Chapter 2
Biology and Management of Red Palm Weevil

Óscar Dembilio and Josep A. Jaques

Abstract The red palm weevil, *Rhynchophorus ferrugineus*, an indigenous species from South East Asia, has recently become one of the most dangerous pests of palms around the globe. The weevil is extensively dispersed in the Old World, and described on 26 palm species in 16 different genera. In date palm, *Phoenix dactylifera*, control methods revolve around the use of food baited pheromone traps, while in the Canary Island date palm, *Phoenix canariensis*, control of this pest is mostly based on the use of insecticides. Environmental and non-target side effects argue for development of more environment friendly and sustainable management practices. In this context, there is an urgent need to (a) develop and deploy tools for early detection of infested palms, (b) enhance the knowledge of the relationships between *R. ferrugineus* and its hosts, especially the preferred association with *P. canariensis* in the Mediterranean basin, and (c) explore alternatives to synthetic organic insecticides. The latter include biopesticides and new semiochemical mediated strategies involving "attract-and-kill", "attract-and-infect" and "push-pull" techniques for eco-friendly management of this insect pest.

2.1 Introduction

The red palm weevil (RPW), *Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Curculionidae) is indigenous to South Asia, but has quickly spread during the last three decades mostly due to the movement of infested palms from the Middle East and Africa to the Mediterranean area. With an extensive geographical distribution in different climates and a broad host range, this pest has been reported in Asia, Oceania, Africa, Europe and South America. The RPW reportedly attacks over 26 species of palm belonging to 16 genera globally. It was originally reported on coconut (*Cocos nucifera* L.) as a pest in Southeast Asia, but now it is known as the major

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pest of the date palms including *Phoenix canariensis* Chabaud and *P. dactylifera* L. in several regions of the world (Morici 1998).

Severe quarantine restrictions have been imposed by different countries to avoid the spread of this notorious pest. The early detection of RPW infestations is critical to prevent palm death and thus serves as an essential element of a successful Integrated Pest Management (IPM) program used to control RPW. As the first signs of RPW infestation are difficult to detect and only later stages of attack are conspicuous, efforts to develop better early detection methods are underway. Once palms are infested by RPW, they are very difficult to treat, especially *P. canariensis* that often dies from the extensive damage already caused by the pest till detection. However, if infested palms are detected and treated in the early stages of attack, there is a good chance of palm recovery. IPM programs, comprising agronomic practices (sanitation), biological and chemical controls and the use of semiochemicals for monitoring and mass trapping of the pest, have been developed and implemented around the world. The present chapter summarizes the research on different aspects of the biology of RPW, and all recent advances related to its management to mitigate the economic impact.

2.2 Distribution and Host Range

Rhynchophorus ferrugineus is one of the most devastating insect pests of palm trees. According to a survey conducted in 2008 (EPPO 2008a, 2009), there is a wide distribution of this pest in Asia, Oceania, Northern Africa, Europe and in the Caribbean (Aruba and Curaçao). This pest is now present on all continents of the world, except Antarctica. It was first described attacking *Cocos nucifera* in South and Southeast Asia, *P. dactylifera* in the Middle East and other regions wherever these two palm species overlap (Fiaboe et al. 2012).

RPW has been described on more than 20 palm species and almost on all Arecaceae including *Arecastrum romanzoffianum* (Cham.) Becc., *Areca catechu* (L.), *Borassus flabellifer* (L.), *Calamus merrillii* (Becc.), *Arenga pinnata* (Wurmb) Merr., *Caryota cumingii* Lodd. ex Mart., *C. nucifera*, *Chamaerops humilis* (L.), *Corypha utan* (Lam.), *Metroxylon sagu* (Rottb.), *Elaeis guineensis* (Jacq.), *Livistona decipiens* (W. Bull) Dowe, *L. chinensis* (Jacquin) R. Brown (ex Martius in C.F.P. von Martius et al.), *Oncosperma horridum* (Griff.) Scheff., *O. tigillarium* (Jack) Ridl., *Roystonea regia* (Kunth) O.F. Cook, *P. dactylifera*, *P. canariensis*, *Washingtonia robusta* H. Wendl. and *Trachycarpus fortunei* (Hook.) H. Wendl. All these species are more or less susceptible to the weevil (Esteban-Durán et al. 1998b; Malumphy and Moran 2007; Dembilio et al. 2009; OJEU 2008; EPPO 2008a, 2009). Although, RPW is native to Central, South and Southeast Asia and is reported primarily from *C. nucifera* (Wattanapongsiri 1966a), only 15 % of the coconut growing countries have reported this pest (Faleiro 2006; Faleiro et al. 2002, 2012, 2014). On *P. dactylifera*, the spread has been rapid for the last two decades, and now it is reported on *P. canariensis* from the entire Mediterranean basin and most of the date palm growing countries.

Chamaerops humilis is a native European species initially thought to exhibit resistance against *R. ferrugineus* (Barranco et al. 2000). But this palm along with *Washingtonia* spp. was included in the list of vulnerable plant species by the European Union (OJEU 2008). However, experiments conducted in 2007 showed that *R. ferrugineus* did not significantly infest *W. filifera* (Lindl.) H. Wendl., whereas *W. robusta* was highly susceptible (Dembilio et al. 2009). Moreover, *C. humilis* could not be naturally infested by RPW. Antixenosis was the major resistance mechanism occurring in this plant species. Interestingly, this mechanism could be by-passed in palms previously damaged, e.g. suffering an attack from the lepidopteran *Paysandisia archon* Burmeister (EPPO 2008b; Dembilio et al. 2009).

Another palm species, *Phoenix theophrasti* Greuter, is indigenous to the eastern Mediterranean area and only found in Crete and some Aegean Islands (Greece) (IUCN 2010). The susceptibility of *P. theophrasti* to RPW was studied using 4 year old plants which were not detected with any natural infestation, but first instar larvae introduced into artificially drilled holes in the trunks did cause infestation. This is in line with some previous findings for *C. humilis*, where infestation of formerly harmed palms (either mechanically by wind or by the activity of other palm pests) served as natural hosts for RPW (Barranco et al. 2000).

2.3 Economic Importance and Damage

The palm family Arecaceae contains 250 genera with about 2,900 species mainly tropical, with some representatives in warm temperate regions (Dransfield 1978). *Phoenix* is one of the largest genus in this family and most popular as containing commercially important palm species abundantly used in landscaping. These are very adaptable palm species growing in variable climates i.e. from the tropics to the deserts, and even in the cooler subtropical and temperate climates throughout the world. As a group, these palm species are probably the most commonly grown palms in the world, particularly in Canary Islands across northern and Central Africa, southeast of Europe and southern Asia including China and Malaysia. The fruit of *P. dactylifera* is high in energy (1 kg pulp of prepared dates provides 3,000 cal) and is a staple diet of people in several countries of the world (Al-Sahib and Marshall 2003). Other *Phoenix* species have only a thin layer of fruit pulp. Among the latter, *P. canariensis*, is an indigenous palm to the Canary Islands (Barrow 1998) where its sap is used to produce palm syrup.

Besides their value as food for humans and cattle, palms are largely used in interior and landscapes. Some monumental specimens have a high ornamental value, especially those at historic sites, like the palm grove of Elche (Valencia, Spain), which is included in the UNESCO World Heritage Site list (UNESCO 2014). In developed countries, like USA, Japan, Australia and Southern Europe, palms are grown by the ornamental industry for use as interior and field-grown plants in landscapes. In contrast, palm orchards are raised for the production of food, oil and several other commercial uses in northern Africa, the near East, India and Central and South America. In Spain, palms grown in urban areas and gardens account for almost half of the products of ornamental nurseries (Horticom 2008).

Larvae of RPW attack stems and growing tissues of the palms and the detection of this pest is very challenging at the start of its infestation. The RPW infestation in *P. dactylifera* usually occurs in young palms (<20 years old) on the trunk within a meter from the ground. Fresh wounds on palm tissue due to frond shaving and offshoot removal pre-dispose the palm to RPW. In *P. canariensis* where infestation mostly occurs in the crown of the palm, only thorough examination of damaged palms leads to the detection of this pest. Currently detection of infested palms in both date palm and the Canary Islands palm is done manually and largely depends on the detection skills and experience of the staff involved. The following symptoms indicate the presence of the pest: perforations in the trunk and/or crown where the digested fibers from larvae are ejected (secretion of brown sticky liquid with a characteristic bitter smell) (Fig. 2.1), and long after the infestation, crown or frond loss with dried offshoots is seen (Fig. 2.2). Secondary infections by opportunistic fungi and bacteria may occur within these injured tissues that contribute to the deterioration of the palm.

2.4 Biology

The complete life cycle of RPW is exhibited in Fig. 2.3. The eggs are laid individually by female weevils in separate holes excavated by its snout. Eggs are creamy white, shiny and oblong with an average size of 2.62×1.12 mm (Menon and Pandalai 1960). Prior to the hatching, larval mouthparts can be observed through the egg shell. Egg hatching occurs between three to several days depending on mean temperatures (Murphy and Briscoe 1999).

Larvae are creamy white, legless, pyriform, up to 50 mm long and 20 mm wide with a brown head and body comprised of 13 segments. The head capsule is brown russet-red to brilliant brown-black with strongly chitinized mouthparts. Depending on diet (Table 2.1) and prevailing temperature, the larval development may last from 24 to 128 days (Butani 1975; Salama et al. 2009). The number of larval instars varies depending on the diet or host plant. For instance, Martín and Cabello (2006) observed 17 instars of RPW, whereas Nirula (1956) described 3 instars when the pest was fed on a meridic diet. On the other hand, Dembilio and Jacas (2011) reported that RPW larvae completed a total of 13 instars in live *P. canariensis* palms. The newly emerged larvae seek their way into the palm by boring through the palm tissues and making tunnels, where damage increases with each molt. Young larvae have a tendency to feed on soft tissues present around apical meristems, then mature larvae move towards the periphery of the trunk or crown and form a cocoon enwrapped in palm fibers.

Fig. 2.1 Holes in the crown and trunk in palms produced by RPW larvae with ejected chewed-up fibers (Photos: Óscar Dembilio)

The larval stage converts to pre-pupae and this stage lasts for 3 days (Viado and Bigornia 1949). The pre-pupae then convert into pupae inside the cocoon (Murphy and Briscoe 1999). The pupae have an average size of 80 × 35 mm (Murphy and Briscoe 1999). Initially pupae are creamy, and then turn brown in color. They are reticulated, greatly furrowed with a shiny surface. The range of pupal development period varies from 11 to 45 days (Viado and Bigornia 1949; Esteban-Durán et al. 1998a).

Adults of RPW are large, rusty red in color (35 × 10 mm long) with a characteristic long and curved rostrum which comprises about one-third of the total length. On the dorsal side of the thorax the weevils exhibit dark spots. In males, the anterior dorsal half of the rostrum has short brownish setae (hairs). By contrast, the female rostrum lacks any hair, and is comparatively narrower, more curved and longer than the male rostrum. The adult weevils have well-developed wings and are capable to

Fig. 2.2 Infested palms with visible frond loss and dried offshoots (Photos: Josep A. Jaques)

undertake long flights (Lepesme 1947), and to cover long distances of 500–800 m (Wattanapongsiri 1966b). Computer-aided flight mill studies to analyze the flying ability of *R. ferrugineus* revealed that 54 % adult weevils are short distance flyers (covering <100 m), 36 were classified as medium (100–5,000 m), and 10 % were categorized as long distance (>5,000 m) flyers (Ávalos et al. 2014). The emerging adults can stay in the same palm until its meristem is completely consumed, which results in the death of either the palm (commonly in *P. canariensis*) and or its offshoots (*P. dactylifera*). Subsequently, adults disperse from the dead host to look for the new palm hosts.

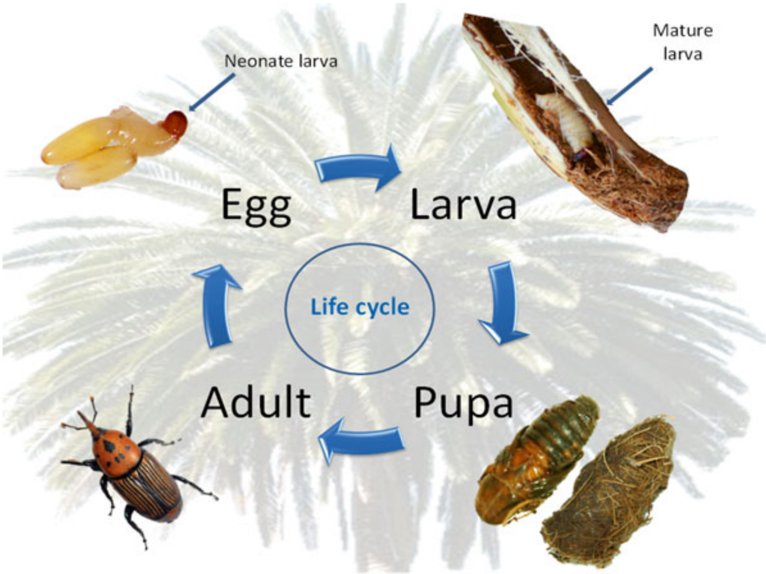

Fig. 2.3 Life cycle of *Rhynchophorus ferrugineus* (Photo: Óscar Dembilio)

Table 2.1 Effect of feeding substrate on life history parameters of *Rhynchophorus ferrugineus* (Dembilio and Jacas 2012)

	Development time (days)					
Feeding substrate	Egg	Larva	Pupa	Total	No. of instar	Reference
Honey in cotton	4–5	–	–	–	4	Shahina et al. (2009)
Sugarcane lumps	4–5	50–80	20–30	74–115	9	Shahina et al. (2009)
Apple slices	4–5	–	–	–	4	Shahina et al. (2009)
Apple slices	–	–	–	–	12	Abe et al. (2009)
Banana slices	5	90	16–20	111–115	5	Salama et al. (2009)
Sugarcane lumps	5	128	25–29	158–162	5	Salama et al. (2009)
Squash fruit	5	83	20–24	108–112	5	Salama et al. (2009)
Apple slices	5	103	16–18	124–126	5	Salama et al. (2009)
Palm crown lumps	5	69	16–19	90–93	5	Salama et al. (2009)
Sugarcane lumps	3–4	82	19	108	–	Kaakeh (2005)
Palm heart lumps	3–4	86	21	124	–	Kaakeh (2005)
Palm leaf base	3–4	84	18	119	–	Kaakeh (2005)
Artificial diet	3–4	70–102	16–23	93–131	–	Kaakeh (2005)
Sugarcane lumps	3–4	88	25	116	11–17	Martin-Molina (2004)
Artificial diet	3–4	93	30	128	7–12	Martin-Molina (2004)

(continued)

Table 2.1 (continued)

Feeding substrate	Development time (days) Egg	Larva	Pupa	Total	No. of instar	Reference
Palm lumps	–	–	–	–	8–15	Martin-Molina (2004)
Banana slices	–	–	13–22	–	–	Salama et al. (2002)
Sugarcane lumps	–	81–89	–	–	7	Jaya et al. (2000)
Sugarcane lumps	–	76–102	19–45	139	–	Esteban-Duran et al. (1998)
Palm lumps	1–6	41–78	–	–	–	Avand Faghih (1996)
Not specified	2–3	60	14–21	76–84	–	Kranz et al. (1982)
Sago palm pith	–	–	–	105–210	–	Kalshoven (1981)
Sugarcane lumps	2–4	24–61	18–34	44–100	–	Butani (1975)
Sugarcane lumps	3–4	32–51	15–28	50–82	–	Rahalkar et al. (1972)
Coconut slices	2–5	36–67	12–21	54–120	3	Nirula (1956)
Coconut slices	3	35–38	11–19	49–70	9	Viado and Bigornia (1949)
Not specified	3	60	15	90–180	–	Lepesme (1947)
Not specified	3	60–120	14	74–134	–	Dammerman (1929)
Sago palm lumps	–	60	13–15	73–75	–	Leefmans (1920)
Palm lumps	3–4	25–61	18–33	48–82	–	Ghosh (1912), (1923)

2.5 Management

2.5.1 Cultural Control

Field and crop sanitation including the elimination of hidden breeding sites is vital for the successful management of RPW. Severely infested palms beyond recovery should be destroyed by shredding. Burning of palms is not recommended as palms do not burn easily when green and could result in pest stages embedded deep inside the palm, escaping the burning procedure and remaining alive. As a component of phytosanitation, it is also essential to treat freshly cut/injured palm surfaces after frond shaving and offshoot removal with insecticide so as to eliminate the palm volatiles that could attract invading female weevils for oviposition.

2.5.2 Trapping and Monitoring

Monitoring the activity of RPW is essential to protect palms against infestation (Faleiro 2006; Rochat 2006; Guarino et al. 2013; Vacas et al. 2013) and depending on mean temperatures, oviposition and egg hatching period may vary in different regions (Fig. 2.4). Mass trapping of adults using food baited pheromone traps plays an important role in the management of *R. ferrugineus* (Faleiro 2006).

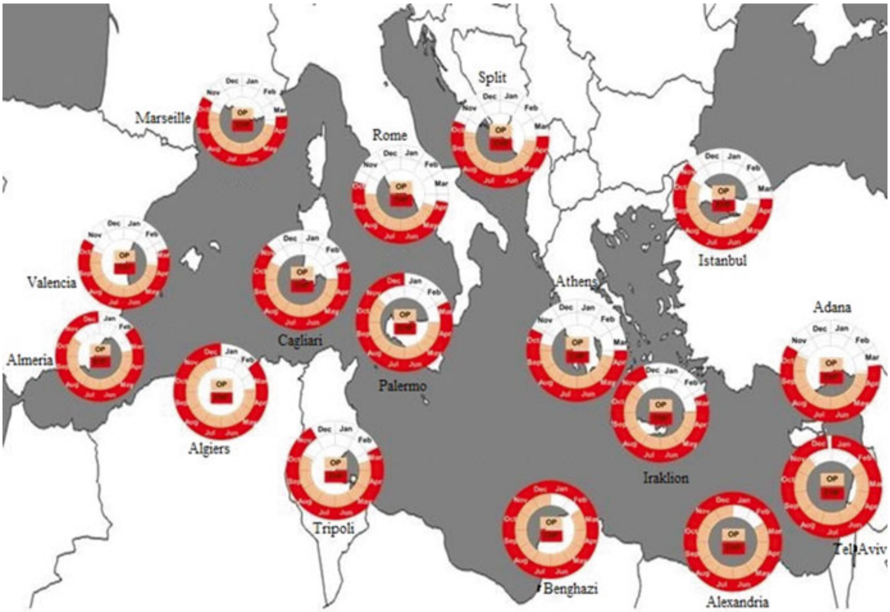

Fig. 2.4 The estimated oviposition (OP) and egg hatching periods (EHP) of *Rhynchophorus ferrugineus* in different temperature regions from the Mediterranean basin (Dembilio and Jacas 2012)

Ferrugineol is the main aggregation pheromone of *R. ferrugineus* (Hallett et al. 1993; Vacas et al. 2014) and is complemented with 4-methyl-5-nonanone in mass trapping used in various countries facing the havoc of RPW (Abraham et al. 1998; Hallett et al. 1999; Vidyasagar et al. 2000). These pheromone traps pre-ferentially catch female over adult male weevils, usually in the ratio of two females for one male weevil captured (Oehlschlager 1998; Vidyasagar et al. 2000; Abraham et al. 2001; Faleiro 2005; Jayanth et al. 2007; Vacas et al. 2013, 2014). Jayanth et al. (2007) reported that 74 % of the pheromone trap-captured adults were female weevils. This result is important for the management of RPW as females are captured before they initiate oviposition triggering new infestations.

Adopting optimum trapping protocols (Hallett et al. 1999; Faleiro 2006; Giblin-Davis et al. 2013) is vital to ensure the benefits of pheromone trapping to manage RPW. The standard four window bucket trap (Faleiro 2006) is widely used in trapping this pest. Besides the pheromone lure, food bait viz. palm tissue, dates, sugarcane (Hallett et al. 1999; Faleiro 2006) mixed in 1 l water in the trap ensures bait-lure synergy and enhanced captures. Black colored RPW have been found to enhance weevil captures (Hallett et al. 1999; Abuagla and Al-Deeb 2012).

While the food bait in RPW traps needs to be replaced every 1–2 weeks, the field longevity of the commercial lure varies according to the product. Ethyl acetate, when incorporated in RPW pheromone traps along with fermenting food, also enhances captures by a factor of two to five times (Oehlschlager 1998; Sebay 2003; Al-Saoud 2013).

In date plantations, pheromone traps are set at ground level (buried half into the soil) or hung on the palm trunk, but the latter practice should be avoided as long as possible. To ensure maximum lure longevity, it is recommended to set traps under shade. In mass trapping programs, trap density depends on the density of the pest in the field and varies from one to ten traps per Ha (Faleiro et al. 2011). Additional traps would require extra work force for their periodical services (change food bait and water). In this context bait free trapping using 'attract-and-kill' technique could be a viable option to food baited traps (El-Shafie et al. 2011).

Several studies have highlighted the potential benefits of the use of food-baited pheromone traps (Faleiro et al. 2003) in mass trapping programs to keep the pest population below economic threshold. Faleiro et al. (2010) recommended that pheromone based area-wide IPM programs need to be implemented at a low infestation level of just 1 % infested date palms. Implementing area-wide management of RPW on the basis of trap captures or infestation reports can be erroneous, as they may either under- or over-estimated the pest density in the field and therefore decisions on infestation levels due to RPW in date palm based on sequential sampling or Geographic Information System (GIS) based models have been developed (Faleiro et al. 2010; Massoud et al. 2012).

2.5.3 Host Plant Resistance

The main mechanisms of host plant resistance to insect pests are categorized as antibiosis, antixenosis and tolerance (Kogan and Ortman 1978; Wiseman 1999; Ju et al. 2011). Antibiosis is a type of resistance in which the mutual interaction of host plant and insect causes physiological or developmental disorders in the insect. In antixenosis (also known as non-preference resistance) the insect is either repelled or even not attracted to its host plant. During a study carried out in Valencia (Spain), these mechanisms of resistance were studied in *C. humilis* and *W. filifera*. The results showed that *W. filifera* had both antixenotic and antibiotic mechanisms of resistance to *R. ferrugineus*, whereas *C. humilis* had antixenosis only (Dembilio et al. 2009). *Chamaerops humilis* fronds are fibrous and only the tender tissues inside the palm apex are accessible for oviposition, this could be the reason why natural infestation is unsuccessful.

Recently, Ju et al. (2011) carried out different experiments based on population growth parameters, where it was revealed that *W. filifera* and *P. canariensis* were more appropriate hosts than *Pinus sylvestris* L. for RPW. In coconut, the cultivar Chowghat Green Dwarf was highly preferred for oviposition by *R. ferrugineus* while very few eggs were laid on Malayan Yellow Dwarf (Faleiro and Rangnekar 2001).

Al-Ayedh (2008) established that the date palm cultivars containing high sugar content promote the growth of RPW. Faleiro et al. (2014) studied the mechanisms of resistance against the weevil in seven major date palm cultivars of the Al-Ahsa Oasis in Saudi Arabia. They determined the extent of attraction of female adults to fresh palm volatiles emitted from frond tissues through a four arm-choice olfactometer® (Analytical Research Systems, Inc., Florida, USA; http://www.ars-fla.com/mainpages/Bio-Assay/4&6-Choice/4&6-Choice.htm). Besides determining oviposition, the antixenosis and feeding antibiotic effects by these cultivars were also assessed. The results revealed that the popular date palm cultivar Khalas was highly susceptible to *R. ferrugineus*, and none of the cultivars tested exhibited any antibiotic effect against the pest. Further studies are needed to understand palm defense mechanisms against this pest.

2.5.4 Plant Quarantine Treatments

The main issue associated with infestations by RPW is the difficulty to detect early symptoms of its attack (Nakash et al. 2000; Al-Shawaf et al. 2013; Giblin-Davis et al. 2013). Red palm weevil has been unwittingly dispersed by deliberate exportation of infested plants and this situation gave rise to a rapid spread of *R. ferrugineus* in the Mediterranean basin (EPPO 2008a, b). During 2007, the EU imposed emergency preventive measures to avoid new invasions of this pest within the European Community (OJEU 2007, 2008, 2010). However, plant quarantine procedures are not included in these measures.

Chemical and physical treatments are the key protocols for managing arthropod pests from a produce. Among chemical treatments, fumigants are widely used to deal with the insect infestation problems. For instance phosphine (PH_3) and methyl bromide (CH_3Br) penetrate the commodity and are highly toxic to target pests. Methyl bromide, a commonly used fumigant globally, has been banned as a post-harvest treatment due to its role as an ozone-depleting substance, according to the UN Montreal Protocol. However, the PH_3 fumigation continues as an effective and economically feasible fumigant against a wide array of insect infestations (MARM 2014).

Llácer and Jacas (2010) studied aluminum phosphide as a safe quarantine treatment against RPW. The results of theses studies recommended that a 1.14 g/m^3 dose rate of aluminum phosphide applied for 3 days in laboratory conditions is quite sufficient to kill all stages of the weevil. Moreover, fumigation of infested *P. canariensis* palm crowns with phosphine gave a complete control of *R. ferrugineus*. Recently, Dembilio and Jaques (2015) confirmed that a dose of 1.14 g/m^3 for 2 days (1 day less than previous work) was enough to kill all stages of RPW in live palms and demonstrated that there are no phytotoxic effects for up to 1 year after the treatment. This procedure, which could be easily applied in sealed containers used for palm trade, could efficiently reduce risks associated to palm movement worldwide. These findings may provide the basis for the establishment of an excellent quarantine protocol against RPW. Researchers in Saudi Arabia developed an insecticide based quarantine protocol to treat date palm offshoots, wherein dipping of offshoot in 0.004 % fipronil for 30 min before transporting is recommended against RPW (Al-Shawaf et al. 2013).

2.5.5 Biological Control

Biological control of RPW or other *Rhynchophorus* species has been studied in different countries (Faleiro 2006; Mazza et al. 2014). In India, trials conducted in laboratory and field using a predacious black earwig, *Chelisoches morio* (F.) a natural enemy of RPW (Abraham and Kurian 1975) did not show a noticeable effect. A cytoplasmic polyhedrosis virus capable of infecting all developmental stages of RPW has been reported in Kerala, India (Gopinadhan et al. 1990). Infected larvae emerged as deformed adults and led to significant suppression of the weevil populations. Several parasitic mites of RPW have also been reported from India (Nirula 1956; Peter 1989). Recent reports from the Middle East indicate that three species of phoretic mites are associated with adult RPW collected from date plantations of the United Arab Emirates (Al-Deeb et al. 2011).

Entomopathogenic nematodes (EPNs) are also effective control measure alternative to chemicals against *R. ferrugineus* (Saleh and Alheji 2003; Elawad et al. 2007; Llácer et al. 2009; Dembilio et al. 2010a). These nematodes are harmless to non-target vertebrates and the environment. Previous field trials in date palms conducted several years ago yielded conflicting results (Abbas et al. 2001a). However, recent experiments performed by Dembilio et al. (2010a) using *Steinernema carpocapsae* in a formulation of chitosan showed good efficacies. The trials conducted under semi-natural field conditions, including both preventative and curative assays confirmed the efficacy of this nematode against RPW. The treatments were 80 % effective as a curative, and up to 98 % in preventing RPW infestation to Canary Island date palms (Llácer et al. 2009). The high efficacy of this treatment was also proven in *P. theophrasti* (Dembilio et al. 2011). The effects of *S. carpocapsae* and imidacloprid alone or as a combined treatment under field conditions were not significantly different from each other, and efficacies range was 73–95 % (Dembilio et al. 2010a). On the basis of these findings, it is suggested that EPNs should be considered while developing new strategies to control RPW.

Recently in laboratory bioassays, the populations of *Bacillus* (Family: Bacillaceae), entomopathogenic bacteria isolated from RPW cadavers were tested for their ovicidal (at four dose rates ranging 10^3–10^6 CFU/mL), and larvicidal (at a dose of 10^6 CFU/mL) effect against RPW (Francesca et al. 2015). The egg hatchability was significantly affected by nine isolates belonging to seven species, viz. *Bacillus amyloliquefaciens*, *B. cereus*, *B. licheniformis*, *B. megaterium*, *B. pumilus*, *B. subtilis* and *Lysinibacillus sphaericus*. However, *B. licheniformis* (CG62) was the only strain that gave a satisfactory control of RPW larvae, rendering these bacterial isolates more useful as a preventive treatments rather than as curative measures (Francesca et al. 2015).

Entomopathogenic fungi (EPF) constitute another possible biological means to control RPW. On contact with the host insect cuticle, EPF spores germinate and grow through the insect body. The infection spreads in two ways, firstly by direct treatment/contact, and secondly by spread from infected cadavers (horizontal transmission) (Quesada-Moraga et al. 2004). These exclusive qualities make EPF potential candidates in the management of cryptic insects like RPW. The effectiveness of various strains of *Beauveria bassiana* (Balsamo) Vuillemin and *Metarhizium anisopliae* (Metchnikoff) Sorokin has been evaluated against this weevil (Gindin et al. 2006; Dembilio et al. 2010b; Ricaño et al. 2013; Lo Verde et al. 2015). Different strains of these fungi have also been isolated from field collected specimens of RPW.

In 2005–2006, *B. bassiana* isolated from *R. ferrugineus* was used by El-Sufty et al. (2009) in field trials. The fungus generated mortality ranging from 12.8 to 47.1 % in the adult population of RPW. More recently, an indigenous isolate of *B. bassiana* obtained from a cadaver of RPW was successfully used to reduce the field occurrence of RPW in Egypt (Sewify et al. 2009). In 2007, pupae of RPW infected with *B. bassiana* collected from date palms in Spain, successfully infected the egg, larval and adult stages of RPW (Dembilio et al. 2010b). Furthermore, the adult lifespan of infected weevils was reduced from one half to approximately one tenth compared with control treatment. The adult males and females treated with the fungal strain spread the infection to healthy adults at transmission rates ranging from 55 to 60 %. This fungal treatment also significantly affected the fecundity and egg hatchability, which were reduced to 62.6 and 32.8 %, respectively. Moreover, 30–35 % mortality of larvae emerged from the eggs obtained from fungus treated couples led to progeny suppression of 78 % compared to the control treatment.

In preventive field assays *B. bassiana* caused mortality up to 85.7 %, suggesting that infection to exposed healthy adults occurred on contact with the infected ones and confirmed this strain to be an excellent biocontrol agent against RPW. Additionally, the males irradiated by gamma-radiation proved to be an efficient vector for the same strain of *B. bassiana* (Llácer et al. 2013). A recent report from Saudi Arabia found the commercial formulation of *B. bassiana* (Broadband) to have high efficacy against RPW in semi-field trials, with the potential of infecting adult weevils by deploying the fungus in the field through pheromone traps involving the "attract-and-infect" method (Hajjar et al. 2015).

In another study, the successful use of acoustic methods for determining the effect of *B. bassiana* against RPW demonstrated the usefulness of this technique for the evaluation of post-treatment fungal efficacy against internally feeding insect pests (Jalinas et al. 2015). Therefore, EPF should be seriously considered as a new tactic in developing effective biological control of RPW.

2.5.6 Reproductive Control

Initial studies carried out using irradiated sterile RPW adult male weevils during the 1970s in India did not appear promising, due to the high frequency of fertile female weevils collected from the field, after mass release of sterile males (Rahalkar et al. 1974, 1977). In the Middle East, as a first step to develop the Sterile Insect Technique (SIT) against RPW, studies on the impact of γ radiation on the mating behavior, and the effect of different relative humidity levels on the efficacy of SIT, were performed by Al-Aydeh and Rasool (2010). The γ radiation did not affect the mating behavior of RPW and the weevils were sexually stimulated during aggregation. However, the usefulness of this technique remains quite uncertain due to the high cost of mass rearing. Furthermore, the RPW adult mates several times during its life span and a single mating would be sufficient for female weevils to lay fertile eggs (Llácer et al. 2013).

2.5.7 Chemical Control

Since symptoms of infestations in palms by RPW are difficult to identify at early stages, the preventive tactics are, therefore, critically important. Chemical control has been the most common practice and consists of repeated applications of pesticides as preventative and curative measures to suppress the spread of infestation. In India during 1970s, the use of carbamate and organophosphate insecticides was established as the foundation of the chemical approach (Murphy and Briscoe 1999). In recent years, however, besides the above chemical groups, phenylpyrazole and neonicotinoid-based insecticides are used as preventive and curative applications to control this pest (Hernandez-Marante et al. 2003; Dembilio et al. 2010a; Llácer et al. 2012; Al-Shawaf et al. 2013).

In Spain, eight preventative insecticide treatments per season (March–November) were proposed (Valencian Department of Agriculture) with six active substances (neonicotinoids, imidacloprid and thiamethoxam, avermectin, abamectin and organophosphates chlorpyrifos and phosmet) authorized by the Spanish Ministry of Agriculture against RPW (MARM 2014). All these recommended pesticides could be applied in three different ways, as spray on the crown, injected into the trunk, or as a soil drench.

In laboratory and semi-field conditions, imidacloprid SL formulation successfully controlled RPW (Martín et al. 1998; Kaakeh 2006). Reports from Israel recommend preventive treatments against RPW with imidacloprid applied to soil at 5 ml per palm through irrigation water during March, April, and May and again after the harvest of dates in September (Soroker et al. 2005). An oil dispersion (OD) formulation of this insecticide was applied through irrigation in preventative and curative semi-field assays to *P. canariensis* in Spain (Dembilio et al. 2010a; Llácer et al. 2012), and proved highly effective (Llácer et al. 2012). Additionally, preventative efficacy values of more than 95 % were also observed for at least 45 days post-treatment (Llácer et al. 2012). In field trials, just two annual applications of this formulation, successfully decreased *P. canariensis* palms infestation to less than 27 % compared to >84 % infestation observed in palms receiving no treatment (Dembilio et al. 2010a). This insecticide was also tested as trunk injection and compared with abamectin (Dembilio et al. 2015) which revealed that the imidacloprid applied as trunk injection not only showed a better distribution within the palm but also yielded greater persistence than its application as crown spray. When abamectin

Fig. 2.5 New injection device using a pressure control (Photos: Óscar Dembilio)

was injected to infested palms, the accumulated concentration of abamectin in the fronds resulted in 50–90 % mortality in young larvae up to 1 month post-treatment. On the other hand, injected imidacloprid was capable to cause more than 90 % mortality in young grubs for more than 2 months after treatment (Dembilio et al. 2015). On the basis of its performance against RPW under field conditions, imidacloprid was found as a better choice over abamectin. Currently, in date palms stem injection using pressure machines to control RPW infestation is widely practiced technique (Fig. 2.5). It is important to ensure that this approach should be carried out under the supervision of technical staff so that treatment pressure does not exceed 1 bar, to avoid palm tissue damage.

2.6 Future Research

Many scientific documents covering different perspectives of RPWbioecology and control have been published, and research has provided important tools to improve its management. Some of the areas studied and aspects that require further research are as follows.

2.6.1 Early Detection

Arguably, the most vital issue concerning infestations by RPW is early detection. Since new infestations are hardly detected, involuntary movement of infested plants is the common and main cause for the wider distribution of this weevil. Some research groups have focused on the development of acoustic sensors for early detection (Levsky et al. 2007; Potamitis et al. 2009; Gutiérrez et al. 2010). However, sensors developed so far have been limited use in practice. Other detection techniques, including detection of chemical signatures of infested palms, thermal imaging and molecular tools, should be explored.

2.6.2 Plant Quarantine

In addition to current pre-departure and post-entry quarantine protocols (OJEU 2007), the development of either physical or chemical quarantine treatment to disinfest palms (Llácer and Jacas 2010), would greatly reduce the high risk that palm exportations currently impose world-wide. Coordination among enforcement agencies at the national, regional and international level is vital to check the spread of this cryptic pest through planting material either for farming of landscape gardening.

2.6.3 Semiochemicals and Trapping

Semiochemicals are key factors to the detection and management of *R. ferrugineus* in palm groves, and will probably have a central role for its management in non-agricultural areas. However, there are many questions related to their use in monitoring and mass trapping (trap density, maintenance and servicing, location) as well as using new possibilities ("push-pull", "attract-and-kill", "attract-and-infect", "attract-and-sterilize" strategies) which are currently being investigated. Recently, Guarino et al. (2013) identified repellents against RPW that could be used in a push-pull strategy in conjunction with pheromones, to repel adult weevils from the palms.

2.6.4 Biological Control

There is an incomplete knowledge of the natural enemies of RPW in its native habitat (Murphy and Briscoe 1999; Faleiro 2006; Mazza et al. 2014), and this precludes the implementation of any classical biological control program against this insect pest. On the other hand, different entomopathogenic nematodes (Abbas et al. 2001a, b; Llácer et al. 2009; Dembilio et al. 2011) and fungi (Gindin et al. 2006; Sewify et al. 2009; Dembilio et al. 2010b; Hajjar et al. 2015) have been identified. This opens new possibilities of inundative releases of these biocontrol agents, and of their combined use with semiochemicals in "attract-and-infect" strategies.

2.6.5 Chemical Control

Even though highly effective pesticides exist (Barranco et al. 1998; Llácer et al. 2010; Dembilio et al. 2010a), there are many problems related both to the delivery of the product to the target (tunneling larvae within the palm) and also regarding the ecotoxicological profile of these chemicals. New environment friendly products are urgently needed, and alternative application methods (such as trunk injection) or uptake mechanisms (such as systemic products) have already been demonstrated (Dembilio et al. 2015).

2.6.6 Resistance and Induced Plant Defenses

Both antibiotic and antixenotic mechanisms of defense have been identified in some palm species (Barranco et al. 2000; Dembilio et al. 2009). Further research is needed to clarify the basis for such mechanisms, and studies on induced defenses could result in novel approaches for the management of weevil in two major *Phoenix* palms viz. date palm and the Canary Island palm, where infestations due to RPW are known to be severe.

2.7 Conclusions

The invasive red palm weevil, one of the most destructive pests of palms in the world is widely distributed in all continents. In the Mediterranean basin, RPW has become the major pest of palms. A better understanding of the biology and the ecology of RPW and their natural enemies and early detection of infested palms is critical in order to avoid death of palms and is the fundamental to the success of any IPM strategy implemented to reduce this pest. However, in the early stages of attack, palms can recover after treatment with insecticides and/or sanitation procedures. IPM strategies, including field sanitation, agronomic practices, chemical and biological controls and the use of semiochemicals both for adult monitoring and mass trapping, have been developed and implemented in several countries. Further research is needed to improve the management of this pest and to protect the palms against this havoc and thereby continue enjoying *Phoenix* and other palms in our farms, gardens, natural landscapes and parks.

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