red palm weevil, *Rhynchophorus ferrugineus* (Oliv.), (Coleoptera, Curculionidae). J Pest Sci 75:26–29

Saleh MME, Alheji MA, Alkhazal MH, Alferdan H, Darwish A (2011) Evaluation of *Steinernema* sp. SA a native isolate from Saudi Arabia for controlling adults of the red palm weevil, *Rhynchophorus ferrugineus* (Oliver). Egypt J Biol Pest Control 21:277–282

Sallam AA, El-Shafie HAF, Al-Abdan S (2012) Influence of farming practices on infestation by red palm weevil *Rhynchophorus ferrugineus* (Olivier) in date palm: A case study. Int Res J Agric Sci Soil Sci 2:370–376

Sánchez PA, Cerda H (1993) The *Rhynchophorus palmarum* (L.) (Coleoptera: Curculionidae)-*Bursaphelenchus cocophilus* (Cobb) (Tylenchidae: Aphelenchoididae) complex in Palmeras. Bol Entomol Venez 8:1–18

Sánchez PA, Jaffe K, Hernandez JV, Cerda H (1993) Biology and behaviour of the coconut weevil *Rhynchophorus palmarum* L. (Coleoptera: Curculionidae). Bol Entomol Venez 8:83–93

Sattar MN, Iqbal Z, Tahir MN, Shahid MS, Khurshid M, Al-Khateeb AA, Al-Khateeb SA (2017) CRISPR/Cas9: a practical approach in date palm genome editing. Front Plant Sci 8:1469. https://doi.org/10.3389/fpls.2017.01469

Sayan MS (2001) Landscaping with palms in the Mediterranean. Palms 45:171–176

Sewify GH, Belal MH, Al-Awash SA (2009) Use of the entomopathogenic fungus, *Beauveria bassiana* for the biological control of the red palm weevil, *Rhynchophorus ferrugineus* Olivier. Egypt J Biol Pest Control 19:157–163

Shar MU, Rustmani MA, Nizamani SM (2012) Evaluation of different date palm varieties and pheromone traps against red palm weevil (*Rhynchophorus ferrugineus*) in Sindh. J Basic Appl Sci 8:1–5

Soroker V, Suma P, Pergola AL, Cohen Y, Alchanatis V, Golomb O, Goldshtein E, Hetzroni A, Galazan L, Kontodimas D, Pontikakos C (2013) Early detection and monitoring of red palm weevil: approaches and challenges. In: Colloque méditerranéen sur les ravageurs des palmiers. Association Française de Protection des Plantes (AFPP). http://www.gmrcanarias.com/wp-content/uploads/2016/01/palmera_documentos_20130125_001.pdf. Accessed 5 Aug 2018

Suckling DM, Tobin PC, McGullough DG, Herms DA (2012) Combining tactics to exploit Allee effects for eradication of alien insect populations. J Econ Entomol 105:1–13

Suma P, La Pergola A, Longo S, Soroker V (2014) The use of sniffing dogs for the detection of *Rhynchophorus ferrugineus*. Phytoparasitica 42:269–274

Tagliavia M, Messina E, Manachini B, Cappello S, Quatrini P (2014) The gut microbiota of larvae of *Rhynchophorus ferrugineus* Oliver (Coleoptera: Curculionidae). BMC Microbiol 14:136

Triggiani O, Tarasco E (2011) Evaluation of the autochthonous and commercial isolates of Steinernematidae and Heterorhabditidae on *Rhynchophorus ferrugineus*. Bull Insectol 64:175–180

Uddin S, Al-Dousari A, Al-Ghadban A (2009) Mapping of palm trees in urban and agriculture areas of Kuwait using satellite data. Int J Sustain Dev Plann 4:103–111

United States Department of Agriculture—Animal and Plant Health Inspection Service (USDA-APHIS) (2010a) Federal import quarantine order. https://www.aphis.usda.gov/import_export/plants/plant_imports/federal_order/downloads/2010/Palm%20Pests_1-25-10.pdf. Accessed 5 Aug 2018

United States Department of Agriculture—Animal and Plant Health Inspection Service (USDA-APHIS) (2010b) Plants for planting manual. https://www.aphis.usda.gov/import_export/plants/manuals/ports/downloads/plants_for_planting.pdf. Accessed 5 Aug 2018

United States Department of Agriculture—Animal and Plant Health Inspection Service (USDA-APHIS) (2014) Red palm weevil Fact Sheet. https://www.aphis.usda.gov/plant_health/plant_pest_info/palmweevil/downloads/RedPalmWeevilFactsheet.pdf. Accessed 5 Aug 2018

Vacas S, Primo J, Navarro-Llopis V (2013) Advances in the use of trapping systems for *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae): traps and attractants. J Econ Entomol 106:1739–1746

Vacas S, Abad-Payá M, Primo J, Navarro-Llopis V (2014) Identification of pheromone synergists for *Rhynchophorus ferrugineus* trapping systems from *Phoenix canariensis* palm volatiles. J Agric Food Chem 62:6053–6064

Wattanpongsiri A (1966) A revision of the genera *Rhynchophorus* and *Dynamis* (Coleoptera: Curculionidae). PhD dissertation. Oregon State University

Weissling TJ, Giblin-Davis RM (1993) Water loss dynamics and humidity preference of *Rhynchophorus cruentatus* (Coleoptera: Curculionidae) adults. Environ Entomol 22:94–98

Weissling TJ, Giblin-Davis RM, Gries G, Gries R, Pérez AL, Pierce HD, Oehlschlager AC (1994) Aggregation pheromone of palmetto weevil, *Rhynchophorus cruentatus* (F.) (Coleoptera: Curculionidae). J Chem Ecol 20:505–515

Wilson M (1963) Investigations into the development of the palm weevil, *Rhynchophorus palmarum*. Trop Agric Trinidad 40:185–196

Yasin M, Wakil W, El-Shafie HA, Bedford GO, Miller TA (2017) Potential role of microbial pathogens in control of red palm weevil (*Rhynchophorus ferrugineus*)—a review. Entomol Res 47:219–234

Ye W, Giblin-Davis RM, Braasch H, Morris K, Thomas WK (2007) Phylogenetic relationships among *Bursaphelenchus species* (Nematoda: Parasitaphelenchidae) inferred from nuclear ribosomal and mitochondrial DNA sequence data. Mol Phylogenet Evol 43:1185–1197

Zhang R, Ren L, Sun JJ, Zeng R (2002) Morphological differences of the coconut pest insect, *Rhynchophorus ferrugineus* (Oliver), and in related species (Coleoptera: Curculionidae). For Pest Dis 22:3–6