1 Biology and Management of the Red Palm Weevil, *Rhynchophorus ferrugineus*

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The red palm weevil (RPW) *Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Curculionidae) is a palm borer native to South Asia, which has spread mainly due to the movement of cryptically infested planting material to the Middle East, Africa and the Mediterranean during the last two decades. Globally, the pest has a wide geographical distribution in diverse agroclimates and an extensive host range in Oceania, Asia, Africa and Europe. The RPW is reported to attack over 40 palm species belonging to 23 different genera worldwide. Although it was first reported as a pest of coconut (*Cocos nucifera*) in South Asia, it has become the major pest of date palm (*Phoenix dactylifera*), and the Canary Island date palm (CIDP) (*P. canariensis*) in the Middle East and Mediterranean basin, respectively. Recent invasions suggest that it is a potential threat to *P. dactylifera* plantations in the Maghreb region of North Africa and a variety of palm species in the Caribbean, continental USA and southern China. Strict pre- and post-entry quarantine regulations have been put in place by some countries to prevent further spread of this highly destructive pest. Early detection of RPW-infested palms is crucial to avoid death of palms and is the key to the success of any Integrated Pest Management (IPM) strategy adopted to combat this pest. Because signs and symptoms of RPW infestation are only clearly visible during the later stages of attack, efforts to develop early-detection devices are being undertaken. Once infested by RPW, palms are difficult to manage and often die because of the cryptic habits of this pest. However, in the early stages of attack palms can recover after treatment with insecticides. 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. This chapter summarizes the research developed during the last century on different aspects of the RPW, including latest findings on its biology, taxonomy, geographic distribution, economic impact and management, and prevention options.

1.1 Introduction

In his seminal revision of *Rhynchophorus* and *Dynamis*, Wattanpongsiri (1966) laid out a comprehensive overview for the distribution, biology, morphology and taxonomy of these impressive palm-associated weevils. If you compare the distribution maps of *Rhynchophorus* species in Wattanpongsiri (1966) with what is known today, the RPW or Asian Palm Weevil (APW) *Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Curculionidae/Rhynchophoridae/Dryophthoridae) is the only species that has significantly expanded its range. Although not explicitly stated, a quick review of the biology and the cryptic boring behavior of these weevils in Wattanapongsiri's tome adumbrates their invasive potential, especially if whole palms or offshoots are collected from areas where these weevils occur naturally, and moved long distances to areas where they do not occur. It turns out that the temptation to move date palms from infested areas in South and Central Asia to the Middle East and Mediterranean in the 1980s, Spain in the 1990s, France in the mid-2000s and Curaçao and Aruba in 2008 was too much for date growers and landscape developers. The weevil began to appear in new territories, aggressive treatments were attempted to fend off the invasions, epiphytotics often ensued and especially susceptible palms such as the ornamental CIDP (*P. canariensis*) were often available to fan the spread. Although RPW is native to Central, South and South-East Asia and is reported chiefly from *C. nucifera* (Wattanapongsiri, 1966), only 15% of the coconut-growing countries have reported this pest. On *P. dactylifera*, the spread has been rapid during the last two decades and it is now reported from 50% of the date palm-growing countries and the entire Mediterranean basin on CIDP, *P. canariensis*. Because *R. ferrugineus* has expanded its range into areas where other palm weevil species occur, such as the Americas and Africa, this has potentially exacerbated the problem of accurate identification of the *Rhynchophorus* species in some situations. The purpose of this chapter is to revisit what we know about *Rhynchophorus ferrugineus* and closely related species, with a panel of experts with differing vantage points, to gain deeper insight.

1.2 Basic Taxonomy of RPW and Relatives

Weevil borers of palms are members of seven natural lineages within the 'Curculionidae' sensu lato, with the Dryophthoridae (or Dryophthorinae, depending upon the taxonomic authority used) being the most damaging to palms worldwide (Giblin-Davis, 2001). Four tribes within the Dryophthoridae are well-known from palms: the Rhynchophorini which includes the genera *Rhynchophorus* (mostly tropical/subtropical worldwide distribution) and *Dynamis* (Neotropical distribution); the Sphenophorini which includes *Metamasius* (Neotropical distribution), *Rhabdoscelus* (Asian distribution) and *Temnoschoita* (African distribution); the Diocalandrini which includes *Diocalandra* (South-East Asian distribution); and the Orthognathini which includes *Rhinostomus* (worldwide tropical distribution) and *Mesocordylus* (Neotropical distribution). *Rhynchophorus* and *Dynamis* species are most often referred to as 'palm weevils' and are relatively large insects, with adults being up to 5 cm long and 2 cm wide; larvae are up to 6.4 cm long and 2.5 cm wide (Giblin-Davis, 2001). Adults of *Dynamis* species are usually glossy black, in contrast to *Rhynchophorus* species which can be highly variable in coloration, ranging from all black to almost all reddish brown; with a glossy to matte, textured finish. There are nine named species of *Rhynchophorus*, including: *R. cruentatus* from Florida and the coastal southeastern USA and the Bahamas; *R. palmarum* from Mexico, Central and South America and the southernmost Antilles; *R. ferrugineus* (=*R. vulneratus*; see Hallet *et al*., 2004) originally from South-East Asia but with a recently expanded range (see above); *R. phoenicis* from central and southern Africa; *R. quadrangulus* from west-central Africa; *R. bilineatus* from New Guinea; *R. distinctus* from Borneo; *R. lobatus* from Indonesia; and *R. ritcheri* from Peru (Wattanapongsiri, 1966; Hallett *et al*., 2004; Thomas, 2010). *R. distinctus*, *R. lobatus* and *R. ritcheri* are considered rare and localized species and will not be dealt with here.

A recent pest alert was generated to help distinguish the three species occurring in the New World following the recent introduction of *R. ferrugineus* to Curaçao in the Caribbean (Thomas, 2010). This highlights the need to distinguish *R. ferrugineus* from other *Rhynchophorus* species where they may overlap because of expansion of the RPW range. Distinguishing *R. cruentatus*, *R. palmarum* and *R. ferrugineus* adults from each other is relatively easy and can be accomplished with dorsal characters of the pronotum (Thomas, 2010), but other morphological characters are necessary when trying to separate *R. ferrugineus* from the other common species in South-East Asia and Africa. The most reliable characters discussed by Wattanapongsiri (1966) include a combination of traits, including the pronotum, dorsal, lateral and ventral aspects of the head including the basal and distal submentum shape, sungenal suture, scutellum and mandibles (Figs. 1.1–1.8). In the following key we consider the six most common *Rhynchophorus* species that occur in continents or areas where RPW co-occurs or has the potential to co-occur. In essence, the first couplet used by Thomas (2010) works well to remove *R. palmarum* from all of the rest of the species.

Key for adults of the six most common *Rhynchophorus* species:

1. 'Pronotum lobed posteriorly'; mandibles usually bidentate in lateral view; body color black (Figs. 1.1–1.3) *R. palmarum***
– Pronotum flatly curved posteriorly; mandibles not bidentate in lateral view (broadly rounded or sharply tridentate); color black, red and black, or red (Fig. 1.2) 2

2. 'Pronotum abruptly narrowed anteriorly'; giving the appearance of broad shoulders (Fig. 1.4, arrow); mandibles unidentate or broadly rounded in lateral view; males without anterio-dorsal rostral setae*** (Fig. 1.5) 3
– 'Pronotum gradually narrowed anteriorly' (Fig. 1.4, arrow); mandibles sharply tridentate in lateral view; males with anterio-dorsal rostral setae*** (Fig. 1.3) 4

3. a. Nasal plate present, subgenal sutures parallel-sided, wide (>25% of the head width at ventral base) (Figs. 1.5 and 1.6) *R. quadrangulus*
– b. Nasal plate absent, subgenal sutures tapering anteriorly, narrow (<15% of the head width at ventral base) (Figs. 1.5 and 1.6) *R. cruentatus*

4. a. Scutellum tapers acutely to a fine point posteriorly (Fig. 1.7) *R. phoenicis*
– Scutellum tapers broadly to a blunt point posteriorly (Fig. 1.7) 5

5. a. Submentum with straight subgenal sutures (Fig. 1.8) *R. bilineatus*
b. Submentum with concave subgenal sutures (Fig. 1.8) *R. ferrugineus*

**Both *R. palmarum* and members of the Neotropical genus *Dynamis* are black and have the posterior margin of the pronotum lobed posteriorly, but in *Dynamis* the posterior pronotal extension is about twice as deep and the scutellum is less than one-third the size (in volume) of that feature in *R. palmarum* (Fig. 1.1).

***Character requires presence of males. Rostral hairs can be absent in nutritionally deprived and very small males of *Rhynchophorus*.

1.3 General Biology, Detection and Distribution

RPW or APW, *Rhynchophorus ferrugineus*, is reported globally on at least 40 species of palms (i.e., *Areca catechu*, *Arecastrum romanzoffianum*, *Arenga pinnata*, *Borassus flabellifer*, *Calamus merrillii*, *Caryota cumingii*, *Caryota maxima*, *Chamaerops humilis*, *Cocos nucifera*, *Corypha ulan*, *Elaeis guineensis*, *Livistonia decipiens*, *L. chinensis*, *Metroxylon sagu*, *Oncosperma horrida*, *O. tigillarium*, *Roystonia regia*, *P. canariensis*, *P. dactylifera*, *P. sylvestris*, *Sabal blackburniana*, *Trachycarpus fortunei* and *Washingtonia robusta*) (Esteban-Duran *et al*., 1998b, Murphy and Briscoe, 1999; Malumphy and Moran, 2007; OJEU, 2008; EPPO, 2008, 2009; Dembilio *et al*., 2009). RPW is now known from all the continents of the world and is a key pest of coconut (*Cocos nucifera*) in South and

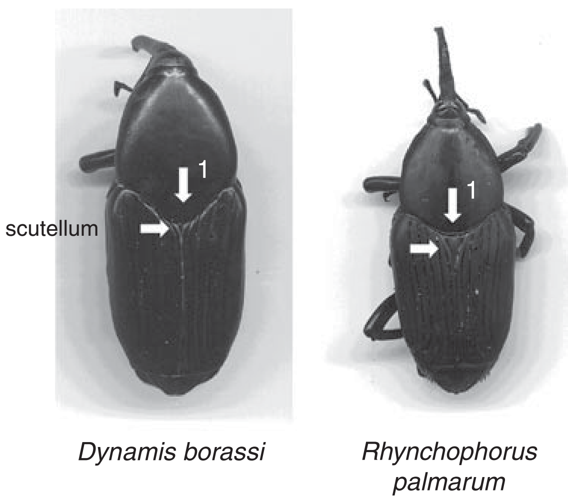

Fig. 1.1 Dorsal views of diagnostic traits (i.e., the posterior pronotum edge (=vertical arrows) and relative scutellum size (=horizontal arrows) between the genera *Dynamis* and *Rhynchophorus*. (Photos: R.M. Giblin-Davis.)

Fig. 1.2 Dorsal views of the posterior pronotum edge (=vertical arrows) showing the differences between *Rhynchophorus palmarum* and five other species of *Rhynchophorus*. (Photos: R.M. Giblin-Davis.)

South-East Asia, date palm (*Phoenix dactylifera*) in the Middle East and *P. canariensis* in Europe, and wherever they overlap. RPW, in common with all palm weevils in the genera *Rhynchophorus*, *Dynamis*, *Metamasius*, *Rhabdoscelus* and *Rhinostomus*, is an internal tissue borer of infested palms. If it is detected in the early stage of attack, the palm host can recover with an insecticide treatment. However, palms in the latter stages of attack exhibit extensive tissue damage in the region of the apical meristem, often harboring several overlapping generations of RPW. These palms are difficult to treat and usually die. The lethal nature of this pest, coupled with the high value of the attacked palm species, warrants early action against RPW.

Palm weevils in general and RPW in particular are attracted to wounded, damaged, or dying palms, and in cases such as the CIDP, to apparently healthy palms (Hunsberger *et al.*, 2000). Males of these weevils produce aggregation pheromones that are synergistically attractive with the kairomones produced by suitable hosts, usually early fermentation products such as ethyl esters and ethanol (Giblin-Davis *et al.*, 1996a). Once they arrive at a palm, males and females typically seek protection from water loss by burrowing down into the petiole bases in the crown region, into

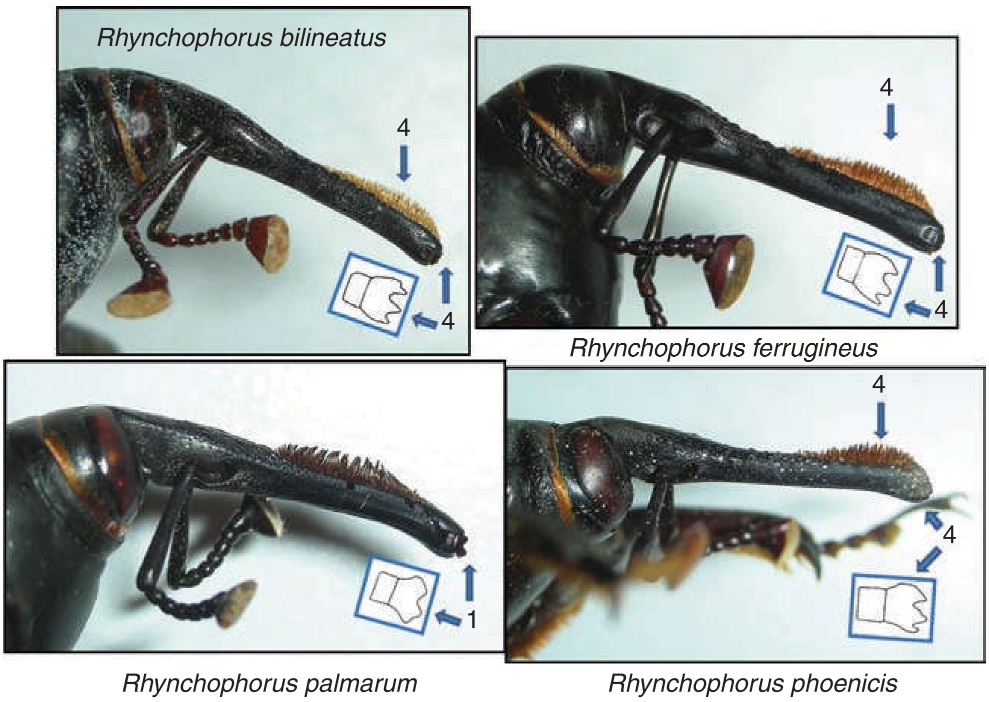

Fig. 1.3 Right lateral views of the heads of males of *Rhynchophorus bilineatus*, *R. ferrugineus*, *R. palmarum*, and *R. phoenicis* showing the dorsal rostral setae and distal mandibles. Insets depict a single mandible redrawn from Wattanapongsiri (1966). (Photos: R.M. Giblin-Davis.)

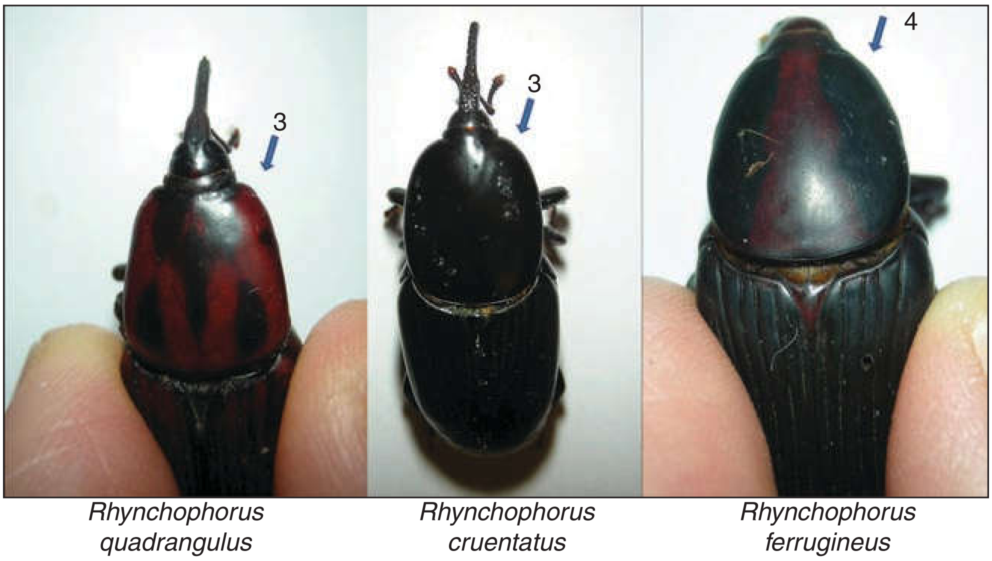

Fig. 1.4 Dorsal views of the anterior pronotal shoulders (=diagonal arrows) comparing *Rhynchophorus quadrangulus* and *R. cruentatus* with *R. ferrugineus*. (Photos: R.M. Giblin-Davis.)

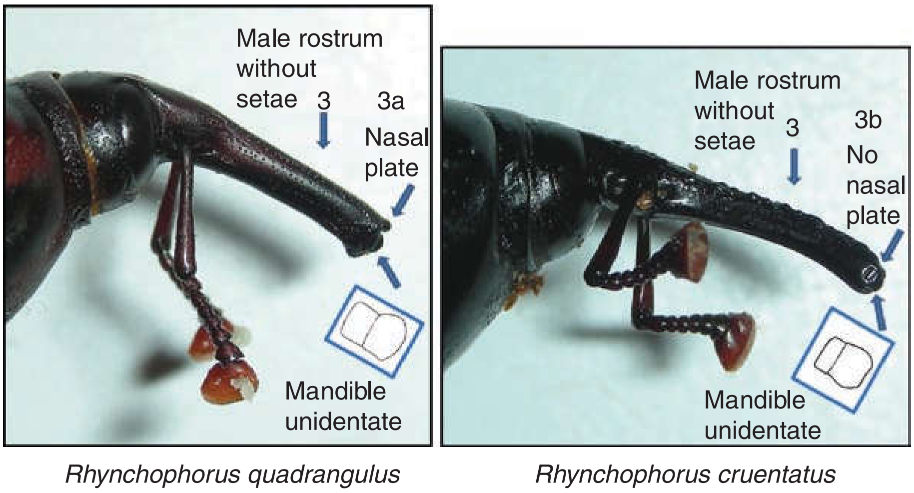

Fig. 1.5 Right lateral views of the heads of males of *Rhynchophorus quadrangulus and R. cruentatus* showing the lack of dorsal rostral setae, presence or absence of a nasal plate and the morphology of the distal mandibles. Insets depict a single mandible redrawn from Wattanapongsiri (1966). (Photos: R.M. Giblin-Davis.)

fleshy wounds, or into the junction between offshoots and the mother stem in palms such as the date palm. Like most weevils, RPW females use small mandibles at the distal tip of the distended rostrum to chew a hole into suitable host tissue before oviposition of a 2–3 mm long yellowish-colored egg. Eggs are often laid in close proximity to one another and take 2–4 days to eclose as small, first instar, legless larvae. The lower temperature threshold for the egg stage is 13.1°C and this stage has a thermal constant of 40.4 ± 2.0 DD (day degrees) (Dembilio and Jacas, 2011). In general, studies suggest that a gravid female will lay about 250 eggs (3–531) over her lifetime (which may last up to 120 days) and may require multiple inseminations to insure fertility. There are 13 larval instar stages of increasing head capsule and body size with increasing damage potential upon each molt (Dembilio and Jacas, 2011). The larvae have large chewing mandibles relative

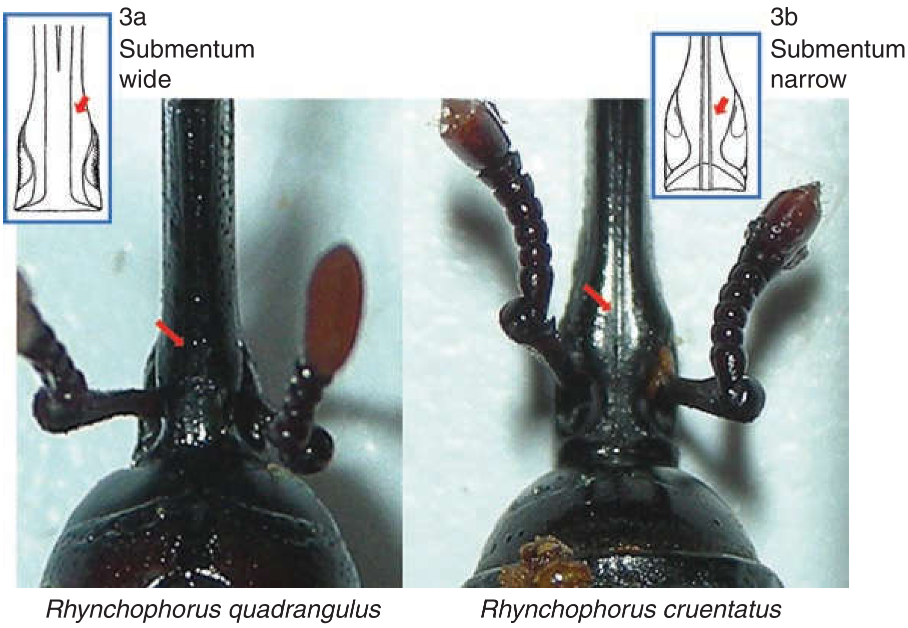

Fig. 1.6 Ventral view of the base of the head of males of *Rhynchophorus quadrangulus* and *R. cruentatus* showing the relative shapes of the submentum delineated by the gular sutures. Insets depict the same view redrawn from Wattanapongsiri (1966). (Photos: R.M. Giblin-Davis.)

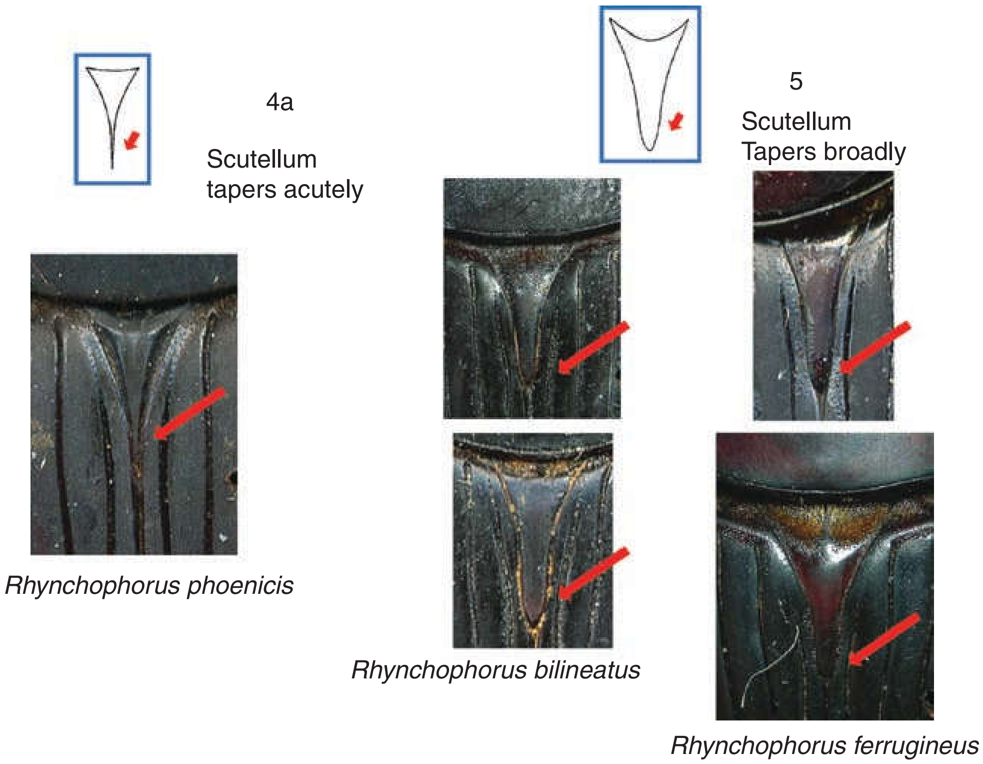

Fig. 1.7 Dorsal views of the scutellum of *Rhynchophorus phoenicis* where it tapers acutely versus *R. bilineatus* and *R. ferrugineus*, where it tapers broadly (see arrows). Insets depict the scutellum redrawn from Wattanapongsiri (1966). (Photos: R.M. Giblin-Davis.)

to the adult stage and move peristaltically through the randomly oriented galleries in the region of the crown (especially in the case of CIDP, but usually in the stem near or in offshoots in the lower 3 m of the stem in date palm and the Mediterranean fan palm *Chamaerops humilis*). The galleries are often filled with a frass that is composed of cross-oriented fibers and feces

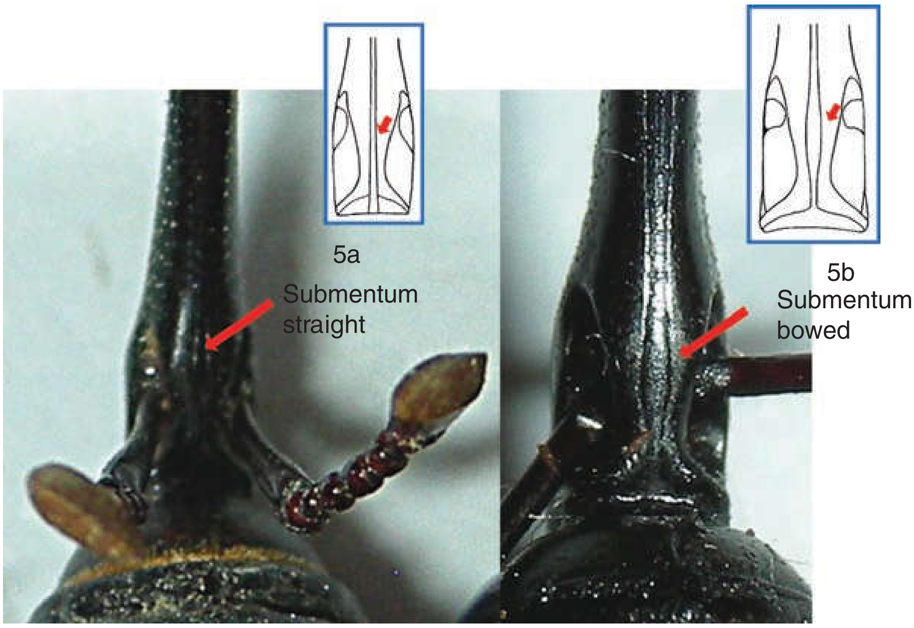

Fig. 1.8 Ventral view of the base of the head of males of *Rhynchophorus bilineatus and R. ferrugineus* showing the relative shapes of the submentum delineated by the gular sutures. Insets depict the same view redrawn from Wattanapongsiri (1966). (Photos: R.M. Giblin-Davis.)

resembling shredded wheat. Research is continuing on the acoustic detection of RPW larval stages using improved methods to discriminate 3–10 ms sound impulses of feeding and locomotory movements from background noise (Mankin *et al*., 2008). Siriwardena *et al*. (2010) have developed and tested an acoustic detection system for field application in coconut that was 97% accurate for RPW larval infestations with a false-positive rate of about 8%. The odor of RPW-infested trees produces a scented signal that dogs can be trained to, but requires frequent retraining (Nakash *et al*., 2000). Lethal infestations of RPW are in the range of 20–100 per palm but easily exceed 200. The duration of the larval phase is variable and depends upon available host nutrition, temperature and humidity, but is usually in the range of 25–105 days before the last-instar larva begins to create a large oblong cocoon (c. 75 × 35 mm) out of host fiber, most often in the petiole bases or stem. Dembilio and Jacas (2011) estimated that 666.5 DD were necessary for complete larval development in live *P. canariensis*. The last instar quickly transforms into the prepupal stage which lasts 2–11 days and retains much of the appearance of the larva but moves in the same characteristic twisting motion of the pupal stage. The next stage to occur in the cocoon is the pupa, which usually lasts for about 11–50 days before the molt to the adult. Dembilio and Jacas (2011) determined that the pupal stage required 282.5 DD, and therefore set the thermal constant of *R. ferrugineus* (egg to adult) feeding in *P. canariensis* at 989.3 DD. The adults can stay in the cocoon for several weeks before they emerge, according to abiotic conditions. Depending upon the condition of the host palm, the weevils may disperse for long distances (>900 m) or remain in the host to mate and recycle for another generation. It often takes 2–3 generations before a CIDP or a date palm will succumb to an RPW infestation. Depending on temperature, these generations can take place in one single year, but often require a minimum of 2 years (Dembilio and Jacas, 2011). Mark-release-recapture studies suggest that RPW can disperse about 7 km in less than a week (Abbas *et al*., 2006).

A symbiotic relationship occurs between RPW and other *Rhynchophorus* species, *Dynamis*, *Metamasius hemipterus*, *Cosmopolites sordidus*, *Scyphophorus yuccae*, *Sphenophorus*, etc. (palm, agave, banana and bromeliad-associated weevils in the Dryophthoridae) and a clade of gamma-proteobacterial endosymbionts. *Nardonella dryophthoridicola* occurs intracellularly in bacteriocytes which comprise a bacteriome organ surrounding the larval intestine. The bacteria also occur in the oocytes of adult females for transovariole vertical transmission (Nardon *et al.*, 2002; Lefèvre *et al.*, 2004). The association is apparently quite ancient, being estimated to be about 125 million years old, and was first observed in RPW in 1965 (Buchner, 1965). The actual role that these symbionts play is unknown, but is presumed to involve supplementation of the weevil host's diet with essential nutrients, insect temperature resistance, host-plant detoxification, or parasite protection (Lefèvre *et al.*, 2004).

1.4 *Rhynchophorus* Nematode Symbionts

RPW is a congener of *R. palmarum*, the chief vector of the red ring nematode (RRN) *Bursaphelenchus cocophilus*, causal agent of red ring disease (RRD) of palm trees in the neotropics (Giblin-Davis, 1993). RRN is a stylet-bearing, obligate plant-parasitic nematode (Superfamily: Aphelenchoidea) that is part of a clade of mostly mycophagous nematodes, i.e. *Bursaphelenchus* (Ye *et al.*, 2007). Plant-parasitic nematodes have not been reported from *Rhynchophorus* species from North America, Asia or Africa. However, as RPW spreads to areas where *R. palmarum* and RRD occur, there is the potential for an association to develop between it and RRN which could change the dynamics of both symbionts. This concern led to a Federal Import Order (effective 10 February 2010) restricting the movement of 17 species of palms that might allow importation of *R. ferrugineus*, *R. palmarum* or *B. cocophilus* into the USA until pest risk analysis is completed to determine if risk avoidance measures are available for these pests.

RRD is one of the most important wilt diseases of coconut and African oil palms in the neotropics, causing annual losses of 10–15% (Giblin-Davis, 1993). It is vectored chiefly by *R. palmarum*, but also potentially by *Dynamis borassi* and *Metamasius hemipterus*, the latter two sharing 4-methyl-5-nonanol (ferrugineol) as their main pheromone with RPW. This suggests that RPW would be co-attracted to sites where it might obtain access to RRN and would likely be a suitable vector for the nematode, as has been suggested for *R. cruentatus*, if it co-occurred with *R. palmarum* and RRD (Giblin-Davis, 1991). Recent introduction of RPW into the New World has challenged our knowledge of how interspecific interactions between different *Rhynchophorus* species will play out, as well as how the exchange of associated organisms such as RRN will be manifested. RRN is transmitted to susceptible palms during oviposition or other activities, and only a few are necessary for successful transmission. In coconut palms, symptoms include a typical wilt with premature coconut drop (except mature nuts), and premature senescence of progressively younger leaves, which often break at the base and hang. Stem, petiole and root cross-sections often show a red ring of anthocyanin-rich pigments and these tissues usually yield large numbers of dispersal third-stage juveniles which occur intercellularly in ground parenchymal tissue. RRN infestation causes an irreversible wilt that kills the tree in a couple of months because of tyloses formation and vascular occlusion of water-conducting xylem in the vascular bundles. Palm weevils colonize RRD trees, and during feeding and tunneling become associated with the dispersal stage of the nematodes which appear synchronized for transmission (Giblin-Davis, 1993).

Acrostichus rhynchophori (Rhabditidae), previously referred to as '*Diplogasteritus* sp.' or '*Acrostichus* (*Diplogasteritus*) sp.' (Gerber and Giblin-Davis, 1990a, b; Giblin-Davis *et al.*, 2006) was cultured from dauer juveniles (JIII) recovered from the genital capsule of *R. cruentatus* from southern Florida, and *R. palmarum* from Colombia, Costa Rica and Trinidad (Kanzaki *et al.*, 2009). This association was shown to be phoretic in nature, and the nematodes feed on bacteria. These two weevil species also share another phoretic bacteriophagous nematode, *Teratorhabditis palmarum* (Gerber and Giblin-Davis, 1990b). In addition to these two species, four species of nematodes, *Bursaphelenchus cocophilus* (RRN, see above), *B. gerberae* (a mycophagous phoretic nematode), *Caenorhabditis angaria* (previously called 'PS1010' or *Rhabditis* sp.) (Sudhaus *et al.*, 2011) and *Mononchoides* sp. (a nematode predator of nematodes) have been reported from *R. palmarum* (Gerber and Giblin-Davis, 1990a, b; Giblin-Davis *et al.*, 2006; Kanzaki *et al.*, 2008, 2009; Sudhaus *et al.*, 2011). In the case of *R. palmarum*, the dauer juveniles of *T. palmarum* were isolated from the genital capsule (ovipositor or aedeagus) and body cavity of the weevils (Gerber and Giblin-Davis, 1990b); the dauer juveniles of *Caenorhabditis angaria* were recovered from the genital capsule (Gerber and

Giblin-Davis, 1990a); and the dauer juveniles of *B. cocophilus* appeared to infect the body cavity (Giblin-Davis, 1993; Griffith *et al.*, 2005). Interestingly, *C. angaria* is chiefly a bacterivorous phoretic associate of *Metamasius hemipterus* which was recently discovered as this weevil invaded south Florida, but is also known from *R. palmarum* and *M. hemipterus* from Trinidad (Sudhaus *et al.*, 2011). The lack of host fidelity in some of these phoretic nematode associations corroborates the notion from the pheromonal research above that these weevils, when occurring sympatrically, can be cross-attracted to the same host tree where they may develop together or in close proximity, allowing for the exchange of some symbionts.

Teratorhabditis synpapillata and *Praecocilenchus ferrruginophorus* are the only reported nematode associates of the RPW (Rao and Reddy, 1980; Kanzaki *et al.*, 2008). The host/vector association of *T. synpapillata* on RPW presumably involves phoresy and reproduction in dead or dying palms, because *T. synpapillata* was found under the elytra and in the frass of larval tunnels of RPW and is very similar to *T. palmarum*, which is carried as dauers by *R. palmarum* or *R. cruentatus* to dead or dying palms where it feeds on bacteria (Gerber and Giblin-Davis, 1990a, b). The sister-species relationship of *T. synpapillata* and *T. palmarum* in our molecular studies suggests that a specialized association with *Rhynchophorus* weevils was already present in the common ancestor of both species. Allopatry between American and Asian weevil host species could have allowed for discontinuity in nematode gene flow and eventual genetic drift and speciation. However, that *T. synpapillata* was twice independently isolated from dung or dung-enriched soil is suggestive of a much looser association where movement of nematodes between soil and arboreal biomes is accomplished by either unknown weevil activities, other insects that frequent and/or reproduce in both biomes, and/or as rotting palm trees are recycled into soil during decomposition (Kanzaki *et al.*, 2008).

Praecocilenchus ferrruginophorus is a stylet-bearing insect-parasitic nematode of the hemocoel of adult RPW (Reddy and Rao, 1980) which is very similar in morphology and apparent biology to *P. rhaphidophorus* which causes qualitative reductions of the ovaries of *R. bilineatus* in New Britain (Poinar, 1969). However, in *R. bilineatus* in New Britain, where *P. rhaphidophorus* occurs naturally in about 15% of populations, the weevils were still capable of reproduction but produced fewer eggs and had reduced fat bodies when compared with uninfested weevils. More work is needed to see if these two insect-parasitic Aphelenchoidids are conspecific, or not, and if the genus occurs in other *Rhynchophorus* species.

Entomopathogenic nematodes have been tested for biological control of RPW and *M. hemipterus* with positive results (Giblin-Davis *et al.*, 1996b; Murphy and Briscoe, 1999; Dembilio *et al.*, 2009). However, these evolutionarily divergent genera (i.e., *Heterorhabditis* and *Steinernema*) have never been recovered as natural nematode associates of *Rhynchophorus* species and will not be dealt with in detail here (see preventative treatments below). They are soil-inhabiting nematodes that have evolved in a mutualistic complex with symbiont bacteria, becoming a commercialized complex available for control of a wide range of insect hosts in moist and often cryptic habitats.

1.5 *Rhynchophorus* Aggregation Pheromones

The first reports suggesting that male weevils of the family Dryophthoridae produce aggregation pheromones attracting adults of both sexes, involved the sugarcane and palm stem-boring weevil, *Rhabdoscelus obscurus* (Chang *et al.*, 1971; Chang and Curtis, 1972). Since then, male-produced pheromones have been confirmed and identified for many weevils in this group including *R. obscurus* and all of the palm-associated *Rhynchophrous*, *Dynamis* and *Metamasius* species that have been examined so far (Giblin-Davis *et al.*, 1996a, 1997, 2000). Eight to 10-carbon, methyl-branched, saturated or unsaturated secondary alcohols comprise the major pheromones for these weevils (Table 1.1). In most cases, there is more than one chemical component to the natural blends that are produced and detected by the antennae of each weevil. It is the *S* enantiomer or *S,S* stereoisomer of the pheromone that is produced and detected in these weevils, and non-natural stereoisomers that result from synthetic production have been shown to be benign (non-interruptive in field applications) (citations in Giblin-Davis *et al.*, 1996a). Thus, relatively

Table 1.1. Male-produced aggregation pheromones and minor components identified from palm-associated or related weevils.

	Common chemical name	*Rhynchophorus bilineatus*	*R. cruentatus*	*R. ferrugineus*	*R. palmarum*	*R. phoenicis*	*Dynamis borassi*	*Metamasius hemipterus*	*Rhabdoselus obscurus*	*Scyphophorus acupunctatus*
Distribution		New Guinea	North America	Asia (expanded)	Neotropics	Central Africa	Neotropics	Neotropics	Asia (expanded)	Neotropics
Common name		New Guinea palm weevil	Palmetto weevil	Red or Asian palm weevil	American palm weevil	African palm weevil	Palm weevil	West Indian sugarcane weevil	New Guinea sugarcane weevil	Agave weevil
3-pentanol	–	–	–	–	–	–	–	minor		
3-pentanone	–	–	–	–	–	–	–	minor		
(4*S*, 2E)-6-methyl-2-hepten-4-ol	rhynchophorol	–	–	–	XX	–	–		XX[a]	
2-methyl-4-heptanol	–	–	–	–	–	–	–	minor	minor[a]	minor
2-methyl-4-heptanone	–	–	–	–	–	–	–	minor		XX
2,3-epoxy-6-methyl-4-heptanol	–	–	–	–	minor	–	–			
2-methyl-4-octanol	–	–	–	–	–	–	–	minor	XX[a]	minor
2-methyl-4-octanone	–	–	–	–	–	–	–	minor		XX
(3*S*, 4*S*)-3-methyl-4-octanol	Phoenicol	–	–	minor	–	XX	–			
(5*S*, 4*S*)-5-methyl-4-octanol	Cruentol	–	XX	–	–	–	–			
5-nonanol		–	–	–	–	–	–	minor		
(4*S*, 5*S*)-4-methyl-5-nonanol	Ferrugineol	XX	–	XX	minor	–	XX	XX		
4-methyl-5-nonanone	–	–	–	XX	–	–	–	minor		

[a]Compound may be a major (XX) or minor aggregation pheromone depending upon the geographic isolate of the weevil.

inexpensive racemic mixtures can be used for field trapping of weevils. In some species such as RPW, minor components such as 4-methyl-5-nonanone have been identified (Table 1.1) and some of these have improved trapping efficiencies (see below).

In studies where lethal traps baited with only pheromones or fermenting host tissue were compared with a combination of both, the combination lures synergized trap efficacy by about 8–20-fold. The major pheromone for RPW, ferrugineol, is also the major pheromone for several other weevils, including the regionally sympatric New Guinea palm weevil, *R. bilineatus* (Table 1.1). Phoenicol, the pheromone for the African palm weevil, *R. phoenicis*, was identified as a potential minor component for RPW (=*R. vulneratus*) (Hallet *et al*., 1993). In addition, synomonal pheromone cross-attraction has been reported for several species of palm-associated Dryophthoridae and may be adaptive in overcoming a palm's defense and time-efficient use of a temporarily suitable host (Giblin-Davis *et al*., 1996a). Interestingly, other non-palm-associating members of the Dryophthoridae such as the agave weevil use similar compounds as their pheromones (Ruiz-Montiel, 2008) (Table 1.1). Empirical studies will be needed to see how different *Rhynchophorus* species are recruited to lethal traps of invasive congeners.

1.6 RPW Trapping Overview

Trapping adult *Rhynchophorus ferrugineus* with food-baited traps to monitor activity of the pest, or mass trapping of adults in the field has been recommended since about 1975 as a component of the RPW-IPM program in coconut plantations of India. Abraham and Kurian (1975) reported that split coconut logs smeared with fresh toddy were effective for trapping RPW in the south Indian state of Kerala. Later, coconut logs treated with coconut toddy + yeast + acetic acid were reported to attract the highest number of RPW adults (Kurian *et al*., 1984). Subsequently, Hallett *et al*. (1993) identified the male-produced aggregation pheromone 'ferrugineol' (4-methyl-5-nonanol) and a minor component (4-methyl-5-nonanone) from RPW and *R. vulneratus*. They also observed interspecific matings between *R. ferrugineus* and *R. vulneratus*, suggesting conspecificity, which was subsequently confirmed using several levels of evidence, i.e., *R. vulneratus* is a junior synonym of *R. ferrugineus* (Hallet *et al*., 2004). Empirical studies from Saudi Arabia showed that the addition of the minor ketone (4-methyl-5-nonanone) in small amounts increased capture rates of food-baited RPW pheromone traps by nearly 65% (Abozuhairah *et al*., 1996). In both sexes, the response to ferrugineol appeared to increase with mating (Poorjavad *et al*., 2009). Controlled olfactometry studies showed that female weevils were more attracted to the pheromone than males, when tested separately. However, after mating, adults were less attracted to the pheromone (Faleiro, 2009). Soroker *et al*. (2005) suggested that preferential RPW female attraction to the pheromone may be due to pressure on females to disperse in search of mates, food resources and/or oviposition sites, but also suggested that further studies were needed. Trapping is most efficient for RPW if the aggregation pheromone is combined with the food bait and ethyl acetate (Oehlschlager, 2005) which is very similar to other palm and sugarcane weevils (Giblin-Davis *et al*., 1994, 1996a,c). An overview of the RPW pheromone trap design and major trapping protocols reported world-wide follows. Generating good bait-lure synergy is essential to sustained trapping efficiency of RPW pheromone traps.

1.6.1 Trapping protocols

The following variables are important for successful RPW trapping and retention; trap design, lure efficiency and longevity, type of food bait, trap density, placement of traps, replacement of food baits and efficacy and repellency of insecticides used in RPW pheromone traps.

Trap design

RPW pheromone traps have been designed to facilitate easy entry of adult weevils into the trap while ensuring operational ease for handling and servicing (renewing food bait and insecticide solution) in the trap. Based on the experience of trapping *R. palmarum* in Latin America (Oehlschlager *et al*., 1993), *R. cruentatus* in Florida (Giblin-Davis *et al*., 1994; Giblin-Davis *et al*., 1996a) and initial RPW pheromone trap designs in Saudi Arabia (Anonymous, 1998) the upright bucket trap (5L) with a rough outer surface/jute sack wrapping was found to be the most suitable because it captured more RPW both in date and coconut plantations in Saudi Arabia and India (Abozuhairah *et al*., 1996; Faleiro *et al*., 1998; Hallett *et al*., 1999, Ajlan and Abdulsalam, 2000). In addition, the upright bucket traps are relatively easy to service (for renewal of food bait, water and insecticide). In the United Arab Emirates (UAE) and India, specially fabricated plastic traps with a rough exterior surface have been designed.

The upright bucket trap with four windows (1.5×5 cm^2) cut equidistantly below the upper rim of the bucket is baited with a new pheromone lure hung from inside the lid of the bucket with a piece of wire. About 200 g of kairomone-releasing food bait (dates, green coconut petiole, sugarcane, etc.) is also added to the trap and is vital to ensure entry of the adults into the trap. Moisture is another critical component in trap design for palm weevils (Weissling and Giblin-Davis, 1993; Giblin-Davis *et al*., 1994). The food bait is mixed in one liter of water laced with insecticide (0.05% carbofuran 3G or 0.1% carbaryl 50WP) solution (Anonymous, 1998; Oehlschlager, 1998) to immobilize and kill the captured weevils. Response of RPW to trap colors has been varied in different reports. In the UAE, black traps recorded higher captures when compared with white traps (Hallett *et al*., 1999). In India, trap color did not significantly influence weevil counts (Faleiro, 2005) while controlled wind-tunnel studies in Spain suggested that RPW adults prefer colored traps (Martinez Tenedor *et al*., 2008).

Pheromone lure efficiency, release rate and longevity

Attractiveness of RPW pheromone lures is important to sustain the efficiency of a pheromone-based trapping program. Studies carried out on this aspect in coconut and date plantations are summarized in Table 1.2. During 1994, Chem Tica International, Costa Rica, first commercially synthesized and formulated pheromone lures (Ferrolure) for RPW, and these are widely used in RPW pheromone-based control programs in several countries. Ferrolure is composed entirely of 4-methyl-5-nonanol, while Ferrolure+ is 10% 4-methyl-5-nonanone and 90% 4-methyl-5-nonanol. The Central Plantation

Table 1.2. Summary of efficacy trials of ferruginol-based pheromone lures for *Rhynchophorus ferrugineus*.

Series no.	Formulations tested	Country; Crop; Duration of trial	Superior lure	References
1	– Chem Tica International (high release/slow release)	Saudi Arabia; Date palm; 90 days	High release	Faleiro *et al*., 2000
2	– Agrisense (fast release/ slow release) - Chem Tica International (Ferrolure, Ferrolure+) - Calliope	Saudi Arabia Date palm 30 days	Ferrolure+	Faleiro *et al*., 2000
3	– Agrisense lures - Chem Tica International (Ferrolure improved and Ferrolure+)	India Coconut Two trials – 45 days each	Ferrolure improved	Faleiro and Chellappan, 1999
4	– Chem Tica International (Ferrolure+) - ISCA Technologies lure - CPCRI lure - Pherobank lure	India Coconut Two trials – 30 days each	Pherobank 400 mg lure	Faleiro, 2005
5	– CPCRI lure - Chem Tica International (Ferrolure+)	India Coconut 150 days	Ferrolure+	Faleiro *et al*., 2004
6	– Chem Tica International (Ferrolure+) - ISCA Technologies lure	India Coconut Trial discontinued after lure was exhausted	ISCA Technologies	Kalleshwaraswami *et al*., 2004
7	– Agrisense lures - Chem Tica International (Ferrolure+)	India Coconut 30 days	Agrisense lures and Ferrolure+	Abraham *et al*., 1999

Crop Research Institute (CPCRI), Kerala, India, synthesized RPW pheromone based on Sri Lankan technology during 2000. At present, Pest Control India (PCI), Bangalore, is the leading manufacturer of RPW pheromone in India. RPW pheromone lures have also been commercially produced by Agrisense, UK; Plant Research International (Pherobank), The Netherlands; and ISCA Technologies, USA (Faleiro, 2006). Thermoplastic spatulas, sachets, vials, glass ampules and plastic cans have been used to dispense RPW pheromone in the field (Faleiro, 2005). It is desirable to have a dispenser in which the lure can be seen so that exhausted lures can be identified easily and replaced with fresh dispensers to sustain the overall trapping efficiency.

It is essential to maintain a uniform release rate of RPW pheromone and also to have a lure that persists in the field. A release rate of ferrugineol at 3 mg per day was recommended by Hallett *et al*. (1999). Trials conducted in Goa, India, showed that ferrugineol sustained trapping efficiency even at a low dose of 0.48 mg per day (Faleiro, 2005). Field studies conducted with the PCI, Bangalore lure in Kerala, India, had a uniform release rate of 1.76 mg/day which sustained the trapping efficiency over a period of 14 weeks (Jayanth *et al*., 2007). An easy scoring technique to identify exhausted pheromone lures (Ferrolure) was devised by Faleiro *et al*. (1999) where it was recommended that lures with less than 5% of the chemical be replaced to maintain the trapping efficiency in area-wide RPW-IPM programs. Traps set in the shade retain the chemical lure for longer periods compared with traps exposed to sunlight. Hence, it is recommended that traps be set under shade to maintain a uniform and sustained release of pheromone into the environment.

Reports from Saudi Arabia suggest that both Ferrolure and Ferrolure+ (700 mg) were exhausted in about 12 weeks during the summer versus 24 weeks during winter, when traps were set under shade (Faleiro *et al*., 1999). Ferrolure+ and Ferrolure persisted in the coconut plantations of India for 150 and 84 days, respectively, as compared with Tripheron® (Trifolio-M GmbH, Lahnau, Germany) which had field longevity of 100 days (Krishnakumar and Maheswari, 2003). However, Tripheron+® had field longevity of 170 days and was superior to Ferrolure but on a par with Ferrolure+ with regard to weevil captures (Krishnakumar *et al*., 2004). The CPCRI lure (78.5 mg) from India was reported to have a field longevity varying from 90 to 150 days (Mayilvaganan *et al*., 2003; Faleiro *et al*., 2004). Further, studies from India have reported longevity in the field of 105 and 245 days for 250 mg and 800 mg Chem Tica lures, respectively, and 126–357 days for 400 mg and 1100 mg ISCA Technologies lures, respectively (Kalleshwaraswamy *et al*., 2004). Plant Research International (Pherobank), The Netherlands, dispensed RPW pheromone using a biodegradable polymer, which allows the pheromone to be emitted gradually at a high temperature (Toussaint, 2006). Under the agro-climatic conditions prevailing in Kerala, India, the PCI, Bangalore lure (800 mg) has field longevity of c. 450 days (Jayanth *et al*., 2007). Unfortunately, a standardized evaluation of all available release devices with set starting volumes and formulations in the field with homogeneous RPW distribution/abundance has not been conducted. Thus, it is difficult to compare them accurately. However, pheromone is a critical component to the synergy of food-baited traps and the cost-effective, long-term release of RPW aggregation pheromones needs to be factored into the trapping equation.

Food baits

Food baits added to RPW and other *Rhynchophorus* species pheromone traps play an important role in orienting the attracted weevils into the trap (Giblin-Davis *et al*., 1996a; Hallett *et al*., 1999) similar to other Coleopteran systems (Borden, 1985). The synergy that occurs between the pheromonal lure and the food bait is vital in enhancing trapping efficiency of food-baited RPW pheromone traps. Weak bait–lure synergy potentially results in the attracted weevils orienting themselves towards nearby palm trees instead of towards the trap. The importance of adding kairomone-releasing food baits in RPW pheromone traps has been emphasized by many, and a summary of recommendations is presented in Table 1.3. Moisture is also an important ingredient of a palm weevil pheromone trap, because RH (relative humidity) enhances bait–lure synergy (Weissling and Giblin-Davis, 1993; Giblin-Davis *et al*., 1996a). Ethyl acetate is one of several important esters that are released during fermentation of host tissues that appears to be

Table 1.3. Food baits recommended for use in *Rhynchophorus ferrugineus* pheromone traps.

Sr. no	Food bait recommended	Reference
1	Sugarcane	Oehlschlager, 1994; Faleiro and Chellappan, 1999; Hallett *et al*., 1999
2	Dates (*khajur*)	Faleiro, 2005
3	Date palm tissue	Anonymous, 1998
4	Coconut petiole	Faleiro, 2005
5	Plantains	Nair *et al*., 2000
6	Sugarcane – molasses	Muthiah *et al*., 2005
7	Coconut shavings	Jayanth *et al*., 2007
8	Palmyrah fruit juice	Muthiah *et al*., 2007

kairomonal to *Rhynchophorus* species (Gries *et al*., 1994; Giblin-Davis *et al*., 1994, 1996a). Increasing levels of ethyl acetate to about 400 mg/day increased attraction of the aggregation pheromone and bait tissue of the palm-associated weevil, *Metamasius hemipterus* (Giblin-Davis *et al*., 1996c), and the same phenomenon has been confirmed in RPW pheromone traps. Experiments conducted in the UAE, Egypt, Oman and Saudi Arabia showed that RPW captures were increased by 2–3 times when ethyl acetate was added to food-baited pheromone traps (Oehlschlager, 1998; El-Sebay, 2003; Abdallah and Al-Khatri, 2005; Shagag *et al*., 2008). Chem Tica International has incorporated both the pheromone and ethyl acetate into a single lure called Ferrolure + HP which can be used in tissue-baited traps (Oehlschlager, 2005). However, ethyl acetate is expensive and substantially adds to the operational costs.

In general, the food bait used for RPW trapping should be easily obtained and cost-effective. Hence, as low-grade dates might be recommended for RPW pheromone traps in the Middle East, green coconut petiole shavings might be ideal in India. RPW were most attracted to bucket traps baited with sugarcane followed by traps baited with coconut exocarp, whereas date fronds were the least preferred bait in date palm orchards in Gujarat state in India (Muralidharan *et al*., 1999). Ideally, the food bait will have a relatively high sugar content (Giblin-Davis *et al*., 1996a; Oehlschlager, 2005). Faleiro (2005) suggested that 200 g of coconut petiole was sufficient for one trap, and found that weevil captures declined progressively when traps were serviced (change of food bait + water) at 10, 20 and 30 days. However, addition of water in traps sustained the trapping efficiency when traps were not serviced beyond 15 days. This emphasizes the need to keep food baits hydrated, because *Rhynchophorus* species are moisture-loving (Wattanpongsiri, 1966; Weissling and Giblin-Davis, 1993), and because moisture is required for the host tissue to continue to ferment and release host kairomones (Giblin-Davis *et al*., 1996c). Oehlschlager (2005) extended the effective life of the food bait in RPW traps from 2 to 7 weeks by adding propylene glycol to the bait to slow down evaporation of water from the trap. Thus, a suitable food bait mixed with water will help improve the bait–lure synergy and enhance RPW captures (Faleiro, 2006). Rochat (2006) suggested that more work is needed to understand the mechanism of additive or synergistic responses to the combined odor of pheromone + palm.

Insecticide in traps

Once the adult weevils enter the RPW pheromone trap it is essential to prevent their escape. This can be achieved by immobilizing/killing the captured weevil with an insecticide mixed with the bait, or by mechanically preventing escape of adults (e.g. by using funnel traps; see Hallett *et al*., 1999). However, as bucket traps have been reported to be the most suitable RPW-pheromone traps, insecticides are commonly used to kill and retain captured adult weevils. Trials from Al-Qateef in Saudi Arabia have shown that among the insecticides evaluated in RPW pheromone traps, deltamethrin had the least repellency as compared with quinalphos, which exhibited the highest repellency to adult weevils (Abozuhairah *et al*., 1996). Trials conducted in India showed that carbofuran and carbaryl were suitable for use in RPW pheromone traps to kill and retain trapped weevils (Faleiro, 2005; Abraham and

Nair, 2001). Soap/detergent has been used to kill and retain captured weevils in bucket traps (Giblin-Davis *et al.*, 1994; Rochat, 2006; Jayanth *et al.*, 2007). Care should be taken to see that the insecticide/detergent used does not counter the odors produced by the lure/bait; this would lower the trapping efficiency.

Trap placement

In order to maximize the lure longevity in the field it is essential to set RPW pheromone traps in the shade. Care should also be taken to avoid setting traps on palms in the age group susceptible to RPW attack of <20 years, or near, or on very susceptible palms, such as *P. canariensis* (Hunsberger *et al.*, 2000). Higher RPW captures were recorded when traps were placed at a height of 1 m from the ground in coconut plantations in Goa, India (Faleiro, 2005). In Israel, UAE and Spain, RPW pheromone traps are currently set at ground level. However, traps placed at waist height on tree trunks are convenient to service when compared with traps set at ground level (Faleiro, 2005). RPW was effectively mass trapped in area-wide pheromone-based IPM programs in Kerala, India, by setting traps about 1.5 m from the ground. In this trial, traps set in the middle of the coconut plantation caught fewer weevils when compared with traps on the periphery. Due to fragmentation of coconut farms, large-scale community-based mass trapping of RPW is likely to be more effective when compared with single-farm trapping (Jayanth *et al.*, 2007).

Trapping density

Initially, Oehlschlager (1994) recommended a trapping density of one trap/ha and one trap/100 ha in mass trapping and monitoring programs, respectively. However, mass trapping of RPW adults in pheromone-based RPW-IPM programs has been implemented at different densities ranging from high density trapping of 10 traps/ha of date plantations in Israel to 1.5 traps/ha in date plantations of the Al-Hassa region in Saudi Arabia. These reports also indicate that monitoring of RPW was done at one trap/ha and one trap/100 ha in Israel and Saudi Arabia, respectively (Abraham *et al.*, 2000; Soroker *et al.*, 2005). In Egyptian date plantations, RPW was effectively mass trapped at a trap density of 0.5 traps/ha (Anonymous, 2004). In coconut plantations in Goa, India RPW pheromone trap density trials for mass trapping programs revealed that a trap density of one trap/ha was sufficient. However, weevil catches doubled by increasing the density to two traps/ha (Faleiro, 2005). Recently, Jayanth *et al.* (2007) reported successful management of RPW in area-wide programs by setting pheromone traps at 2.5 traps/ha. Rochat (2006) recommended that RPW pheromone traps should be set apart from areas bearing high infestation risks due to the characteristics of the palm, or only at low density. The agro-system involved, intensity of the pest, attractiveness of the lure and the resources available to service the traps may influence the trapping density. In a date plantation in Al Hassa, Saudi Arabia, with less than 1% infestation, one trap/ha was sufficient to mass trap the pest. However, in plantations with more than 1% infestation, 10 traps/ha recorded the best and significantly superior weevil captures as compared with other tested trapping densities (i.e., 1, 2, 4 and 7 traps/ha) (Faleiro, 2009). Based on the preceding discussion the best trapping protocols to be adopted are summarized in Table 1.4.

1.6.2 Monitoring, mass trapping of RPW and validating pheromone-based RPW-IPM programs

Monitoring the activity of RPW is essential for keeping a close watch on the establishment and subsequent build-up of the pest. After initial reports of infestation, it is imperative to monitor the activity of adult weevils. Food-baited RPW pheromone traps have been widely used in several countries in surveillance programs to assist and develop early-warning alerts. Adopting the best pheromone-trapping protocols is essential in such surveillance programs to minimize the risk of the pheromone traps becoming devices for spreading RPW (Rochat, 2006; Faleiro, 2006). Combining weevil activity as gauged through RPW pheromone traps along with geographic information systems (GIS) can serve as a valuable tool to improve and support decision-making capabilities, especially when trying to manage invasive pest populations in area-wide operations. GIS allows storage of vast amounts of data on the spatial and temporal spread of a pest, and also assists in predictive analysis.

Table 1.4. Suggested pheromone trapping protocols for *Rhynchophorus ferrugineus*.

Trap component/ protocol	Recommendation
Trap design	Capture adult weevils with bucket traps with four windows (1.5 × 5 cm^2) (5 L capacity) cut equidistantly below the upper rim of the bucket having rough outer surface
Pheromone lure	Use commercially available lures that are efficient and long lasting
Food bait	Should be easily available, cost effective and generate good bait–lure synergy. Dates (200 g) in one liter water are the best
Ethyl acetate	Significantly enhances weevil captures when incorporated in food-baited RPW pheromone traps
Insecticide in trap	Add non-repellant insecticide to the water and food bait in the trap. Soap/ detergent may repel adult weevils
Trap servicing (renewing food bait and insecticide solution)	Once every 7–10 days (vital to generate strong bait–lure synergy)
Trap density for surveillance	1 trap/100 ha *or* 1 trap every 1–2 km along motorable roads.
Trap density for mass trapping	High density: 4–10 traps/ha; low density: 1 trap/ha (depending on the intensity of the population and resources available for servicing the traps)
Trap placement	Preferably set traps on the periphery of the plantation, 1 m above the ground, under shade. Hang traps on trunks of old palms with hardened trunk tissue (>25 years old)/non-host trees. Ground or surface trapping can also be practiced. Do not set traps near young palms with offshoots.
Lure replacement	Go by manufacturer's recommendation. Prefer long lasting and efficient lures.

Ferrugineol-based pheromone traps attract and capture twice as many females as adult male weevils (Oehlschlager, 1994; Hallett *et al*., 1999; Vidyasagar *et al*., 2000a; Abraham *et al*., 2001; Faleiro, 2005; Soroker *et al*., 2005, Jayanth *et al*., 2007). From the vantage of weevil management, this is desirable because female weevils initiate damage to the palms through oviposition and subsequent larval development. Examination of the reproductive status of female weevils captured in RPW pheromone traps has shown that most of these females are young, gravid and fertile (Abraham *et al*., 2001; Faleiro *et al*., 2003; Jayanth *et al*., 2007) and many had initiated egg development (Kalleshwaraswamy *et al*., 2005). Furthermore, Jayanth *et al*. (2007) reported that 74% of the pheromone traps captured female weevils that had not yet initiated oviposition. These studies highlight the potential benefits of using food-baited pheromone traps in mass-trapping programs to suppress population build-up in the field.

Successful management of RPW in large areas of date (El-Ezaby *et al*., 1998; Abraham *et al*., 2000; Vidyasagar *et al*., 2000a, b; Al-Khatri, 2004; Soroker *et al*., 2005; Oehlschlager, 2006) and coconut plantations (Rajapakse *et al*., 1998; Faleiro, 2005; Sujatha *et al*., 2006; Jayanth *et al*., 2007) have been reported from several countries. These programs are long term in nature and need substantial investment over a period of time. The report of enhanced infestations around RPW pheromone traps by Rochat (2006) from date plantations in Iran requires further investigation. It would be advisable to protect young palms in a radius of 50–100 m from the traps by periodic insecticide cover sprays (Faleiro, 2006). It is also important to further understand the mechanism of semiochemical attraction in RPW, to minimize the risk involved in attracting RPW female weevils to young palms near the traps, and also to examine potential repellants that could be used to reduce host apparency in critical locations. Based on experiments with repellants for *R. palmarum* in oil palm, Oehlschlager (2005) suggested that they could be used in 'push–pull' strategies for the management of palm weevils.

Faleiro (2006) recommended that pheromone-based area-wide IPM programs need to be implemented at a low infestation level of just 1% infested coconut palms. Implementing area-wide management of RPW on the basis of trap captures or infestation reports can be inaccurate, as they may either under- or over-estimate the pest intensity in the field. The aggregated nature of this pest (Faleiro *et al*., 2002) may also result in inaccurate estimation of infestation levels. Faleiro and Kumar (2008) proposed sampling plans based on the concept of sequential sampling which was developed using the formulae given in Southwood and Henderson (2000). The sampling plans allow for rapid and accurate classification of RPW infestation in coconut plantations of India, by inspecting palms to detect infestation levels in a sequence that allows a decision to be made to either implement or not to implement an area-wide management program of RPW control. A similar decision-making sampling plan to initiate area-wide management of RPW in date plantations in Al-Hassa, Saudi Arabia, was also developed (Faleiro, 2008). These plans classify the intensity of the pest in the field, allowing for a surveillence program to be upgraded to a mass trapping-based IPM operation. Conversely, sequential sampling plans could be used to validate RPW-IPM programs to arrive at an accurate decision of scaling-down mass trapping of the pest to surveillance mode or withdrawing the traps from the field. These plans are based on the hypothesis that 'area-wide management of RPW is not required' and are developed at risk factors of 'a' and 'b' set at 0.05, where 'a' is the probability of error that a low infestation level is wrongly categorized as high, and 'b' is the reverse situation where a high level of infestation is categorized as low. The plan also takes into account the assumed action threshold of infested palms for initiating control and the aggregation index (K).

The pheromone-based area-wide RPW-IPM program in date palms in Al-Hassa, Saudi Arabia, was validated during 2008 on a 100-ha scale (10,000 palms), where fewer than 42 RPW-infested palms/100 ha suggested that infestation levels were below the assumed action threshold of 1% and that the strategy was having an impact. Situations where there were more than 54 RPW-infested palms/100 ha implied that the damage levels were above the action threshold and that the IPM program needed major improvement. At intermediate infestations of 42–54 infested palms/100 ha, damage levels were approaching the action threshold (1%) and the strategy in these areas needed to be strengthened.

1.7 RPW-IPM Programs in Date Palms

Due to prevailing economic and social conditions in Saudi Arabia and other parts of the Middle East, date groves are often neglected or abandoned over time, making them reservoirs for RPW and leading to the capture of several times more adult weevils in pheromone traps than in farms that are well-tended (Abozuhairah *et al*., 1996). Systematic clearing of abandoned date gardens helps to temper area-wide epizootics of RPW by reducing their breeding sites.

Irrigation practices can play a key role in the spread of RPW infestations in date palms in the Middle East. Some farmers use flood irrigation, creating a situation where water is always in contact with the base of the date palm and its offshoots. This creates an environment very favorable for the weevils to lay their eggs (Aldryhim and Al-Bukiri, 2003a, b). Studies of the distribution of RPW in drip and flood irrigation within a palm grove showed that 89% of the total infested trees were detected in plots with flood irrigation. This suggested that irrigation management and soil moisture are key factors in the dispersion and colonization success of RPW in date palms (Aldryhim and Al-Bukiri, 2003a, b).

Cultural management practices can also involve the removal and destruction of infested offshoots and the application of soil mixed with a pesticide or gypsum which can be effective for preventing the entry of RPW into the date palm. Pesticides are used either for preventing the entry of RPW or for curing an already infested date palm. The chemicals used in the IPM program in Saudi Arabia include Supracide® (Gowan Co., Yuma, Arizona, USA), Metasystox® (Bayer, Isando, Germany), Cypermethrin, Dimethoate (27.8%), Chlorpyrifos (22.2%) and Trichlorphon (Vidyasagar *et al*., 2000a). Date palm stems with RPW infestations can be treated by wound cleaning and inundation with a pesticide. The identified infestation is first cleaned by removing the softer, damaged tissues. Slanting holes 20–25 cm deep are then created around the stem wound, where a pesticide is introduced following the labeled recommendations, and sealed with wet mud.

The treated palms are then monitored to confirm the cessation of oozing sap from these sites and the subsequent drying of the wound, which can suggest successful control of RPW (Abozuhairah *et al*., 1996). In regions where the humidity is very high, deeply damaged stems are treated by stem cleaning followed by filling these cavities with wet sand mixed with pesticide dust. These sand-filled stems are covered with a polyethylene sheet to retain the humidity. This method was successfully applied for several palms in the Eastern Province of Saudi Arabia (Vidyasagar, pers. obs., 2010).

1.8 Recent Invasions of RPW

1.8.1 Northern Mediterranean Basin and the Canary Islands

In Europe, palm trees are mainly grown for ornamental purposes in urban areas and resorts, and therefore cannot be considered as a conventional crop. Only palms grown in groves or nurseries should be considered as a traditional crop. This makes the European case completely different from that in most RPW-infested countries up until now, where palms are mostly grown in regular orchards or around oases for their products (oil, dates, fronds, etc.). In Europe, palms have been widely used in gardens, parks and avenues since the 18th century (Morici, 1998), especially the highly prized but very RPW-susceptible CIDP, *Phoenix canariensis*. Other exotic palm species, such as *Trachycarpus fortunei* and *Washingtonia* spp., or the indigenous *Chamaerops humilis* palm in Europe, are also highly valued as ornamentals (Fig. 1.9). In addition, palms in Europe have other environmental or historical value. For example, the Theophrastus palm tree forest at Vai in Crete (Greece) has the largest subpopulation of the threatened Cretan date palm, *P. theophrasti*, which can be found on other Aegean Islands. The date palm grove at Elx (south-eastern Spain, with about 240,000 palms) is catalogued as a World Heritage Site by UNESCO, and nearby groves at

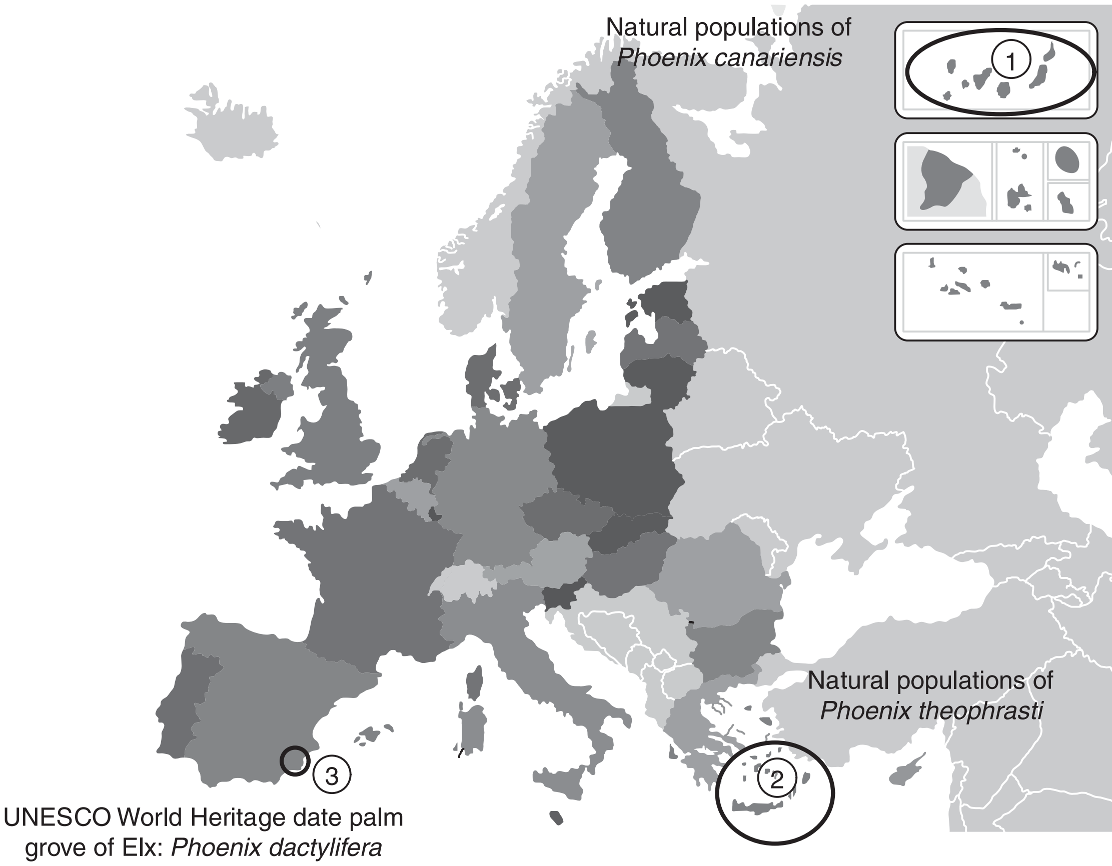

Fig. 1.9 Important palm locations in the EU threatened by the recent expansion of RPW (red palm weevil, *Rhynchophorus ferrugineus*): (1) Canary Islands off the north-western coast of Africa; (2) Crete and other Aegean Islands; and (3) South-eastern Spain. (Prepared by J.A. Jacas.)

Alacant and Orihuela have been declared Historic Sites by the Spanish Government. Last but not least, the wild forests of *P. canariensis*, in their native Canary Islands, constitute the most important source of genetic variation for this species. For all the above reasons, the detection in Europe of *R. ferrugineus* raised new questions in a scenario that was completely different to what had gone before.

Rhynchophorus ferrugineus was first detected in the Mediterranean basin in 1992, when it was found in date palms in Egypt (EPPO, 2008). Three years later, the occurrence of *R. ferrugineus* in south-east Spain (Almuñécar, Autonomous Community of Andalusia) (Fig. 1.10) was officially acknowledged and control measures against it were immediately put into place. These measures were partially successful and until 2000 the pest remained localized in municipalities around the initial focus of Almuñécar (Fig. 1.10). As a consequence, that year, Spanish restrictions to palm movement were partially lifted. Unfortunately, the relaxation of the containment measures led to massive imports of infested palms from Egypt (Fig. 1.11). These palms were extensively used in new urban areas and resorts set along the Mediterranean coastal districts of Spain in conjunction with the housing market bubble occurring at that time. Luckily, in 2003 fear of new *R. ferrugineus* outbreaks prompted Spanish authorities to prohibit the import of any palm species into the World Heritage palm grove of Elx, as an urgent preventive measure against the weevil. In 2006, this protection extended to the historical date palm groves of Alacant and Orihuela, and palm movement within a radius of 5 km around them (protecting an area of 23,562 ha for the three historical sites) was restricted. However, in 2004, an outbreak of *R. ferrugineus* occurred in Olocau (province of Valencia) (Fig. 1.10), more than 600 km north-east of the initial focus of Almuñécar and about 200 km north of Elx. Additional foci appeared during 2005 (Murcia and Catalonia) and 2006 (Balearic Islands), and by the end of that year all the Mediterranean Autonomous Communities of Spain were officially infested (Fig. 1.10).

In 2005, *R. ferrugineus* was detected in two resorts in the Canary Islands of Fuerteventura and Gran Canaria (Fig. 1.10). In 2006, strict measures to protect native forests of *P. canariensis*, including an eradication program and

Fig. 1.10. Spanish Autonomous Communities infested by RPW (red palm weevil, *Rhynchophorus ferrugineus*) (year of detection in parentheses) with important locations related to the spread of the pest in Spain (dots). (Prepared by J.A. Jacas.)

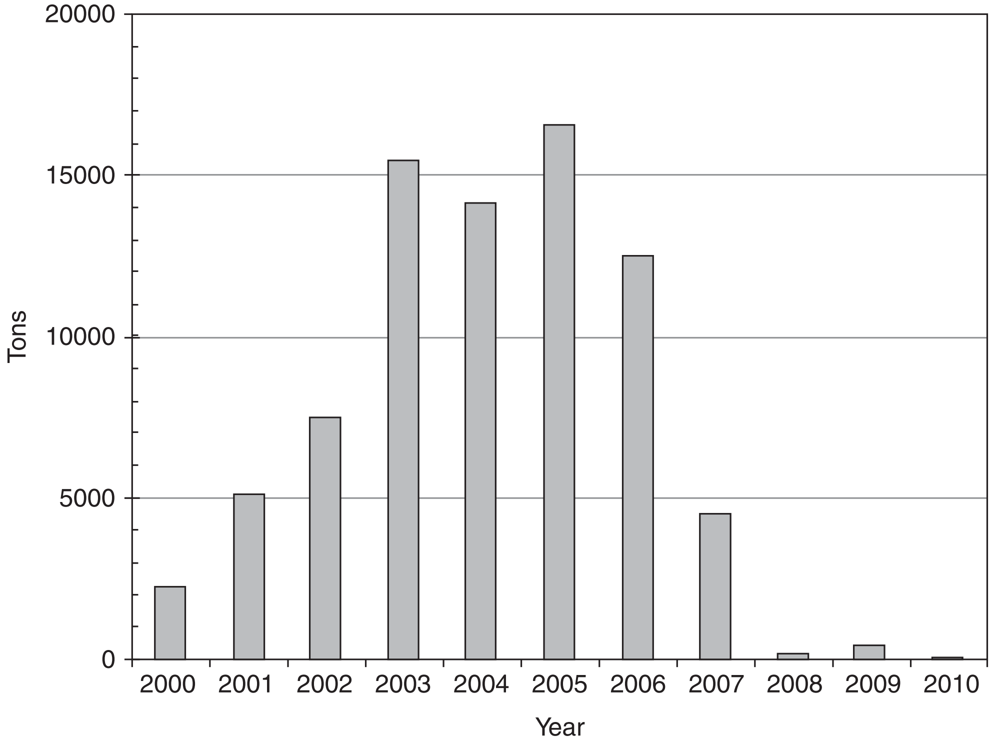

Fig. 1.11. Adult *Phoenix dactylifera* palms (tonnes) imported from Egypt to Spain from 2000 to May 2010 (source: EU Conference on the Red Palm Weevil, Valencia, May 2010). (Prepared by J.A. Jacas.)

the prohibition of importation of any palms from outside the Islands, were established for the whole Autonomous Community of the Canary Islands (BOC, 2007), which have their own phytosanitary regulations apart from those in force in the rest of Spain. New foci appeared up until 2008, including an outbreak in the hitherto uninfested island of Tenerife in 2007. However, no additional foci have been detected since 2008, and the islands of El Hierro, La Gomera, Lanzarote and La Palma have remained pest-free.

In parallel to the situation in Spain, *R. ferrugineus* spread through southern Europe. It was officially declared in Italy in 2004, in Greece in 2005, in France and Cyprus in 2006, in Portugal, Malta and Turkey in 2007 and in Georgia and Slovenia in 2009 (Fig. 1.12). As in all previous cases in Europe, infestations are presumed to have occurred earlier, from 1–2 years prior, depending on local temperatures. Dead palms or those close to death are easily detected by the untrained eye, and 1–2 years is the time necessary for *R. ferrugineus* to complete two to three generations in a single palm, the time that a new infestation takes to result in palm death (Dembilio and Jacas, 2011).

1.8.2 *R. ferrugineus* legal issues in the EU: local, regional, national and European regulations

First detection of *R. ferrugineus* within the EU took place in the Spanish Autonomous Community of Andalusia (Fig. 1.10). As a consequence the Department of Agriculture and Fisheries of the Andalusian Government (Junta de Andalucía) was the first European legal body to take action against this pest. Immediately after detection, palm movement from the nurseries in the provinces of Almería, Málaga and Granada (those around the initial focus of Almuñécar, Fig. 1.10) was prohibited for 2 months. During this time all nurseries had to protect their palms with a soil treatment of Aldicarb. In the meantime, the Spanish Ministry of Agriculture, Fisheries and Food (MAPA) published an Order (BOE, 1996) establishing a series of provisional

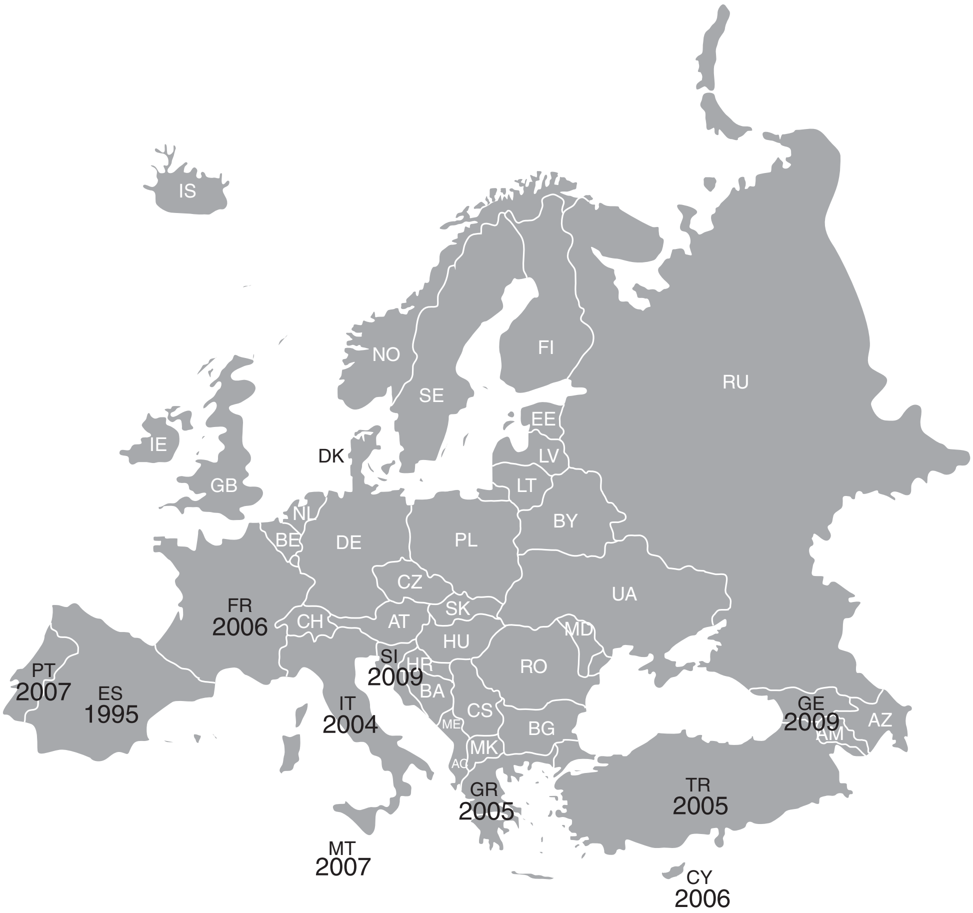

Fig. 1.12. Year of detection of RPW (red palm weevil, *Rhynchophorus ferrugineus*) in different European countries. (Prepared by J.A. Jacas.)

measures against *R. ferrugineus*. These measures were relatively strict and included:

- prohibition of the import of Palmaceae from non-EU countries (third countries);
- compulsory use of the EU Plant Passport for any movement of Palmaceae originating within the EU; and
- eradication measures, including chemical treatments, pheromone trapping and destruction of infested specimens both in public and private gardens in the infested area.

In June 1997, the Andalusian Government established further measures against *R. ferrugineus* (BOJA, 1997), including the obligation of all palm producers, dealers and importers in Andalusia to enroll with the Spanish Official Register of Plant Producers, Dealers and Importers regulated by the Real Decreto 2071/93 (BOE, 1993). As a consequence, all these agents were subjected to Official Phytosanitary Inspections, which are compulsory to qualify for the EU Plant Passport. Andalusian Government measures also included serious limitations for the movement of palms within infested areas, which was always subjected to the non-detection of symptomatic palms within the nursery, as described in the same Real Decreto (Article 7, point 6).

The presence of *R. ferrugineus* in Spain obviously affected EU regulations, and the Council Directive 77/93/EC on protective measures against the introduction into the Community of organisms harmful to plants or plant products and against their spread within the Community in force at that time, had to be adapted.

Research activities carried out during these years by the Spanish National Institute for Agronomic Research (INIA) (Esteban-Durán *et al*., 1998a, b) and the Universidad de Almería (Cabello *et al*., 1997; Barranco *et al*., 1998, 2000) improved current knowledge on the weevil bio-ecology and control. This information, together with that gathered from technicians working in the infested area, allowed the Spanish MAPA to derogate the former Order (Orden de 18 de Noviembre de 1996; BOE, 1996) and to approve a new one (Orden de 28 de Febrero de 2000; BOE, 2000), where restrictions to palm movement both within EU and from third countries were partially lifted. These restrictions, though, were extended to other *Rhynchophorus* species (*R. bilineatus*, *R. cruentatus*, *R. palmarum*, *R. phoenicis*, *R. quadrangulus* and *R. vulneratus* [=variant of *R. ferrugineus* see Hallet *et al*., 2004]), and referred to all specimens belonging to the Palmaceae family with an upper diameter of >5 cm, with the exception of seeds and fruits.

No further legal changes occurred until 2004, in coincidence with the explosive spread of *R. ferrugineus* in Europe starting that year (Fig. 1.12). Both local and national regulations changed with the detection of the weevil in their territories. Finally, the alarm created within the EU by this situation prompted the EU to publish the Commission Decision 2007/365/EC on emergency measures against the introduction and spread within the EU of *R. ferrugineus* (OJEU, 2007). This decision was modified in October 2008 (OJEU, 2008) and August 2010 (OJEU, 2010), and was incorporated into national, regional and local laws. The main points are:

- *Specific import requirements*: palms should have been grown throughout their life either in a country where *R. ferrugineus* is not known to occur, or in a *R. ferrugineus*-free area. Otherwise, palms should have been grown during a period of at least 1 year prior to export in a place of production subjected to official inspections certifying that no signs of *R. ferrugineus* presence have been observed.
- *Conditions for movement*: plants should be accompanied by a plant passport and, if originating from an infested area, they should have been grown during a period of 2 years prior to the movement in a site with complete physical protection against *R. ferrugineus*, and no signs of its presence should have been observed during official inspections.
- *Establishment of demarcated areas within the EU infested countries*: these areas should include the infested zone plus a buffer zone of at least 10 km beyond the boundary of the infested zone. Extensive monitoring and appropriate measures against *R. ferrugineus* aimed at its eradication should be carried out within these areas.

Although the aforementioned measures have been applied by affected EU countries, new foci of *R. ferrugineus* have been continuously detected, and the situation within the EU has worsened. For example, in Spain (Fig. 1.10) 49,800 palms, mostly *P. canariensis*, were killed by *R. ferrugineus* from 1996 to 2009. In the case of the Autonomous Community of Valencia, control measures taken against the weevil during this period, mainly an eradication program, cost about €11 million (Dembilio and Jacas, 2011). Until now, eradication has been successful only in the Canary Islands (Figs. 1.13–1.14), with the first pest-free foci being declared in 2010 after 3 years of non-detection of infested palms and no collection of adults in pheromone-baited traps in the demarcated areas.

Reasons for the failure of the eradication program up until now include: (i) the difficulty of the early detection of infested palms; (ii) the lack of a sound quarantine treatment against the weevil; (iii) the difficulty of involving homeowners in the process; (iv) the risks associated with the use of mass trapping in uninfested areas; (v) the lack of highly effective, environmentally safe plant protection strategies (biological control, semiochemicals, soft pesticides, etc.) suitable for public areas such as gardens, parks and avenues; and (vi) the incomplete knowledge of the bioecology of *R. ferrugineus* developing in *P. canariensis* under the Mediterranean climate. Research is therefore urgently needed to fill these gaps.

1.8.3 Current strategies against *R. ferrugineus*: the Spanish case

The current strategy against *R. ferrugineus* in Spain includes different actions including chemical, biological, cultural, biotechnological and legal/regulatory controls as well as sanitation:

- *Preventive treatments*. A minimum of eight treatments per season (from March to November) are recommended. Only five active substances were authorized by the Spanish Ministry of Agriculture in winter 2011.

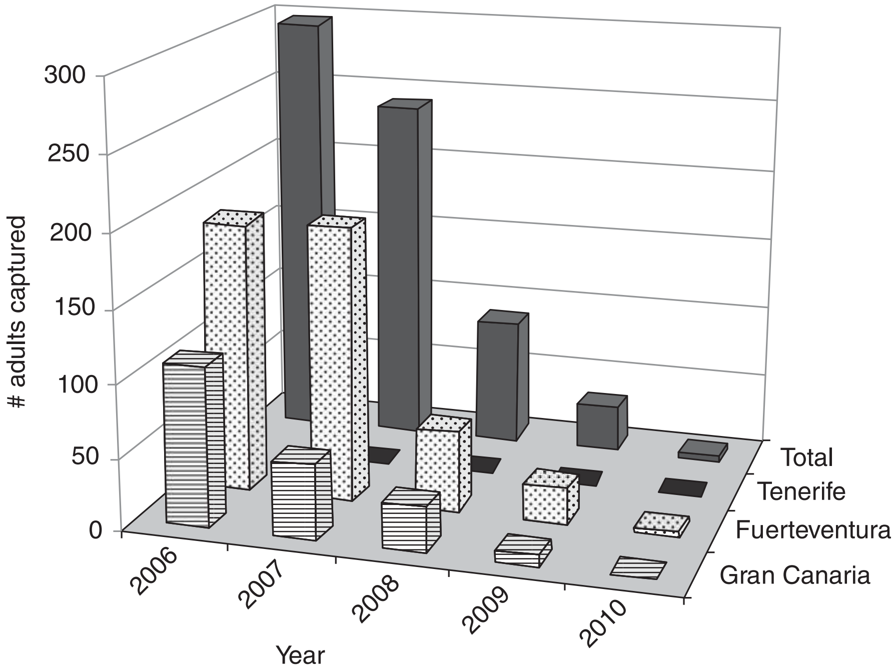

Fig. 1.13. Number of adult RPW (red palm weevil, *Rhynchophorus ferrugineus*) captured in pheromone- and tissue-baited traps in the Canary Islands from 2006 to May 2010 (source: EU Conference on the Red Palm Weevil, Valencia, May 2010). (Prepared by J.A. Jacas.)

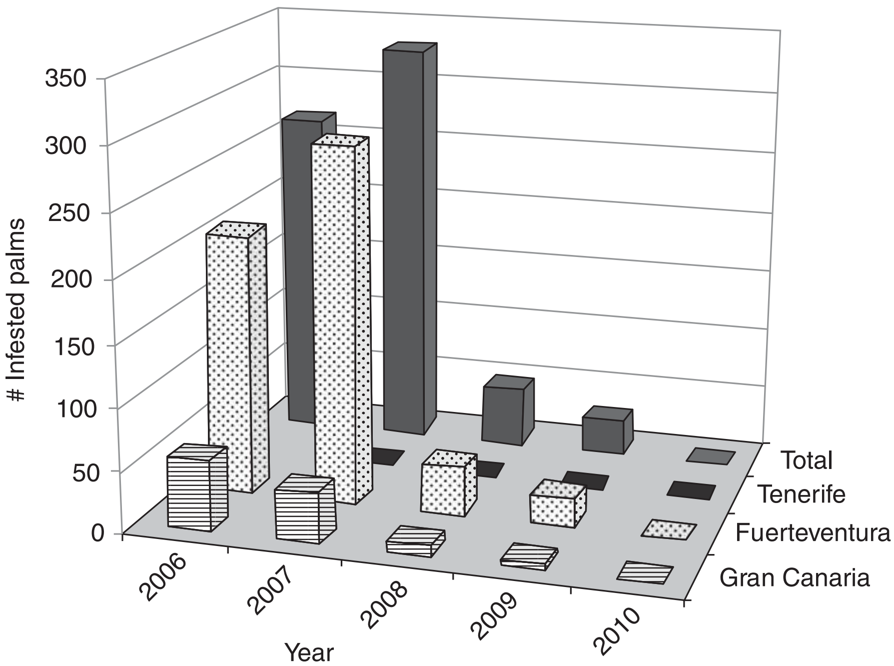

Fig. 1.14. RPW- (red palm weevil, *Rhynchophorus ferrugineus*) infested palms destroyed in the Canary Islands from 2006 to May 2010 (source: EU Conference on the Red Palm Weevil, Valencia, May 2010). (Prepared by J.A. Jacas.)

These were abamectin, chlorpyrifos, imidacloprid, phosmet and thiametoxam (MARM, 2011), as well as the entomopathogenic nematode *Steinernema carpocapsae* (Weiser) (Nematoda: Steinernematidae), which proved highly effective when applied in a chitosan formulation (Llácer *et al*., 2009; Dembilio *et al*., 2010a). The latter has also proved effective as a curative treatment (Llácer *et al.*, 2009). To solve the problem of reaching the top of the palm when treating tall palms with either nematodes or other pesticides, the use of a fixed 4-mm polyethylene pipeline holding 2–4 micro-sprinklers on the top of the stipe is becoming popular in many Spanish cities. In Valencia, for instance, most palms in public gardens have such a pipeline fixed on the top of the stipe down to a height of 2.5 m. When needed, this line is directly connected to a pump on a transport platform and the pesticide is applied from it with no need for a worker to get to the top of the palm stipe (Fig. 1.15).

- *Pruning*. Wounds, such as those from pruning, emit volatiles that attract adult *R. ferrugineus*, and thus pruning can increase the likelihood of a new infestation. This is the reason why pruning and any other activity producing wounds are best performed in winter, when adult *R. ferrugineus* activity is reduced and immature mortality is highest (Dembilio and Jacas, 2011). All wounds, regardless of the time of year (for example, after cutting an 'inspection window' into the palm canopy), should be immediately treated with an appropriate insecticide.
- *Sanitation: arboreal surgery*. Based on the traditional production of 'palm syrup' from *P. canariensis* in the Canary Island of La Gomera (Fig. 1.16), infested palms can be mechanically sanitized. This is a technique especially valuable for old monumental palms that must be saved from RPW. Provided that the inner meristematic tissues have not yet been affected by the weevil, the palm can recover in a few months.

Fig. 1.15. Treatment application pipeline (left-pointing arrow in left and top right photos) and inspection window in the crown region of a specimen tree of CIDP (Canary Islands date palm, *Phoenix canariensis*) (ellipses) in a public palm garden in the city of Valencia, Spain. See text for description of how this is used for frequent applications of pesticides or biological control agents into the vulnerable crown region of legacy palms. Bottom-right: a residential site where two CIDP have died, exhibiting typical crown symptoms due to RPW infestations (right-pointing arrows) One CIDP is a candidate for curative and prophylactic treatment using the inspection window and pipeline (left-pointing arrow). (Photos: J.A. Jacas.)

Fig. 1.16. Traditional palm syrup extraction in the Canary Islands, demonstrating the resiliency of mature CIDP (Canary Islands date palm, *Phoenix canariensis*) to occasional severe leaf and petiole removal. Upper images: palm management just above the apical meristem for syrup collection. Lower figures: palm recovery after syrup extraction. (Source: Mr Gerardo Mesa Noda.)

- *Monitoring for early detection*. Trained gardeners and technicians are necessary for early detection of *R. ferrugineus* infested palms. In general, the Departments of Agriculture of the different Spanish Autonomous Communities are responsible for the training courses addressed to the technicians who will later work either for private companies or for the municipalities involved.
- *New plantations*: Any palm used in a new plantation, landscape project or garden should have a valid EU Plant Passport. This should ensure that these plants have followed the strict rules regulating plant production and movement in agreement with the Commission Decision 2007/365/EC.
- *Removal and destruction of affected palms*. Infested palms should be removed and destroyed. Municipalities and homeowners are responsible for the cutting of the palms and their transportation to a designated destruction site where they are ground to powder. Burning is not recommended for destruction because palms do not burn easily, and complete destruction of *R. ferrugineus* cannot be guaranteed in this case.
- *Trapping*. Mass trapping is only allowed under direct supervision of the technicians of the Departments of Agriculture of the different Spanish Autonomous Communities. A trap set in an uninfested area can easily lead to its infestation by weevils responding to the attractive plumes coming from the trap. In addition, a trap can greatly increase the incidence of *R. ferrugineus* in an area if neighboring palms are not adequately protected. This is especially true in the case of the highly susceptible *P. canariensis*.

1.8.4 North Africa

Date farming is an important component of the agrarian economy in North Africa on which millions of farm families earn their livelihood. Egypt and the five Maghreb countries (Algeria, Morocco, Tunisia, Libya and Mauritania) in North Africa account for nearly 25% of the global date production. RPW apparently entered Saudi Arabia in 1987 through importation of ornamental palms and then spread to date palm plantations, causing serious loss to palms in the Eastern Province and later in most of the palm-growing regions of the country (Abraham and Vidyasagar, 1993) (Fig. 1.17). In date palm, propagation involves the use of offshoots produced from the base (bole region) of the stem of palms. RPW is attracted to cracks where these offshoots connect and wounds made during their harvest for transplantation. Unfortunately, hidden stages of RPW are easily transported for long distances and can establish in new locations (Abraham and Vidyasagar, 1993; Abraham *et al*., 1998). RPW was reported in North Africa from Egypt in the early 1990s (Cox, 1993) and has since spread to all of the major date-palm oases of that country, mainly through transportation of infested palm trees.

The Maghreb region of North Africa is critically situated between several RPW-infested countries including Egypt in the east, the Canary Islands in the west and countries of the Mediterranean basin including Spain, Portugal and Italy in the north. The Maghreb countries did well to keep this dreaded pest of palms at bay until 2008, when RPW was recorded on *P. canariensis* from the Tangier region in Northern Morocco bordering Spain during December 2008, and on *P. dactylifera* from Tabrouk in the north-east of Libya bordering Egypt during January 2009. In order to eradicate/control RPW in Morocco and Libya and prevent its spread to the other countries of the Maghreb region (Algeria, Tunisia and Mauritania), the Food and Agriculture Organization (FAO) of the United Nations initiated an expert consultation in early 2010 aimed at strengthening the national capacities for the management of RPW in these countries.

In the infested countries of Morocco and Libya, strict quarantine regulations banning imports of palms from abroad and movement of

Fig. 1.17. Typical red palm weevil (RPW) symptoms in date palm (*Phoenix dactylifera*) orchards in Saudi Arabia. Top left: Damage hole seen before excavation; Bottom left: same palm after excavation and cleaning showing a large hollowed-out cavity and toppled palm. Top right: an adult RPW near a damage hole at the base of the stem, Bottom right: brown viscous ooze coming from stem, indicating RPW infestation (Photos: P.S.P.V. Vidyasagar.)

palms from the infested regions of these countries are in place. Besides quarantine, a RPW pheromone-based strategy comprising mass trapping adult weevils, preventive insecticidal treatments and eradication of infested palms has been implemented to combat the pest in Morocco. In Libya, pheromone traps are used to monitor the situation throughout the country, including the infested area of Tabrouk where all ornamental (c. 4000) and date palms (c. 1500) are being eradicated, to ensure elimination of the pest from this area to prevent its spread to the nearest date palm oasis of Jagboub (Faleiro, 2010). The uninfested Maghreb countries of Algeria, Tunisia and Mauritania have also banned imports of palms from abroad, regulate the palm nursery industry and are in the process of building capacities to monitor the situation.

1.9 Future Research

In recent years, many scientific papers covering different aspects of *R. ferrugineus* bioecology and control have been published, and research has provided important tools to improve its management. Some of the areas explored include:

- *Early detection*. As already mentioned, an important problem associated with *R. ferrugineus* is the difficulty of early detection. Because recently infested palms can be easily mistaken as pest-free, inadvertent movement of infested plants has been common and has greatly contributed to the current distribution of this weevil. Different groups have focused on the development of acoustic sensors for early detection (Levsky *et al*., 2007; Mankin *et al*., 2008; Potamitis *et al*., 2009, Gutiérrez *et al*., 2010). However, the degree to which sensors developed so far have been used in practice remains unclear. Other detection techniques, including molecular tools, should be explored.
- *Plant quarantine*. In addition to current predeparture and post-entry quarantine protocols (OJEU, 2007), the development of a quarantine treatment to disinfest palms, either chemical (Llácer and Jacas, 2010) or physical, would greatly reduce the enormous risks that palm movement imposes worldwide at present.
- *Chemical control*. Although 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 (tunnelling larvae within the palm) and to the ecotoxicological profile of these biocides. New environmentally friendly products are urgently needed, and alternative application methods (such as trunk injection) or uptake mechanisms (as systemic products) should be investigated further.
- *Biological control*. There is an incomplete knowledge of the natural enemies of *R. ferrugineus* in its native habitat (Murphy and Briscoe, 1999; Faleiro, 2006), and this precludes any classical biological control program against it. On the other hand, different entomopathogenic nematodes (Abbas *et al*., 2001a, b; Llácer *et al*., 2009) and fungi (Gindin *et al*., 2006; El-Sufty, 2009; Sewify *et al*., 2009; Dembilio *et al*., 2010b) have been identified. This opens new possibilities of inundative or augmentative releases of these biocontrol agents, and of their combined use with semiochemicals in attract and infect strategies.
- *Semiochemicals and trapping*. Semiochemicals are key to the management of *R. ferrugineus* in palm commercial groves (see above), and will probably have a central role for its management in non-agricultural contexts. However, there are many open questions related to their use for monitoring and mass trapping (trap design, density, maintenance and servicing, location) as well as new possibilities for use (push-and-pull strategies, attract-and-kill, attract-and-infect, attract-and-sterilize).
- *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 the weevil.

There is a clear need for research to help us improve the management of *R. ferrugineus*. This should allow us to continue enjoying palms in our parks, gardens and natural landscapes.

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