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Review Article

The red palm weevil as an alien invasive: biology and the prospects for biological control as a component of IPM

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Abstract

The red palm weevil, *Rhynchophorus ferrugineus*, invaded the Gulf states in the mid-1980s, where it is now causing severe damage to date palms. This polyphagous insect is widely found in southern Asia and Melanesia where it is a well-known problem for the damage it causes to coconuts grown in plantations. In this region, the weevil is sympatric with four other Asian *Rhynchophorus* species but the taxonomic status of some of these is unclear and some may be conspecific with the red palm weevil. Current tactics to manage the weevil in the Gulf and Asia are largely based on insecticide applications although there are now deep concerns about environmental pollution. Much research has been conducted on other techniques, notably pheromone traps. However, there is now a strong emphasis on the development of integrated pest management (IPM) based on pheromone traps and biological control rather than insecticides. Here we review the biogeography, basis of population outbreaks and current management tactics for the red palm weevil and related species, and then assess the potential of biological control to underpin the development of an IPM programme for it.

A Threat to Palms

The date palm, *Phoenix dactylifera* (Palmae) is the most common and widely cultivated plant in the arid regions of the Middle East and North Africa where, in many areas, its fruit has provided the staple carbohydrate food of local people for nearly 5000 years (Purseglove, 1972; Jones, 1995). In the Arabian peninsula, the tree is grown by smallholder farmers and commercially in large plantations; it also grows wild on steep hillsides (Collenette, 1985). For example, it is the main agricultural crop in Oman, occupying 83% of the total area grown under fruits and 50% of the total cultivated land. However, the greatest production is in Iraq, Iran and Saudi Arabia (Purseglove, 1972); in 1996 Saudi Arabia produced 570,000 tonnes of dates worth US$203 million, with exports valued at over US$30 million (Anon., 1998).

The date palm crop in these countries is now under threat. In the mid 1980s the red palm weevil, *Rhynchophorus ferrugineus* (Olivier) (Col., Curculionidae) was discovered attacking palms in the Arabian peninsula (Gush, 1997; Abraham *et al*., 1998). The larval stages of this insect feed within the trunk of palms and this behaviour frequently kills the trees. Since its discovery, the weevil has expanded its range westwards very rapidly. It was recorded for the first time in the United Arab Emirates in 1986; it was then found in Saudi Arabia in 1987 and in the Islamic Republic of Iran in 1992. However, it has now crossed the Red Sea into North Africa, as the latest record is from the Sharqiya region of Egypt (Cox, 1993). By 1995 it had infested over 10,000 farms across Arabia. In infested plantations, yields have been estimated to have dropped from 10 tonnes to 0.7 tonnes per hectare (Gush, 1997).

The weevil is widely found in southern Asia and Melanesia, where it feeds on a broad range of palms including coconut, sago, date, and oil palms. In some areas within this region it has also been recorded as a serious pest of introduced palms, particularly coconut (Kalshoven, 1981; Rajamanickan *et al*., 1995). For example in Tamil Nadu, India, yield losses of 10-25% have been recorded in plantations of this palm (P. C. Sundara Babu, pers. comm.).

Because of the concealed nature of the larvae, effective methods for the management of the red and other palm weevils have been difficult to develop. Current methods recommended for the management of *Rhynchophorus* species have focused on integrated pest management (IPM) involving surveillance, pheromone lures, cultural control and chemical treatments (Abraham *et al*., 1998). However, recent concern of Gulf countries about the side-effects of chemical pesticides on the environment has resulted in the restriction in the use of these products. Thus, interest has now turned to biological control. Current efforts are examining the potential of developing a biopesticide, based on nematodes, viruses and bacteria (Gush, 1997).

Here we review the biogeography of the red palm weevil and its relation with other tropical Asian *Rhynchophorus* species which feed on palms; all of these species are closely related and some authors consider that at least two of these species should be synonymized with the red palm weevil. We review the ecology of the red palm weevil and the natural enemies of this and other palm weevils and the basis of population outbreaks. We then use this information to assess the prospects for improving current management techniques through the development and integration of biological control.

Biogeography of Asian *Rhynchophorus* Species

Rhynchophorus palm weevils are large insects (usually greater than 25 mm long) which belong to the Rhynchophorinae, a subfamily within the Curculionidae (Borror *et al*., 1964). The Rhynchophorinae, commonly known as the billbugs and grain weevils, contains many important and well known pests such as the rice weevil, *Sitophilus oryzae* (L.) (Col., Curculionidae). The genus *Rhynchophorus* was erected by Herbst in 1795 and has since undergone several extensive revisions (Wattanapongsiri, 1966). The last-named author made the most recent revision and recognized ten species: three New World, two African and five tropical Asian. All *Rhynchophorus* species are polyphagous and have a similar life history (see below). The Asian species include: *R. ferrugineus*, *Rhynchophorus vulneratus* (Panzer), *Rhynchophorus distinctus* Wattanapongsiri, *Rhynchophorus lobatus* (Ritsema) and *Rhynchophorus bilineatus* (Montrouzier). Interestingly, red palm weevil type damage was reported from palms in Iraq earlier this century but no insect specimens were collected to confirm this (Buxton, 1920).

Table 1. Geographical records of Asian *Rhynchophorus* species[1].

R. ferrugineus	*R. vulneratus*	*R. lobatus*	*R. distinctus*	*R. bilineatus*
Egypt	Thailand	Indonesia	Indonesia	Malaysia
Oman	Philippines	Sumatra	Kalimantan	Sarawak
UAE[2]	Malaysia			Indonesia
Saudi Arabia	Malaya			eastern islands
Iran	Sarawak			Irian Jaya
Pakistan	Singapore			Papua New Guinea
India	Indonesia			Solomon Is.
Sri Lanka	Sumatra			
Myanmar	Java			
Thailand	Kalimantan			
Cambodia	Lombok			
Vietnam	Sulawesi			
China	Timor			
Taiwan	Papua New Guinea			
Philippines	Solomon Is.			
Malaysia				
Sabah				
Sarawak				
Indonesia				
Sumatra				
Java				
Kalimantan				
Lombok				
Sulawesi				
Timor				
Irian Jaya				
+ many of the smaller islands				
Papua New Guinea				
Solomon Is.				

[1] Records from: Wattanapongsiri (1966); IIE (1992); S. A. H. Al-Khatri, pers. comm.

[2] United Arab Emirates.

Table 2. Host plant records for Asian *Rhynchophorus* species[1].

a. *Rhynchophorus ferrugineus.*

Host species	Common name	Location of records	Native range of plant (or genus*)[2]
Phoenix sylvestris	date palm	India, Indonesia	India
Borassus flabellifer	plamyru/toddy palm	India, Indonesia	India/Malaysia
Arenga pinnata	sugar palm	Indonesia, Philippines	India/SE Asia
Corypha gebanga	gebong	Indonesia	*India, Vietnam, Laos, Malaysia, Philippines, Indonesia, PNG, Australia
Corypha elata	buri palm	Philippines	*India, Vietnam, Laos, Malaysia, Philippines, Indonesia, PNG, Australia
Caryota maxima	pugahan	Philippines	Malaysia/Indonesia
Caryota cumingii		Philippines	Philippines
Areca catechu	betel nut palm	Philippines	Malaysia/Indonesia
Metroxylon sagu	sago palm	Indonesia	Papua New Guinea/Maluku
Cocos nucifera	coconut	Indonesia, Philippines	?western Pacific
Roystonea regia	royal palm	Philippines	Cuba
Elaeis guineensis	oil palm	Indonesia, Philippines	West Africa

b. *Rhynchophorus vulneratus.*

Host species	Common name	Location of records	Native range of plant (or genus*)[2]
Phoenix sylvestris	date palm	Singapore	India
Arenga saccharifera	sugar/kabong	Malaysia	*India, S. China, Malaysia, SE Asia, PNG, Australia
Corypha gebanga	gebong	Malaysia	*India, Vietnam, Laos, Malaysia Philippines, Indonesia, PNG, Australia
Areca catechu	betel nut palm	Malaysia	Malaysia/Philippines
Livistona cochinchinensis	serdang	Malaysia	*N. Africa, India, Indonesia, PNG, Solomon Is.
Oncosperma tigillaria	nibung palm	Malaysia	SE Asia
Oncosperma horrida	bagas	Malaysia	SE Asia
Metroxylon sagu	sago palm	Malaysia	PNG/Maluku
Cocos nucifera	coconut	Malaysia	?western Pacific
Roystonea regia	royal palm	Singapore	Cuba
Elaeis guineenis	oil palm	Malaysia/Singapore	West Africa

c. *Rhynchophorus bilineatus.*

Host species	Common name	Location of record[2]	Native range of plant[2]
Metroxylon armicarum	Caroline ivory nut palm	Malaita I., Solomon Is.	Caroline I., Guam
Metroxylon sagu	sago palm	PNG	PNG/Maluku
Metroxylon solomonense		Solomon Is.	Malaysia
Cocos nucifera	coconut	PNG	?western Pacific

[1] Records from: Wattanapongsiri (1966).

[2] PNG: Papua New Guinea; Maluku: formerly known as the Moluccas.

The geographical distributions of these five species are given in Table 1. *Rhynchophorus ferrugineus* is the most widely distributed species within tropical Asia and its range within this region extends from Pakistan, through Southeast Asia to Melanesia. The host plants are listed in Table 2a. A wide range of genera within the Palmae is attacked although the literature records provide no evidence of any preference by the weevil for palm species or genera for breeding purposes. There are records of the weevil from palm genera native to all areas apart from Pakistan and Melanesia, which suggests that all or part of the region extending from India through to Southeast Asia could be an area of endemic focus. Nirula (1956) observes that in natural and uncultivated areas within southern India, *R. ferrugineus* is normally a rare and local insect. However, the commercialization of coconut and oil palm growing within tropical Asia, particularly the development of plantation monocultures, has facilitated the range expansion of this insect. Equally the commercialization of date palm growing in the Middle East has created ideal conditions for the rapid spread of the red palm weevil between countries in that region.

The remaining four species of *Rhynchophorus* have more restricted ranges, all of which are sympatric with *R. ferrugineus*. *Rhynchophorus vulneratus* (called the red stripe weevil in the Oriental Region) is distributed from Southeast Asia through to Melanesia (Table 1) and is found from a wide range of palm species native and exotic to the region (Table 2b). This weevil has been recorded as a pest of coconut in Malaysia and Thailand. Considering only those palms that are in its native range, *R. vulneratus* has been recorded from some species/genera common to *R.. ferrugineus*, e.g. *Arenga, Corypha* and *Areca.* Interestingly, there are no records from *Caryota*, which is a common host for the red palm weevil. Palm genera attacked by *R. vulneratus* from which the red palm weevil has not been recorded include *Livistona* and *Oncosperma;* Wattanapongsiri (1966) reports that the Southeast Asian *Oncosperma tigillaria* is a preferred host for breeding. *Rhynchophorus vulneratus* has been synonymized with *R. ferrugineus* several times in the past but Wattanapongsiri (1966) considers these as distinct species. Nonetheless, Perez *et al*. (1996) could find no differences in the chemical composition of the pheromones produced by these species and suggest that, unless other pre- or post-zygotic reproductive isolating mechanisms are discovered, the species should be synonymized.

Rhynchophorus lobatus and *R. distinctus* have very restricted distributions and there appear to be no host plant records for these species in the literature. The former species was described from a specimen collected in Sumatra in the late 1800s but Wattanapongsiri (1966) suggests that this species is synonymous with either *R. ferrugineus* or *R. vulneratus*. Wattanapongsiri (1966) describes *R. distinctus* from a single specimen collected from Kalimantan, Indonesia.

The remaining Asian species, *R. bilineatus,* is essentially a Melanesian species although there is one record from Sarawak, Malaysia (Table 1). In this region it has only been recorded from coconut and *Metroxylon* palms; the latter are native to this part of the world (Table 2c). The preferred host for breeding is *Metroxylon solomonense*. Interestingly, this species was originally known as a sub-species of *R. ferrugineus: Rhynchophorus ferrugineus papuanus* Kirsch (Kalshoven, 1981).

In summary, the taxonomic status of most of the Asian *Rhynchophorus* species is clearly uncertain and at least two of the species may be conspecific with *R. ferrugineus*. Thus the taxonomy of this genus is in urgent need of revision. Traditional morphometrical analyses could be complemented using DNA-based fingerprinting techniques in order to determine the relationship between species (P. Bridge, pers. comm.).

Ecology and Basis of Population Outbreaks

Life history and feeding behaviour

Rhynchophorus ferrugineus is found over a very wide geographical area, involving many different climates and farming systems; the species is also highly polyphagous. Several observations and studies have been made on the life history and feeding behaviour of the weevil from different parts of its range. These were mostly made in the first half of the century in India and Southeast Asia and have been summarized by Wattanapongsiri (1966). The studies have been on coconut, sago and date palm. Here we describe the general features of the life history of *R. ferrugineus* and then consider some specific life history parameters.

The beetles are attracted to dying or damaged parts of palms but it is possible that undamaged palms are also attacked. The males of *R. ferrugineus* produce a pheromone which causes the weevils to aggregate on damaged trees (Gunawardena & Bandarage, 1995). The larvae can only bore in soft tissue; for example, in the tree crown, upper part of the trunk and at the base of petioles. They can also bore into the trunk of young palms and the decaying tissue of dying palms; Kalshoven (1981) reports that they can develop in the refuse formed during the processing of sago.

To oviposit, females use the rostrum to bore into the tissue to form a hole in which to lay their eggs. Kalshoven (1981) states that, on coconuts, oviposition occurs most frequently in crowns which have been damaged by scarabaeid *Oryctes* spp., and that in young coconuts, oviposition takes place in wounds and at leaf scars. On young, growing date palms, the weevils take shelter under the splitting bark and lay eggs within the newly emerging roots (Abraham *et al*., 1998). The light-yellow eggs (approx. 2.5 mm long) are laid close to the surface of the incision or wound. Several are laid together but not in contact, and then the hole is cemented over to protect the eggs. When hatched, the whitish-yellow young larvae feed on the surrounding tissue. As the larvae feed, they produce frass (chewed up plant fibre) which combines with the plant sap and this fills the tunnels made by the larvae. In severely infested palms, cavities are formed by the feeding larvae which weaken the crown of the tree. Once mature, the larvae form an oval cocoon (approximately 80×35 mm) within the destroyed tissue of the tree. Inside the cocoon, the larvae pupate.

Because the red palm weevil is a concealed tissue borer, symptoms of attack at an early stage of infestation are difficult to detect although recent research has noted that it is possible to detect physiological changes in infested trees (Bokhari & Abuzuhairah, 1992). This raises the possibility that it may be feasible in the future to detect infestations before any symptoms are visible. Later in the infestation process the presence of larvae can be detected through the occurrence of tunnels on the trunk and at the bases of leaf petioles, and through the presence of frass and plant sap which oozes from these tunnels. When a palm is severely infested, the stem or crown sometimes breaks off the tree (Abraham *et al*., 1998).

A summary of some of the developmental and other life history parameters recorded by various authors is given in Table 3. There is a lot of variation in the parameters, within and between countries, and no clear pattern related to climate. The shortest larval development times and total life cycle period reported are those from the Philippines. On average, females are capable of laying 250 eggs which take three days to hatch. The larval period takes two months and the pupal period three weeks. Wattanapongsiri (1966) states that the life histories of most of the *Rhynchophorus* species are very similar. In the case of *R. vulneratus*, the developmental and other life history parameters all fall within the ranges summarized for *R. ferrugineus* in Table 3, and this further supports the notion that these two species are conspecific. *Rhynchophorus ferrugineus* may consist of a number of biotype populations each adapted to feeding on a particular group of palm genera

Table 3. Life history characters of *Rhynchophorus ferrugineus*[1]. (Time periods in days.)

Character		Country where study was conducted				
		India	Indonesia	Myanmar[2]	Philippines	Iran[3]
No. eggs/female		127-276	531	300	162-350	3-186
Incubation period		3-4	3	3-4	3	1-6
Larva:	No. moults	-	-	-	9	
	Larval period	25-61	60-105	30-105	35 male 38 female	41-78
Pupa:	Prepupal period	-	3-6	-	2-11 male 2-11 female	
	Pupal period	18-33	13-17	17-50	11-19 male 12-19 female	15-27
Life cycle period		48-82	60?	60-165	45-68 male 45-67 female	57-111
Longevity:	male	50-90	107	-	63-109	39-72
	female	50-90	107	-	39-72	20-120

[1] Modified from Wattanapongsiri (1966).

[2] Formerly Burma.

[3] Data for Iran from Avand Faghih (1996).

Natural enemies

Very few studies have been conducted on the natural enemies of *R. ferrugineus* or other *Rhynchophorus* species within their native ranges. The species recorded which attack *R. ferrugineus* in the host tree are summarized in Table 4a; records of other similar natural enemies include those from *R. bilineatus* (Table 4b) and those from the New World *Rhynchophorus palmarum* (L.) (Table 4c). Although it would not be expected that concealed insect borers such as *Rhynchophorus* species would support a diverse community of natural enemies (Hawkins, 1993), it is likely that the dearth of natural enemy species does represent the lack of study rather than species-poor natural enemy communities. On *R. ferrugineus*, the community of natural enemies include a nematode, a bacteria, a virus and predatory insects. The insect species are generalist feeders and this is to be expected given the polyphagous feeding behaviour of the weevil. Two mite species, *Hypoaspis* sp. and *Tetrapolypus rhynchophori* Ewing (Pymotidae) have also been recorded infesting the adult beetles, but the status of these species as parasites is uncertain (Peter, 1989). There are no records of natural enemies of the red palm weevil in its adventive range (i.e. the Middle East).

Records of natural enemies from *R. bilineatus* include a nematode, which may be the same as, or a biotype of, the species recorded from *R. ferrugineus*, and a pathogenic fungus (Table 4b). The studies on the natural enemies of *R. palmarum* in the Neotropical Region have only revealed that this weevil is attacked by members of the parasitic dipteran family, Tachinidae; however, some species of this family have proved to be important biological agents.

The biology and impact of each of the more important natural enemy species in these communities are given below.

Nematodes

Nematodes of the order Aphelenchida are recorded as having a broad range of relationships with many types of Coleoptera (Hunt, 1993). These can range from the simply phoretic via a commensal to a strictly parasitic relationship. A notorious example between palm weevils and nematodes is the relationship between *Rhadinaphelenchus cocophilus* (Cobb) Goodey (Parasitaphelenchidae), the causal agent of red ring disease of coconut, and *Rhynchophorus palmarum* in Central and South America.

The two recorded nematode parasites of *Rhynchophorus* species are closely related species of the aphelenchid genus *Praecocilenchus* Poinar; the type species *Praecocilenchus rhaphidiophorus* (Poinar) and *Praecocilenchus ferruginophorus* Rao & Reddy (Entaphelenchidae). *Praecocilenchus rhaphidiophorus* was recorded parasitizing *R. bilineatus* in New Britain in 1969 while *P. ferruginophorus* was recovered from *R. ferrugineus* in India in 1980. There are few slight morphological differences between these species so further analysis is required to establish whether they are conspecific.

Nematodes of both species may be found in the trachea, intestine and fat bodies of infected weevil larvae and also in the uterus and haemocoel of infected adults. The size of nematodes found in the haemocoel ranges from small intrauterine females to large (approx. 1.7 mm) mature female parasitic forms, which suggests several simultaneous and unsynchronized life cycles occur in the weevil. The nematodes are probably dispersed during ovipositing as the ovipositors of infected female weevils are packed with nematodes. Nematodes may also exit through the gut wall of the weevil to be passed with the faeces.

Table 4. Natural enemies of *Rhynchophorus* species.

a. *Rhynchophorus ferrugineus.*

Species	Location of record	Crop	Reference
Nematodes			
Entaphelenchidae			
Praecocilenchus ferruginophorus	India, Kerala	coconut	Rao & Reddy (1980)
Bacteria			
Pseudomonadacae			
Pseudomonas aeruginosa	India, Kerala	coconut	Banerjee & Dangar (1995)
Viruses			
Cytoplasmic polyhedrosis virus	India, Kerala	coconut	Gopinadhan *et al.* (1990)
Mites (ectoparasites?)			
Laelapidae			
Hypoaspis sp.	India, Tamil Nadu	coconut	Peter (1989)
Pymotidae			
Tetrapolypus rhynchophori	?	?	Peter (1989)
Insects			
Forficulidae			
Chelisoches morio	India, Kerala	coconut	Abraham *et al.* (1998)
Scoliidae			
Scolia erratica	Indonesia, Java	?	Peter (1989)
"	Singapore	?	Wattanapongsiri (1966)
Sarcophagidae			
Sarcophaga fuscicauda	India	?	Peter (1989)
"	India, Kerala	coconut	Iyer (1940)

b. *Rhynchophorus bilineatus.*

Species	Location of record[1]	Crop	Reference
Nematodes			
Entaphelenchidae			
Praecocilenchus rhaphidophorus	PNG, New Britain	coconut	Bedford (1974)
Fungi			
Hyphomycetes			
Metarhizium anisopliae	PNG	coconut	Prior & Arura (1985)

c. *Rhynchophorus palmarum.*

Species	Location of record	Crop	Reference
Nematodes			
Rhabditidae			
Teratorhabditis sp.	Trinidad & Tobago	coconut	Gerber & Giblin-Davis (1990)
Diplogasteridae			
Diplogasteritus sp.	"	"	"
Mononchoides sp.	"	"	"
Insects			
Tachinidae			
Paratheresia menezesi	Brazil, Bahia	oil palm	Moura *et al.* (1993, 1995)
Paratheresia rhynchophorae	"	"	Guimaraes *et al.* (1977)

[1] PNG: Papua New Guinea.

The confirmed pathological effects on the beetles are reduced ovary size and egg production and, as Poinar (1969) reports, a reduced life span of infected weevils is suspected. Further work should be done to determine whether these nematodes could be reared and released as effective biological control agents.

Gerber & Giblin-Davis (1990) report the presence of three nematode species in the bodies of adult *R. palmarum* (Table 4c) but their pathogenicity is unclear.

Bacteria

The only record of infection of red palm weevils by a bacterial pathogen is the report of Banerjee & Dangar (1995) who isolated *Pseudomonas aeruginosa* (Schroeter) Migula (Pseudomonadacae) from naturally infected specimens collected in Kerala, India. Laboratory assays demonstrated this bacteria was pathogenic to weevils when ingested through force feeding or when insects were forced to wade through a suspension of bacterial cells. The consequent mortality occurs eight days after inoculation with the bacteria.

Viruses

There is one record in the literature of viruses being recovered from palm weevils. In 1990 Gopinadhan and co-workers (Gopinadhan *et al.*, 1990) found a highly potent cytoplasmic polyhedrosis virus (CPV) specific to red palm weevil in Kerala, India. The virus infected all stages of the insect and laboratory infection of the late larval stages resulted in the development of malformed adults.

Although not directly related to red palm weevil it should be noted that there are also examples of baculoviruses being produced and used against *Oryctes* species, the white grub pests of date palm plantations. The inclusion of viruses into a biocontrol programme is therefore a real possibility.

Fungi

Metarhizium anisopliae (Metsch.) Sorok (Hyphomycetes/ Mitosporic fungi) was isolated from *R. bilineatus* and other beetles in New Guinea (Prior & Arura, 1985). In this study an isolate of *M. anisopliae* recovered from the scarabaeid *Scapanes australis* Boisduval was grown on brown rice and released into the frond axils of young palms. It was found that *S. australis* adults were infected by the fungus and some incidental infection of *Rhynchophorus* also occurred. Interestingly the rice inoculum could be recovered and the fungus re-isolated up to 84 days after release. An appropriate field survey may be able to recover a *Rhynchophorus* isolate of this pathogen.

Insects

Hymenoptera – *Scolia erratica* Smith: *Scolia* species belong to the family Scoliidae. This family of usually large, dark hairy wasps belong to the Aculeata and the larvae feed ectoparasitically on the larvae of the family Scarabaeidae and, less commonly, on the larvae of large Curculionidae. In this respect they have obvious affinities with the Parasitica. Adult wasps are commonly found on flowers where they feed on nectar. The female wasp searches for a beetle grub, and when one is located it is stung. The wasp usually lays some eggs on the paralyzed larva and then constructs a cell around it. The female then leaves to search for more beetle larvae (Clausen, 1940). No biological information has been published on *S. erratica*. *Scolia* species have been used successfully as classical biological control agents.

Diptera – *Sarcophaga fuscicauda* Bottcher: *Sarcophaga fuscicauda* is included in the family Sarcophagidae (Cyclorhapha). This family of predaceous and parasitic flies are mostly larviparous in their method of reproduction. Sarcophagid larvae feed on the larvae and adults of their hosts. Many *Sarcophaga* species are parasitic in the nymphs and adults of locusts but the range of host preferences in this genus is very large (Clausen, 1940). Iyer (1940) reports that *S. fuscicauda* attacks the adults of *R. ferrugineus*.

Diptera – *Paratheresia* species: These species are tachinids. The larvae of the members of the Tachinidae are all internal parasitoids, mainly of other insects although the larvae of Lepidoptera and Coleoptera are the most common hosts (Clausen, 1940). Most of the species have a very narrow host range and several members have been successfully used in classical biological control programmes. *Paratheresia menezesi* Townsend is a gregarious parasitoid of *R. palmarum* and has been recorded from the oil plantations in Bahia, Brazil (Moura *et al*., 1993). Studies by these authors in the early 1990s indicated that approximately 50% of the *R. palmarum* population was parasitized. Guimaraes *et al*. (1977) reports *Paratheresia rhynchophorae* (Blanchard) as a parasitoid of *R. palmarum* but no studies seem to have been conducted on this tachinid.

Dermaptera – *Chelisoches morio* (F.): This species belongs to the family of earwigs, the Forficulidae. Most earwigs are scavengers but a few species have predatory habits. Abraham *et al*. (1973) found *C. morio* to be a common predator in the crown of coconuts in Kerala, India. They estimated that the daily average consumption by nymphs and adults of the predator was, respectively, 5.3 and 8.5 *Rhynchophorus ferrugineus* eggs, or 4.2 and 6.7 larvae.

Population dynamics

Rhynchophorus ferrugineus can breed in a wide range of climates, and this is largely because the larvae feed protected within their host palms (Wattanapongsiri, 1966). Several authors have also reported that the weevil is able to complete several generations in a year (Rajamanickam *et al*., 1995; Avand Faghih, 1996); frequently, several generations can be passed in the same host tree before the tree collapses. Besides this, *R. ferrugineus* is also a strong flyer. Uninterrupted dispersal distances include 0.9 km in Indonesia and between 0.8 and 1.2 km in Sri Lanka (Wattanapongsiri, 1966). In addition, in the Middle East, the bulk and quick movement of date palm offshoots as planting material has led to the rapid spread of the pest (Abraham *et al*., 1998). All of these factors (along with others, such as being polyphagous) contribute to the weevil's ability to colonize and breed at new sites and for populations to reach outbreak levels. Nonetheless, as already mentioned, in uncultivated areas within southern India, a country that falls within part of its native range, *R. ferrugineus* is normally a rare and local insect (Nirula, 1956). Kalshoven (1981) considers that the main factor limiting numbers is the number of suitable breeding sites. These will be far more numerous in a managed plantation than in a natural habitat. However, under some circumstances natural enemies are also very likely to be important in limiting the distribution and incidence of the red palm weevil. For example, studies in oil palm plantations in Sabah, Malaysia strongly suggest that the removal of ground cover leads to general pest outbreaks whereas the presence of ground cover is correlated with fewer pest problems. It seems that the presence of ground cover in the plantations enhances the diversity and activity of insect and other natural enemies (Wood, 1976). These observations provide one hypothesis for the high incidence of the red palm weevil in exotic palm (e.g. coconut) plantations in tropical Asia. The excessive use of insecticides is also likely to limit the activity of natural enemies in plantations. More importantly, the apparent general absence of natural enemies in the date palm plantations in the countries of the Middle East would explain why the red palm weevil has had a particularly devastating impact in this region.

IPM and the Prospects for Biological Control

Current methods of control

The methods currently employed to control red palm weevil are largely based on the application of large quantities of synthetic chemical insecticides (Abuzuhairah *et al.,* 1996) which, applied in the conditions of the sandy soils of the Gulf, has lead to the pollution of water courses around areas with palm weevil infestation (R. A. Abuzuhairah, pers. comm.). Insecticides are also commonly used in Central and South America for the control of *R. palmarum* (e.g. Moura *et al.,* 1995). However, other techniques of management such as sanitation, baits and traps of palm weevils have been researched in tropical Asia (particularly India) and the Americas, and when used in combination with chemicals have proved effective in field trials (Abraham *et al.,* 1989; Moura *et al.,* 1995). We first review some of these other techniques before considering the prospects for biological control in IPM.

Insecticides

Insecticides are applied in a range of preventative and curative procedures designed to limit and contain the spread of an infestation. These procedures have been developed and refined since commencing in India in the 1970s when work on application of organophosphates and carbamates ensured these chemicals became the mainstay of the chemical approach to control. Methods employed have ranged from the precise, such as dusting of the leaf axils after pruning, to more general spraying or soaking of the tree trunk, to the direct injection of chemicals into the trunk of date or other palms.

The choice of chemicals now regularly used in the field developed through laboratory work on promising compounds. For example, Abraham *et al.* (1975) tested seven insecticides in the laboratory. The three insecticides with the lowest LC_{90}s (dichlorvos, trichlorphon and propoxur) were then tested in the field on naturally infested coconut palms in Kerala, India, where trichlorphon gave the best control, with 92% of the infested palms recovering from weevil infestation. Sevin or carbaryl has also seen regular field use in Indonesia following similar laboratory tests and was found to give effective field control if applied continually every two months (Soenardi *et al.,* 1978).

Direct injection of insecticide into the trunk of the coconut palm was first reported by Rao *et al.* (1973). They demonstrated that the direct injection of 0.2% fenthion gave effective control of larvae in the tree. This work was developed by Muthuraman (1984) who demonstrated that 10 ml of monocrotophos, or the same volume of a combination of monocrotophos and dichlorvos (5 + 5 ml), when injected into a pre-drilled 10-cm-deep hole above the infestation site, gave good control of *R. ferrugineus*. Tree recovery was recorded as being 100% after this treatment. The most recent and relevant publication on the injection method was carried out in United Arab Emirates by El-Ezaby (1997) who investigated control of red palm weevil under both laboratory and field conditions. Under laboratory conditions he studied the effect of certain insecticides on larval, pupal and adult stages and high mortality was obtained with the insecticides carbosulfan, pirimiphos-ethyl and 'Rogodial'. In a subsequent field experiment concentrated insecticides were injected into small date palms that had previously been artificially infested with red palm weevil larvae. High mortality was obtained with all three insecticides. Date palms were injected with these insecticides in the field as part of an integrated pest management approach and the treatment was reported as being 98% successful.

An alternative to directly injecting insecticides into the tree is to seal inside the tree a tablet form of a slow release fumigant. Phostoxin tablets (aluminium phosphide) applied at a rate of at 0.5-1 tablet/tree were effective in controlling larvae, pupae and adults of *R. ferrugineus* on coconut (Rao *et al.,* 1973). Muthuraman (1984) alternatively used two 3-g Celphos (aluminium phosphide) tablets crushed and placed in holes in date palm. All holes were then sealed with a paste of cement and copper oxychloride to contain the highly toxic phosphine gas released by the tablets.

The field application of insecticide to cut leaf petioles followed on from the work of Abraham (1971) who found that leaves cut at the time of pruning at a point beyond the region where leaflets emerge at the base prevented larvae, hatching from eggs laid at the cut ends of petioles, from making their way into the trunk before the petiole stump dried. The rationale behind this finding was extended to include the prophylactic practice of treating the wounds in the trees with a repellent and by filling the leaf axils with dusts of BHC or chlordane mixed with sand as reported by Butani (1975). Abraham *et al.* (1989) have since developed this approach into an integrated system of pest management for *R. ferrugineus* for coconut palms by combining this use of chemicals with the improved plant and field sanitation in Kerala, India, which resulted in an initial level of infestation of 69 out of 1005 young palms in 1970 being reduced to almost to zero by 1982.

Further refinement of application methods has been reported by Abraham *et al.* (1998) who have demonstrated that soaking of trees in insecticides such as chlorpyriphos and endosulfan is an effective preventative measure. The absorption of insecticide by the matted fibre on the tree gives protection to the cracks and crevices on the tree that are favoured by the weevil for egg laying. The chemicals are now applied with an adapted soaking lance that drenches the palm in a more accurate manner than conventional sprayers.

Baiting and trapping

Baiting and trapping of weevils uses a mixture of materials that are available to the smallholder and the commercial farmer. A trap receptacle such as a plastic bucket containing host plant material producing fermenting plant volatiles plus a quantity of synthetic aggregation pheromone is known to attract palm weevils (El-Garhy, 1996). It has been established that plant kairomones strongly enhance pheromone attractiveness but when the volatiles have been identified, such as ethyl acetate, ethyl propionate or ethyl butyrate, and added to a pheromone trap the synergistic effect is not as great as when naturally fermenting plant tissue is used (Giblin-Davis *et al.,* 1996). Much work has been conducted on the use of pheromone traps to capture and monitor weevil populations over the last ten years in Asia and the Americas (Gunawardena & Herath, 1995; Oehlschlager *et al.,* 1995) and this in turn has lead to the chemical structure of many species-specific pheromones being elucidated (Morin *et al.,* 1997). The study of orientation behaviour of foraging weevils to semiochemical devices has helped to design and test traps for weevil capture (Giblin-Davis *et al.,* 1996).

Palm weevil pheromones comprise eight to ten carbon secondary alcohols, and (4S, 5S)-4-methyl-5-nonanol, known colloquially as ferrugineol, is the major aggregation pheromone for *R. ferrugineus*. Interestingly, *R. vulneratus and R. bilineatus* and the weevils *Metamasius hemipterus* (L.) and *Dynamis borassi* (F.) (Col., Curculionidae) are also attracted by the same compound (Giblin-Davis *et al.,* 1996). Synthetic versions of these naturally occurring compounds are now included in experimental and commercially available traps. Generally only a few milligrams per day of a synthetic pheromone plus insecticide-treated plant tissue constitute very attractive and effective trap baits (Giblin-Davis *et al.,* 1994). Potential exists for pheromone-based mass-trapping of weevils both to reduce their populations and for monitoring their population dynamics to facilitate pest management decisions. More work needs to be done on optimizing the use of these traps under field conditions, such as the optimal position of the trap on the tree and the duration of the trapping period.

Where trapping has become routine an immediate effect has been to reduce the quantity of chemicals used as drenches or sprays through the targeting and restricting of chemicals to certain times or parts of the tree; a development which would clearly be beneficial for producers and consumers of dates in the Gulf.

The Development of IPM for Red Palm Weevil through the Integration of Biological Control

IPM seeks to reduce chemical input through the inclusion of a range of methods which are environmentally compatible. The development of a successful IPM strategy against red palm weevil can readily take up on the extensive research work already conducted on palm weevils. For example, the improvement of pheromone traps and other technologies (e.g. improved surveillance) that have been developed could be applied to the situation with the red palm weevil in the Gulf states and other parts of Asia.

The prospects for the development of a biological control component for an integrated management strategy are good, given the evidence for the importance of natural enemies in controlling palm weevil populations in natural environments. However, even though some natural enemies have been recorded from the red and other palm weevils (Table 4) the possibilities for biological control would be greatly enhanced by further work on the composition of palm weevil natural enemy communities. The incomplete state of knowledge on the extent and types of natural enemies highlights the need to conduct extensive surveys for insect natural enemies and pathogens. Such surveys should concentrate as a priority on finding new natural enemies from the region of the geographical centre of origin of *R. ferrugineus* and from those areas into which weevils are considered to have migrated. The survey should also cover all the major host palms of *R. ferrugineus* and the other Asian *Rhynchophorus* species. Particular attention should be paid to the natural enemies of palm weevil species thought to be conspecific, such as *R. vulneratus*, but attention should also be paid to the natural enemies of *R. palmarum* which may also be effective in the Asian context. Following exploratory survey work any new agents recovered would be identified, characterized and attempts could be made to establish them in culture under laboratory conditions; it would then be possible to assess their potential for inclusion in a biological control programme.

Besides enhancing the action of local natural enemies through reduction in insecticide applications, biological control strategies could include classical biological control methods – the introduction of host specific natural enemies from the area of origin of the pest – and/or the development of a biopesticide.

Classical biological control

Evidence of effective insect agents (Table 4) combined with information from new surveys may give scope for introducing some species to complement native natural enemy communities (where they exist) in Asia, including the Gulf. However, the establishment and effectiveness of these species may depend on the intensity of management practices in palm plantations.

For example, the Tachinidae is the family of insects that could contain a potential classical biological control agent for red palm weevil. This dipteran group has a notable record of success against a range of pests, including the sugarcane weevil, *Rhabdoscelus obscurus* (Boisduval) (Col., Curculionidae), a coconut defoliator, *Levuana iridescens* (Bethune-Baker) (Lep., Zygaenidae), and the green vegetable bug, *Nezara viridula* (L.) (Hem., Pentatomidae). Greathead (1986) has ranked them alongside the important families of Hymenoptera as control agents. To date at least 30 species of tachinids have been used successfully against 27 species of pest in classical biological control. A major problem with this group has been the development of successful techniques for mating in captivity. Although this has been overcome for many species, some agents have had to be rejected because a suitable technique could not be found. Tachinids may provide a high background mortality of a pest species as evidenced by the high rates of parasitism in the previously cited example of the tachinid *Paratheresia menezesi* in Brazil. This group also has a narrow host range, which meets the criteria laid out in the FAO Code of Conduct (FAO, 1996) as they will pose little threat to non-target organisms in date palm plantations and gardens. Other potential dipteran natural enemies could be found amongst members of the Sarcophagidae but, as with the scoliids mentioned below, these insects are much less host specific, and hence are less likely to fulfill the Code criteria.

As representatives of the hymenopteran parasites, *Scolia* spp. have also been released successfully against large coleopteran larvae, especially scarab larvae. However, these species are more generalist in their feeding habits and thus the host range of candidate agents would need to be studied carefully. An example is *Scolia oryctophaga* (Cocquerel), a wasp that is known to attack numerous species of rhinoceros beetles (*Oryctes* spp.) and at least one species of sugarcane grub, *Phyllophaga smithi* (Arrow) (Col., Scarabaeidae). The adult female wasp locates the white grub in the soil and then stings it to induce paralysis. A hole or cell is dug out of the soil into which she places the paralyzed grub before laying a single egg on the victim. This species was released in Mauritius where it gave good control of the sugarcane pest *Orcytes tarandus* (Olivier) (Col., Scarabaeidae) such that no serious outbreaks of the pest occurred following the introduction.

There are few cases of the successful release of nematode parasites as classical biocontrol agents. The most renowned example is the release of the tylenchid *Deladenus siricidicola* Thorne (Tylenchida: Neotylenchidae) against the wood wasp *Sirex noctilio* F. (Hym., Siricidae) in Australia. The level of control achieved by the release of this nematode has been spectacular and, perhaps just as importantly, stable since the introduction of the nematode. Monitoring procedures ensure any reduction in control is swiftly met with a release of laboratory-reared stock. As so little is known about the biology of *Praecocilenchus* spp. it would be rash to predict any effect of a release of this parasite into the red palm weevil populations of the Gulf, but further investigations into the biology of these nematodes would indicate whether such a release could be worthwhile.

Biopesticides

In addition to the introduction of classical biological control agents there is also scope for the development of biological control agents to replace directly or to reduce the use of chemical pesticides. Agents such as viruses, bacteria, fungi and entomopathogenic nematodes can all be mass-produced, formulated and applied to a target pest in a similar manner and with the same equipment that is used for chemical pesticides; hence the collective term biopesticide.

Biopesticides are now achieving a level of success against insect pests and it is this type of alternative control where a potential replacement for many of the chemical insecticides currently in use may emerge. These agents may be applied singly or, in certain circumstances, in combination with each other but, unlike the introduction of classical biocontrol agents such as parasitoids, they do not always persist or recycle in the environment and may therefore require repeated and usually inundative application. Regulations relating to the registration and release of these agents vary depending on the type of organism and the country where release has been proposed. The ease of release of these agents in the countries of the Gulf will depend on their country of origin and the level of host specificity they display in laboratory tests.

It is worth noting that in 1990 total world sales of biopesticides was valued at US$120 million and this total was estimated to represent only 0.5% of the world agrochemical market. *Bacillus thuringiensis* Berliner (*Bt*) sales accounted for 90% of this total but growth of the sector is rapid, at between 10-25% p.a., and expansion of the market is likely to continue as alternatives for chemicals are sought and discovered (Neale, 1997). The types of agent with proven biopesticide utility are mentioned below.

The use of the bacterium *Bacillus thuringiensis* is now widespread in many agricultural systems but a major drawback with the use of *Bt* is the build up of resistance to the bacterial toxin in a target insect population. There are well-documented cases of resistance arising through the over or misuse of *Bt*. For example, in Southeast Asia the rapid development of resistance in the diamondback moth, *Plutella xylostella* (L.) (Lep., Plutellidae) demonstrates that the application strategy for introducing and managing biopesticides must be in place before any long term use commences. Control of palm weevils has not yet been attempted with *Bt* as no specific strains have been isolated from these insects, although strains are in culture from other types of weevil.

The use of fungi as biopesticides is now well established. A good example being the use of *Metarhizium flavoviride* Gams & Rozsypal to control orthopterans (Thomas *et al.*, 1995). This fungus has been successfully formulated in oils and applied, in dry habitats similar to those found in the Gulf, to control the desert locust *Schistocerca gregaria* (Forskål) and the grasshopper *Zonocerus variegatus* (L.) (Acrididae). The chances of finding and characterizing similar fungal agents from red palm weevil specimens will be high.

From the USA, China, Australasia and Europe, there are examples of effective control with entomopathogenic nematodes (EPNs) belonging to the families Steinernematidae and Heterorhabditidae. In the USA EPNs are regularly applied over large areas to high value crops such as cranberries. In China *Carposina niponensis* (Walsingham) (Lep., Carposinidae) is regularly controlled by the application of *Steinernema carpocapsae* (Weiser) (Rhabditida: Steinernematidae) around apple trees, and shade trees have been injected with suspensions of *S. carpocapsae* to control the cossid borers *Holcocerus insularis* Standinger and *Zeuzera multistrigata* Moore (Lep., Cossidae). In Europe the successes of EPNs are limited to pests of high value protected crops such as ornamental plants which are treated with *Heterorhabditis* spp. to control the black vine weevil *Otiorhynchus sulcatus* (F.) (Col., Curculionidae) or to mushrooms treated with *Steinernema feltiae* (Filipijev) (Steinernematideae) for the control of mushroom sciarid and phorid flies.

The potential for using EPNs has been reviewed by Hanounik (1998). From this review it is known that larvae of red palm weevil are susceptible to infection by nematodes, with very encouraging results obtained in laboratory tests, but so far attempts at control in the field have been less successful (Abuzuhairah, pers. comm.). In such cases, however, it must be remembered that biocontrol agents have to be applied at the most opportune time and situation and that factors such as temperature are critical when using biological rather than chemical agents.

At present no indigenous strains of any of the pathogens listed above have been isolated in the Gulf region. Surveys for indigenous pathogens should be conducted to find and develop agents that could be pre-adapted to the extremes of temperature encountered in the date farms and gardens of the Gulf region.

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