Handbook of Major Palm Pests

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Biology and Management

Edited by

Victoria Soroker
The Volcani Center, Israel

Stefano Colazza
University of Palermo, Italy

WILEY Blackwell

This edition first published 2017 © 2017 by John Wiley & Sons Ltd

Registered office:
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial offices: 9600 Garsington Road, Oxford, OX4 2DQ, UK
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK
111 River Street, Hoboken, NJ 07030-5774, USA

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Library of Congress Cataloging-in-Publication Data Applied for:

9781119057451

A catalogue record for this book is available from the British Library.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Cover image: Victoria Soroker and Pompeo Suma

Set in 10/12pt WarnockPro by SPi Global, Chennai, India

1 2017

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Contributors

Victor Alchanatis
Institute of Agricultural Engineering
Agricultural Research Organization
The Volcani Center
Rishon LeZion
Israel

Neil Audsley
Fera Science Ltd
Sand Hutton
York
United Kingdom

Shay Barkan
Department of Entomology
Agricultural Research Organization
The Volcani Center
Rishon LeZion
Israel

Joan Manel Barroso
Endoterapia Vegetal SL
Girona
Spain

Laurence Beaudoin-Ollivier
Centre de coopération internationale en recherche agronomique pour le développement (CIRAD)
Biological System Department
Research Unit Bioagresseurs
France

Gregor Belušič
Department of Biology
Biotechnical Faculty
University of Ljubljana
Slovenia

Paul Benjamin
Bahá'í Gardens
Bahá'í World Center
Haifa
Israel

Maurane Buradino
INRA PACA Center
National Institute of Agriculture
UEFM
Entomology and Mediterranean Forest Unit
France

Yafit Cohen
Institute of Agricultural Engineering
Agricultural Research Organization
The Volcani Center
Rishon LeZion
Israel

Yuval Cohen
Department of Fruit Trees Sciences
Institute of Plant Sciences
Agricultural Research Organization
The Volcani Center
Rishon LeZion
Israel

Stefano Colazza
Department of Agricultural and Forest Sciences
University of Palermo
Italy

Oscar Dembilio
Universitat Jaume I
Department of Agricultural and Environmental Sciences
Campus del Riu Sec
Spain

Abd El Moneam El Banna
Agriculture Research Center
Egypt

Brigitte Frérot
Institute of Ecology and Environmental Sciences of Paris
Sensory Ecology Department (UMR 1392)
Institut national de la recherche agronomique
France

Inmaculada Garrido-Jurado
Unidad Entomologia Agricola
Dpto. Ciencias y Recursos Agricolas y Forestales
Campus de Rabanales C4 2 planta
Spain

Stella Giorgoudelli
Benaki Phytopathological Institute
Athens
Greece

Eitan Goldshtein
Institute of Agricultural Engineering
Agricultural Research Organization
The Volcani Center
Rishon LeZion
Israel

Ofri Golomb
Institute of Agricultural Engineering
Agricultural Research Organization
The Volcani Center
Ofri Golomb
Israel

Salvatore Guarino
Department of Agricultural and Forest Sciences
University of Palermo
Italy

Rachid Hamidi
Institute of Ecology and Environmental Sciences of Paris
Sensory Ecology Department (UMR 1392)
Institut national de la recherche agronomique
France

Amots Hetzroni
Institute of Agricultural Engineering
Agricultural Research Organization
The Volcani Center
Rishon LeZion
Israel

Mohamud Hussein
Food and Environment Research Agency
Sand Hutton
York
N. Yorkshire
United Kingdom

Marko Ilić
Department of Biology
Biotechnical Faculty
University of Ljubljana
Slovenia

Nunzio Isidoro
Department of Agricultural, Food and Environmental Sciences
Marche Polytechnic University
Italy

Josep A. Jaques
Universitat Jaume I
Department of Agricultural and Environmental Sciences
Campus del Riu Sec
Spain

Mohamed Kamal Abbas
Agricultural Research Center
Plant Protection Research Institute
Department of Wood Borers and Termites
Egypt

Filitsa Karamaouna
Department of Pesticides' Control and Phytopharmacy
Benaki Phytopathological Institute
Athens
Greece

Dimitris Kontodimas
Department of Entomology & Agricultural Zoology
Benaki Phytopathological Institute
Athens
Greece

Alessandra La Pergola
Department of Agricultural, Food and Environment
Applied Entomology Section
University of Catania
Italy

Paolo Lo Bue
Department of Agricultural and Forest Sciences
University of Palermo
Italy

Alan MacLeod
Food and Environment Research Agency
Sand Hutton
York
N. Yorkshire
United Kingdom

Ourania Melita
Benaki Phytopathological Institute
Athens
Greece

Dana Ment
Department of Entomology
Agricultural Research Organization
The Volcani Center
Rishon LeZion
Israel

Panos Milonas
Department of Entomology & Agricultural Zoology
Benaki Phytopathological Institute
Greece

Roxana Luisa Minuz
Department of Agricultural
Food and Environmental Sciences
Marche Polytechnic University
Italy

Sandro Nardi
Servizio Fitosanitario Regionale
Agenzia Servizi Settore Agroalimentare delle Marche
Italy

Vicente Navarro Llopis
Universitat Politècnica de València
Center for Agricultural Chemical Ecology
Mediterranean Agroforestal Institute
Spain

Lola Ortega-García
Unidad Entomologia Agricola
Dpto. Ciencias y Recursos Agricolas y Forestales
Campus de Rabanales C4 2 planta
Spain

Stavros Papageorgiou
Bytelogic
Athens
Greece

Ezio Peri
Department of Agricultural and Forest Sciences
University of Palermo
Italy

Primož Pirih
Graduate University for Advanced Sciences
Sokendai
Kanagawa
Japan

Costas Pontikakos
Department of Agricultural Economy and Development
Informatics Laboratory
Agricultural University

Enrique Quesada Moraga
Unidad Entomologia Agricola
Dpto. Ciencias y Recursos Agricolas y Forestales
Campus de Rabanales C4 2 planta
Spain

Paola Riolo
Department of Agricultural, Food and Environmental Sciences
Marche Polytechnic University
Italy

Didier Rochat
Sensory Ecology Department (UMR 1392)
Institute of Ecology and Environmental Sciences of Paris
France

Roberto Romani
Department of Agricultural, Food and Environmental Sciences
University of Perugia
Italy

Sara Ruschioni
Department of Agricultural, Food and Environmental Sciences
Marche Polytechnic University
Italy

Frosa Samiou
Directorate of Parks and Landscaping
Region of Attica
Athens
Greece

Victoria Soroker
Department of Entomology
Agricultural Research Organization
The Volcani Center
Rishon LeZion
Israel

Pompeo Suma
Department of Agricultural, Food and Environment
Applied Entomology Section
University of Catania
Italy

Elisabeth Tabone
INRA PACA Center, National Institut of Agriculture
UEFM, Entomology and Mediterranean Forest Unit
France

Sandra Vacas
Universitat Politècnica de València
Center for Agricultural Chemical Ecology
Mediterranean Agroforestal Institute
Spain

Elisa Verdolini
Department of Agricultural, Food and Environmental Sciences
Marche Polytechnic University
Italy

Nomenclature

N1: Common palm names

Palm species of the most common palms in Southern Europe and the Mediterranean basin. Only the most important, either local or very common as ornamental, palm species are mentioned.

Palm common name	Scientific name
Canary palm	*Phoenix canariensis*
Date palm	*Phoenix dactylifera*
Cretan date palm	*Phoenix theophrasti*
Pygmy date palm	*Phoenix roebelenii*
European fan palm	*Chamaerops humilis*
Desert fan Palm	*Washingtonia filifera*
Mexican fan palm (or Mexican Washingtonia)	*Washingtonia robusta*
Chusan palm	*Trachycarpus fortunei*
Trachycarpus	*Trachycarpus fortunei* "Wagnerianus"
Syagrus (Queen palm or Cocos palm)	*Syagrus romanzoffiana*
Alexander palm	*Archontophoenix alexandrae*
Doum palm	*Hyphaene thebaica*
Kentia palm	*Howea forsteriana*
African oil palm	*Elaeis guineensis*

N2: Palm organs

Term	Definition
The crown	
Crown	The cluster of leaves growing at the top of the stem forming the canopy
Meristem	The non-differentiated region of a plant where new cells and organs are developed
The palm "heart"	The central region of the crown including the apical meristem and the younger, developing leaves
Shoot apical meristem	The meristematic region at the central of the "palm heart." All new organs (leaves and inflorescences) are generated by the shoot apical meristem

Term	Definition
The stem	
Stem/stipe (trunk)	The main axis of the palm. Unlike the trunk of most dicot trees, it has a rather constant diameter. Its outer portion is composed of leaf sheets
Single stemmed palms/multi-stemmed (clustering)	Multi-stemmed palms are generated by branching of axillary meristems (buds) usually at the lower parts of the stem
Offshoot	A new shoot branched from the main stem, growing from an axillary bud
Vasculature, vascular bundles	Xylem (water-conducting tissue) and phloem (carbohydrate-conducting tissue) vascular bundles scattered throughout the central cylinder of the stem. They are interspersed within a matrix of parenchyma cells
Leaves (fronds)	
Palmate leaf	Shaped like a fan or the palm of the hand. All leaflets or leaf segments arise from a central area
Pinnate leaf	Feather-like leaf, leaflets arising along a central axis (rachis)
Leaf sheath	The base of the leaf, where it is tubular and completely surrounds younger leaves. It can split after maturity
Leaf blade	The open, wide part of the leaf (in palm it includes the leaflets or the leaf sections)
Leaflet	A leaf-like part of a compound leaf. Divisions of pinnate (and sometime palmate) leaf blades
Spear leaf	The youngest, emerging, unopened palm leaf
Primordial leaves	Developing leaves before emergence. Develop within the "palm hearth"
Inflorescences	
Axillary buds	Meristems located at the base of leaves. They can form offshoots (branching) at the juvenile stage and inflorescences once the palm has transitioned into a reproductive state
Inflorescence	A branch that bears flowers, including all its bracts and sub-branches
Bracts	A modified leaf associated with the inflorescence
Spathe	A large sheathing bract, covering the inflorescence. Botanically, depending on species, can be either the prophyll or the peduncular bract
Peduncle	The fruit stalk, the primary stalk, the lower unbranched part of an inflorescence
Petiole	The stalk of a leaf
Rachis	In a leaf: the axis of a leaf beyond the petiole; in an inflorescence: the axis beyond the peduncle
Rachilla	The inflorescence branches that bear the flowers (sometimes called spikelets)

The current list of terms is a compromise between botanical morphological terms and common terms used by farmers, gardeners and at nurseries.

Additional resources for palm terminology can be found at:

- *The Glossary of the European Network for Palm Scientists* (EUNOPS), http://eunops.org/content/glossary-palm-terms.
- Dransfield, J., Uhl, N. W., Asmussen-Lange, C. B. et al. (2008). *Genera Palmarum: Evolution and classification of the palms*. Royal Botanic Gardens, Kew.

N3: Semiochemicals

Chemical names	Common name	Biological Function	Comments
4-methyl-5-nonanol	Ferrugineol	Major component of RPW aggregation pheromone	The naturally produced compound is the (4S,5S)-ferrugineol
4-methyl-5-nonanone	Ferrugineone	Minor component of RPW aggregation pheromone	The naturally produced compound is the (4S)-ferrugineone
(2E,13Z)-octadecadien-1-ol	E2,Z13-18:OH	Major compound isolated from male PBM mid-tarsae	The chemical is assumed to be a male PBM pheromone

Introduction

Neil Audsley[1], Victoria Soroker[2] and Stefano Colazza[3]

[1] *Fera Science Ltd, Sand Hutton, York, United Kingdom*
[2] *Department of Entomology, Agricultural Research Organization, The Volcani Center, Israel*
[3] *Department of Agricultural and Forest Sciences, University of Palermo, Italy*

Invasive Alien Species

The EU commission's definition of an invasive alien species is "an animal or plant that is introduced accidentally or deliberately into a natural environment where they are not normally found, with serious negative consequences for their new environment" (European Commission 2016). Alien species occur in all major taxonomic groups and are found in every type of habitat. The EU-funded project DAISIE (Delivering Alien Invasive Species Inventories for Europe) reported that over 12,000 alien species are present in Europe and 10–15% of them are considered invasive (DAISIE 2016). The globalization of travel and trade and the expansion of the human population have facilitated the movement of species, especially in Europe, where travel is unrestricted between most member states.

The ingress, establishment, and spread of alien pest species are of high importance because their impacts are wide ranging. As well as reducing yields from agriculture, horticulture, and forestry, they can cause the displacement or extinction of native species, cause habitat loss, affect biodiversity, disrupt ecosystem services, and pose a threat to animal and human health.

The risks posed to the EU region by non-native species are widely recognized and have led to legislation to combat their threat, the most recent of which (Regulation (EU) No. 1143/2014) came into force on January 1, 2015 (European Commission 2016). This regulation aims to minimize or mitigate the adverse effects of invasive alien species. It also supports preceding directives on invasive alien species (European Commission 2016). This directive highlights anticipated interventions to combat invasive alien species, including prevention, early warning, rapid response, and management. Despite this regulation, it can be assumed that the introduction of new invasive alien species into Europe will continue, and the spread of those species that have become established is likely to continue as well. Climate change may well make it easier for some species to become established in Europe, hence the risks posed by the invasive alien species are likely to increase.

Huge costs are associated with invasive species; in the USA, damage has been estimated at more than €100 billion a year, with insects contributing around 10% of this damage (Pimentel, Zuniga, and Morrison 2005). In Europe, damage exceeds €12 billion annually, but this is most likely an underestimate because, for many alien species in Europe, the potential economic and environmental impacts are still unknown (European Environment Agency 2012). It is clear that failure to deal with invasive species in a timely and efficient manner can be extremely costly. The DAISIE project has produced fact sheets of the worst 100 of these species (http://www.europe-aliens.org/speciesTheWorst.do), which include insects such as the Mediterranean fruit fly *Ceratitis capitata* and the Western corn rootworm *Diabrotica virgifera*, describing their economic, social, and environmental impacts.

Failure to detect and eradicate pest populations at some point prior to, during, or following transportation facilitates the introduction, spread, and establishment of invasive alien pests. This is exemplified by the establishment of the RPW and PBM in and around the Mediterranean basin.

R. ferrugineus and *P. archon*: Invasive Pests of Palm Trees

Palm trees in the Mediterranean basin and elsewhere are under serious threat from the RPW and PBM, two invasive species that were accidentally introduced through the import of infested palms. The larvae of both of these insects bore into palm trees and feed on the succulent plant material stem and/or leaves. The resulting damage remains invisible long after infestation, and by the time the first symptoms of the attack appear, they are so serious that, in the case of the RPW, they often result in the death of the tree (Ferry and Gómez 1998; Faleiro 2006; EPPO Reporting Service 2008a; Dembilio and Jaques 2015).

The PBM, native to South America, was first reported in Europe—in France and Spain—in 2001, but it is believed to have been introduced before 1995 on palms imported from Argentina. It has since spread to other EU member states (Italy, Greece, and Cyprus) with isolated reports in the UK, Bulgaria, Denmark, Slovenia, and Switzerland (Vassarmidaki, Thymakis, and Kontodimas 2006; EPPO Reporting Service 2008b, 2010; Larsen 2009; Vassiliou *et al.* 2009). Although *P. archon* has not been reported to be a significant pest in South America, with the exception of reports from Buenos Aires (Sarto i Monteys and Aguilar 2005), it has been the cause of serious damage and plant mortalities, mainly in ornamental palm nurseries, in France, Italy, and Spain (Riolo *et al.* 2004; Vassarmidaki Thymakis, and Kontodimas 2006). It may also increase the risk of RPW spread by creating primary damage to palms, which then attracts the weevil.

The RPW is native to southern Asia and Melanesia (Ferry and Gómez 1998; EPPO Reporting Service 2008a), but is now spreading worldwide. After becoming a major pest in the Middle Eastern region in the mid-1980s (Abraham, Koya, and Kurian 1989), it was introduced into Spain in the mid-1990s (Barranco, de la Peña, and Cabello, 1996) and rapidly spread around the Mediterranean basin to areas where susceptible palm trees are grown outdoors (EPPO Reporting Service 2008a and b). Its range now also includes much of Asia, regions of Oceania and North Africa, the Caribbean, and North America (EPPO Reporting Service 2008a, 2009; Pest Alert 2010). Of the EU member states, Italy and Spain are the worst affected, accounting for around 90% of the total number of outbreaks reported, but the RPW is also prevalent in France (DRAAF-PACA 2010).

The high rate of spread of the RPW in Europe following its introduction is most likely due to a combination of factors that resulted in inadequate eradication and containment of this weevil. The lack of effective early-detection methods, the continued import of infested palms, and the transportation of palms and offshoots from contaminated to non-infested areas have had a major impact (Jacas 2010).

By 2007, the spread of the RPW had become uncontrollable, resulting in the adoption of emergency measures to prevent its further introduction and spread within the community (Commission decision 2007/365/EC 2007). These measures included restricted import and movement of susceptible palms and annual surveys for RPW. However, although the interceptions of infested material decreased, the procedures to prevent spread were not fully effective.

In 2010, new recommendations on methods for the control, containment, and eradication of RPW were made by a Commission Expert Working Group and at the International Conference on Red Palm Weevil Control Strategy for Europe, held in Valencia, Spain. They recognized that:

- in most areas, eradication of RPW was unlikely to be achieved so containment would be more appropriate;
- better enforcement of EU legislation for intra-community trade and imports from third countries was required to prevent the further spread of the RPW within EU member states;
- there was a need for research and development of programs focused on the early detection, control, and eradication of RPW.

A successful program for RPW eradication was undertaken in the Canary Islands to protect the native *Phoenix canariensis* after this insect was detected in the resorts of Fuerteventura and Gran Canaria in 2005. This included a ban on the importation of any palms from outside the Islands and a program of work that included monitoring for the pest, inspection of palms and nurseries, accreditations for transplantation and movement of palms, elimination of infected palms, plant health treatments, and mass trapping, and an awareness campaign that included a website, talks, seminars, courses, newsletters, and leaflets. In 2007, an outbreak was reported on Tenerife, but since 2008 no additional weevils have been detected (Giblin-Davis 2013; Gobcan 2009).

The key aspects of protective measures against the RPW and PBM (and other invasive pests) are:

- to rapidly and accurately detect these insects in imported palms, or palms being moved between different areas;
- to rapidly detect new infested areas;
- to take appropriate measures to eradicate the pests;
- where eradication is unlikely, i.e. in areas where these pests are already established, take appropriate action to contain and control the pests within that area to prevent further spread within the community.

However, the threats posed by the RPW and PBM are now greater than ever because:

- one or both of these pests is already present in almost all countries around the Mediterranean basin where susceptible palms are grown;
- previous measures have proven insufficient and often ineffective;
- eradication in "uncontrolled" areas, such as private gardens, is difficult;

- re-infestation of "clean" areas can occur due to a single untreated palm tree;
- infestations in some rural areas may go undetected;
- import of palms from third countries, which themselves have RPW and/or PBM infestations, continues;
- climate change may have an impact on the range of these invasive species and their host palm trees.

Despite EU legislation and measures taken to eradicate and contain these invasive pests, the RPW remains the most damaging pest of palm trees, and the PBM has become established in the Mediterranean basin. The main options for the eradication, control, and containment of these quarantine insects are through integrated pest management, relying on innovative early detection, effective monitoring and mass trapping, preventative and curative treatments, and quarantine and education procedures.

Palm Protect

Palm Protect (strategies for the eradication and containment of the invasive pests *R. ferrugineus* Olivier and *P. archon* Burmeister) was a three-year project (2012–2014) involving 13 organizations from seven countries, funded by the European Union's Seventh Framework program. Its aims were to develop reliable methods for the early detection, eradication, control, and containment of the RPW and the PBM by:

- providing a more comprehensive understanding of the biology of the RPW and the PBM to facilitate decision-making for risk assessment and optimization of monitoring and control methods;
- combating the spread and establishment of the RPW and the PBM by developing technologies for the early detection and monitoring of these pests;
- developing methods to eradicate, control, and contain both RPW and PBM, to restrict their further invasion of EU territories.

Some of the major results and outcomes of Palm Protect are included in this book.

Overview

In this book, we have assembled chapters written by internationally recognized experts who are at the forefront of their fields. Each chapter highlights the major findings of the project, and presents the state of the art on the management of RPW and PBM, including recent advances and future challenges. The book contains 13 chapters organized in two parts. The first part, basic aspects, starts with a chapter focusing on the major insect herbivores affecting palm trees (Chapter 1). The insect pests are listed according to their preferred part of the palm (i.e. crown/meristem, leaves, fruit bunches, fruit, inflorescences, and roots) and the main biological information is provided. Palms are unique trees in that they are monocotyledons and have evolved a unique morphology, anatomy, and physiology. Chapter 2 reviews these special features of palms, and discusses their relevance to RPW and PBM damage and treatment. Palm trees are indeed an important component of urban landscapes, and the benefits provided by palms in terms of ecosystem services are discussed in Chapter 3, to provide an indication of what is being threatened by these invasive pests. The following chapters cover the main biological, ecological, and physiological aspects of RPW (Chapters 4 and 5) and PBM (Chapters 6 and 7), providing the necessary background information for management of these palm pests, and assessment of recent scientific advances.

The second part of this book focuses on the management and control of the RPW and PBM. Chapter 8 provides a detailed overview of their natural enemies. A key aspect in the management of these two pests is to define a robust method for the accurate detection of early infestations. Chapter 9 identifies and characterizes visible palm symptoms induced by RPW and PBM infestations. The detection methods, based on chemical, acoustic, and thermal cues, as well as pest monitoring by semiochemicals, are reviewed in Chapter 10. The following two chapters focus specifically on the RPW. In particular, the implementation of a Location Aware System, which is an optimized version of the commercially available CPLAS (Bytelogic.gr) for the integrated management of the RPW, is presented in several case studies (Chapter 11). Chapter 12 discusses the pros and cons of the different approaches for the management of RPW, from preventive cultural practices and legal measures, including quarantines and official inspections, to curative chemical and biological control methods, sanitation, and those methods based on the use of semiochemicals. The last chapter (Chapter 13) gives suggestions for strengthening the capability to deal with the problems associated with these invasive species. An overview of the European legislation regarding introduction, control, and eradication (when available) of both pest species is also provided.

Conclusion

This book is very timely and touches on a key area of public interest. Following the accidental introduction into Europe of the devastating palm pests RPW and PBM, there has been a growing demand for detailed information on their distribution, data, and on the impact/damages observed in EU countries, and practical tools for their detection and monitoring. Ultimately, the data provided in this book represent a valuable inventory that could also be used to test mathematical models of the spread of insect pests.

Acknowledgment

The research for this book was funded by the EU project "Palm Protect: Strategies for the eradication and containment of the invasive pests *Rhynchophorus ferrugineus* Olivier and *Paysandisia archon* Burmeister" (7th European Union Framework Programme under Grant Agreement FP7 KBBE 2011-5-289566).

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Some Representative Palm Pests: Ecological and Practical Data

Laurence Beaudoin-Ollivier[1], Nunzio Isidoro[2], Josep A. Jaques[3,], Paola Riolo[2], Mohamed Kamal[4] and Didier Rochat[5]*

[1] *Centre de coopération internationale en recherche agronomique pour le développement (CIRAD), Biological System Department, Research Unit Bioagresseurs, France*
[2] *Department of Agricultural, Food and Environmental Sciences, Marche Polytechnic University, Italy*
[3] *Universitat Jaume I, Department of Agricultural and Environmental Sciences, Campus del Riu Sec, Spain*
[4] *Agricultural Research Center, Plant Protection Research Institute, Department of Wood Borers and Termites, Egypt*
[5] *Sensory Ecology Department (UMR 1392), Institute of Ecology and Environmental Sciences of Paris, France*

1.1 Introduction

Almost all palms species (Arecaceae), around 2600 worldwide, are arboreal plants adapted to tropical or arid conditions; only a few, such as *Trachycarpus fortunei* (Chusan or windmill palm), are adapted to cooler temperate climates (Howard *et al.* 2001; APG 2009; Eiserhardt *et al*. 2011; Palmweb 2011; eMonocots 2013).

Some palm species produce large bunches of fruit that are rich in sugars or lipids. These species have long been cash crops, of which the famous coconut palm (*Cocos nucifera* L.), date palm (*Phoenix dactylifer*a L.), and African oil palm (*Elaeis guineensis* Jacq.) can be highlighted. Many other palm species hold local economic importance as food or for other technical uses.

Being among some of the most familiar plants, palms bear an exotic appeal with their unique shape, which has made, for instance, the Canary Island date palm (*Phoenix canariensis* Hort ex. Chabaud) one of the most planted ornamental palms worldwide, and particularly in Mediterranean countries. Owing to easy planting, rapid growth, and simple maintenance, many other palm species have been important ornamental plants for over a century and have great economic value. Their trade has increased considerably in recent years due to their prevalence in new urbanized areas and tourist resorts (André and Tixier Malicorne 2013). For example, 51,000 individual plants belonging to 421 palm species were introduced into La Réunion between 2000 and 2006 for a palm botanical garden project (Meyer, Lavergne, and Hodel 2008). Overall, palms are memorial markers of landscapes, either natural or artificial, such as orchards, botanical gardens, parks, and avenues, some of which have become UNESCO heritage sites.

Palms are characterized by rapid growth from a unique meristem where the stem, the fronds, and the inflorescences develop, forming large amounts of soft tissue that is rich in water and nutrients (see Chapter 2, this volume). They often produce large fronds

*J.A. Jaques was formerly J.A. Jacas

Handbook of Major Palm Pests: Biology and Management, First Edition.
Edited by Victoria Soroker and Stefano Colazza.

and large fruit bunches. Because of their diversity and these morphophysiological properties, palms shelter a great diversity of arthropods and are exploited by many herbivores, including insect and mite species. Less than 10% of the thousand arthropod species living on palms have been recognized as serious palm pests for cultivated species. These pest species have been repeatedly reviewed (Lepesme 1947; Bedford 1980, 2013; Mariau 2001; Howard *et al.* 2001) and interested readers should refer to these reviews for comprehensive information about these insects.

Lepesme (1947) reported that insects cause very little damage on wild palms. However, as soon as these species are cultivated in large areas, they become more susceptible to pest attack. The rapid and exponential increase of planted areas for coconut, date, and oil palms over the last 50 years (Rival and Levang 2013; Statistical series from FAO stat website 2015, http://faostat3.fao.org/home/E), especially under vast monocultures, and the increased trade of tall specimens of ornamental palms have favored the outbreaks of several species, reaching pest status (e.g. *Oryctes rhinoceros* (L.); see Section 1.3.2). Furthermore, some arthropods have colonized new areas where they have adapted to palm species that are absent from their native areas. Today, all cultivated palms are affected by native and invasive pests, such as *Rhynchophorus ferrugineus* (Olivier) (Section 1.3.4) and *Paysandisia archon* (Burmeister) (Section 1.3.6) in the Mediterranean, with both environmental and economic impacts (Chapin and Germain 2005).

This chapter is an overview of the main types of palm pests—23 species that were selected as an example of the relationships between palms and herbivorous arthropods from among the most damaging taxonomic groups: Lepidoptera, Coleoptera, and Hemiptera. These species are mostly pests of coconut, date, and oil palms, but also of ornamental species and sometimes wild endemic palms. They show some extremes in size and lifestyles under various latitudes.

For convenience, the pests included in this chapter are classified according to their main feeding habit/lifestyle: crown borers (5 species), defoliators (5 species), sap feeders (4 species), frond, inflorescence, or fruit dwellers (8 species), and root feeders (1 species). Some of these species have broader feeding habits and could have been classified otherwise. Each category is introduced by providing some general features that apply to a common lifestyle and practical consequences for their management. Subsequently, for each species, we briefly present and illustrate, using a datasheet format, typical ecological features: cycle, damaging stage(s), main host species, and distribution. Finally, we provide information about the pest's invasive status and possible interaction with other insect species.

1.2 General Features About Palms and their Pests

1.2.1 Palm Features are Suited to Arthropod Herbivores

Palms make up a homogeneous group of monocots, which have evolved for about 100 million years together with herbivorous arthropods (APG 2009; Eiserhardt *et al.* 2011; Thomas 2013). Insects have remarkably diversified to exploit all niches offered by higher plants: leaves, sap, stipe, roots, fruit, and seeds (Rochat *et al.* 2013). Thus, many insects have adapted to palms, sometimes as their exclusive food resource, and co-evolved with them, as in the case of palm weevils (*Rhynchophorus* spp.) (O'Meara 2001).

Palms share anatomical and physiological traits that make them unique (see Chapter 2, this volume), such as their typical growth and leaf organization in an apical bouquet at the top of a single woody stem. Growth rate (stem elongation and frond production) is very rapid in most palms. For instance, oil palm can produce up to two new fronds per month (Corley and Tinker 2003; Jacquemard 2011). The apical part of the stem, including the forming fronds and inflorescences, is an area of intense metabolism and cell multiplication with a large amount of soft tissue that is highly hydrated and rich in nutrients. Sap flows and exudation upon cutting these tissues are generally quite plentiful. This amount of nutritious tissue is especially suitable for, and accessible to, borers. These tissues are sustained by the unfolded functional fronds, which display large photosynthetic areas that are available to sap feeders and defoliators.

Aerial roots grow, sometimes abundantly, at the base of the stem. This area has higher metabolism and cell multiplication than the rest of the stem and also offers food and shelter to other herbivores. In species that produce offshoots, such as the date palm or caespitose palms, the base of the stem is also a place worth feeding on as it gathers the root and crown properties, with actively growing tissues rich in water and nutrients (Lepesme 1947; Peyron 2000).

A peculiar vascular system from the roots to the fronds makes palms highly tolerant to stem damage, ensuring water and nutrient supply to the foliage. The stem/stipe, essentially made up of living parenchyma, also serves as an important stock of water and nutrients, which help the plant survive or recover from severe foliage or root losses. This organ is exploited by specialized borers (Lepidoptera, Coleoptera: Cerambycidae) (Lepesme 1947).

Finally, most palms produce large inflorescences that are protected in a spathe before blooming. Pollination is achieved in most palms by highly non-hymenopteran insects (Henderson 1986). The female inflorescence generally develops in large fruit bunches as in the date palm, coconut palm and African oil palm, which provide large nutrient resources that can be exploited by different species, which are often quite generalist, including post-harvest pests.

1.2.2 Main Arthropod Pests on Palms

All types of arthropod herbivores can be found on palms: polyphagous species that also feed on other plant taxa, and specialized species that develop only on Arecaceae. Owing to the large and diverse food resources offered by palms, all groups of herbivorous arthropods can be found on them. The species either live on the plant—the defoliators and sap feeders, or inside it—the leaf miners and borers, the latter able to reach large sizes sheltered in large and wide galleries. As an example, Carpenter and Elmer (1978) reported 54 species of mite and insect pests of date palm worldwide. In Israel, 16 major and 15 minor species have been recorded on this palm species (Blumberg 2008). Among them, Lepidoptera is the largest group (about 240 species) of pests on coconut, date, and oil palms. Caterpillars, of several species of Limacodidae, are among the most damaging. They are leaf eaters, attacking unfolded spathes and folded fronds. Other members of the Lepidoptera are miners of fronds, flowers, fruit, stems, nursery seedlings, or roots (Mariau 2001).

Lepesme (1947) described 167 species of Hemiptera living on the coconut palm and 74 on the oil palm *E. guineensis* Jacq. A large number of them were common to both palms species. Other hemipterans feed on date palm in dry climates. Some species are known or suspected to transmit diseases, such as various heart rots by *Lincus* sp. (Perthuis, Desmier de Chenon, and Merland 1985) or lethal yellowing diseases by *Myndus* sp. (Howard *et al*. 2001).

Coleopterans are also serious palm pests: many species of the family Scarabaeidae attack oil, date, and coconut palms in their adult form, whereas for other species (e.g. Curculionoidae and Chrysomelidae) the larvae damage the palm.

Many other insects living on palms, such as *Segestes decoratus* (Orthoptera, Tettigoniidae), *Graeffea crouanii* (Phasmida, Phasmatidae), *Macrotermes* spp. (Isoptera), and several species of Thysanoptera, are common on flowers (Mariau 2001).

1.2.3 Damage and Pest Management

Owing to (1) the importance of palm products, particularly oil, fruit, and their ornamental value; (2) the increase in planting in recent decades; and (3) palm pest diversity, damage can have huge economic consequences.

Borers are by far the most difficult group to manage. In the past, important use of insecticides was more or less successful but carried with it increasingly broad environmental concern. Many insecticides used in the past have been or are being progressively banned. In Indonesia, for example, the cost of controlling *O. rhinoceros* was estimated at $10 million in 1995. Control was based on manual collection of the larvae in breeding sites before replanting and of adults feeding in the galleries burrowed in the young palms, and on the application of insecticide granules on every palm every two weeks till the age of 2 to 3 years.

Integrated pest management includes alpha-cypermethrin and lambda-cyhalothrin applications given alternately every 10 days on the spear if more than 4% of fresh attack per interline is observed (Jacquemard 2011). Destruction of dead stems of palm trees and shredding of the infested stems are also recommended (Jacquemard 2011).

In the 1980s, Baculovirus strains were used against *O. rhinoceros* with some success, but the scarab population increased with the creation of new plantations and could no longer be controlled by this entomopathogen. The discovery of an aggregation pheromone (Hallett *et al.* 1995; Morin *et al.* 1996) led to evaluating the possible use of the mass trapping of adults. However, this technique did not prove useful as the young adults, which feed on the palm, responded poorly to the pheromone. Furthermore, beetle populations were so high and the insect so mobile that, despite important captures, damage could not be lowered (Beaudoin-Ollivier, unpublished). In the case of *Rhynchophorus* sp., chemical control offers interesting alternatives together with mass trapping based on aggregation pheromones (Hallett *et al.*, 1993) and kairomones (see Chapters 5 and 12, this volume).

Species feeding on the aboveground parts of the palm can be managed using methods based on their lifestyle. Monitoring and sanitation are particularly important to preventing catastrophic outbreaks. Most species co-occur with a guild of natural enemies, which can be managed by either conservation or augmentation. For example, the parasite *Rhysipolis* sp. is effective on *Stenoma cecropia* (Lepidoptera Gelechioidea Stenomatinae) in Ecuador and Columbia (Jacquemard 2011). *Stichotrema dallatorreanum* and gregarines are active on *Sexava coriacea* and *Segestes decoratus* (Orthoptera Tettigonioidea Tettigoniidae) (Jacquemard 2011). Specific commercial virus strains or those originating from infested caterpillars are also used on *Setora nitens*, *Setothosea asigna*, *Thosea* spp., and *Darna* spp. (Lepidoptera Zygaenidae Limacodidae) in Indonesia. *Cordyceps* on *Setothosea* spp. and *Paecilomyces farinosus* on *Euclea diversa* are also found (Jacquemard 2011).

1.3 Crown and Stem Borers

1.3.1 Pest Ecology, Damage, and Management

The insect species in this section exhibit tunneling activity in the crown for feeding during either the larval or adult stages, or both. In most species, the galleries are made in the growing tissues, which have the highest nutritional content. They affect the tissues of the stem and the growing fronds and inflorescences more or less randomly. Some preference for specific organs can be observed in certain palm borers, but this is the exception. Borers can attack the growing tip of either the mother stem or the offshoots in palm species that produce them, as in the date palm.

Injury is both mechanical and physiological. The galleries weaken the crown and/or stem, which can break as a consequence of the increasing weight of the fruit bunches, with a direct impact on production, or simply as a consequence of wind, rain, or nesting birds. The galleries also alter sap conduction. Injury to the apical meristematic tissues is lethal to palm trees as they grow from this unique point (see Chapter 2, this volume). In a few cases, specific palm pathogens can be vectored by these borers, such as that responsible for red ring disease by *Rhynchophorus palmarum* L. (Goodey 1960; Griffith 1974). In turn, tunneling of many borers favors the development of saprophytic microorganisms in the injured tissue and can cause the palm's decline and eventual death. In addition, severe tunneling induces malformations, particularly of fruit bunches and fronds, which also reduce the yield and decrease the ornamental value of the palms.

The management of these borers is difficult because they are essentially located in the crown, far from the ground and often deep inside the plant tissues. Contact insecticides can be efficient against the adults, which visit the palms for feeding and egg-laying. In turn, only systemic or fumigant insecticides are active against the insects present in the galleries. Some bio-insecticides (fungi, nematodes, and viruses) can penetrate the galleries or be carried by boring adults and offer alternatives to conventional insecticides. Since the 1990s, mass trapping using aggregation pheromones has been implemented against certain palm weevils (*Rhynchophorus* spp.) and rhinoceros beetles (*Oryctes* spp.) (El-Sayed *et al*. 2006).

1.3.2 *Oryctes rhinoceros* Linnaeus 1758 (Coleoptera: Scarabaeidae)

Oryctes spp. constitutes the most important pests of the coconut palm worldwide. They are typical horned beetles (Dynastinae, Oryctini) (Fig. 1.1a). Adults are stocky insects with morphological adaptation of the prothorax and forelegs bearing powerful spines or points dedicated to burrowing in plant tissues. *O. rhinoceros* (rhinoceros beetle, name often applied to most Oryctini species) in Southeast Asia and the Pacific and *Oryctes monoceros* Olivier in Africa are the most harmful.

The insect reproduces mainly in decaying palm wood where males emit an aggregation pheromone (Gries *et al*. 1994; Hallett *et al*. 1995; Morin *et al*. 1996; Allou *et al*. 2006). The adults are nocturnal and feed individually on the palms prior to mating (Morin, personal communication). Larvae contribute to wood recycling with their symbionts.

Distribution: Introduced into New Britain (Papua New Guinea), New Ireland (Bismarck Archipelago), Manus Island, Western and American Samoa, Tonga, Fiji, Wallis Island, Micronesia, Mauritius, and the Cocos Islands (Bedford 1974, 1980). It occurs from Southeast Asia to the Philippines and China, and several Pacific islands.

Host palms: *C. nucifera*, *E. guineensis*.

(a) (b) (c)

Figure 1.1 (a) *O. rhinoceros* adult. (b) Coconut palm damaged by *O. rhinoceros.* (c) Coconut crown damaged by *O. rhinoceros*.

Primarily found attacking coconut and oil palm, *O. rhinoceros* has occasionally been recorded on banana (Sharma and Gupta 1988), sugarcane, papaya, sisal, and pineapple (Khoo, Ooi, and Ho 1991). In Mauritius, ornamentals such as the royal palm (*Roystonea regia*), the cabbage palm (*Livistona chinensis*), the talipot palm (*Corypha umbraculifera*), and the raphia palm (*Raphia ruffia*) are also attacked (Bedford 1980).

Secondary hosts: *Musa paradisiaca* (plantain), *Saccharum officinarum* (sugarcane), *Carica papaya* (papaw), *Ananas comosus* (pineapple), Lantana, *Metroxylon sagu* (sago palm), and *Agave sisalana* (sisal hemp).

Harmful stage and damage: Adults. They feed by mining galleries at the base of the young leaves, which affects palm development and photosynthesis. They bore into the cluster of forming fronds, causing wedge-shaped or V-shaped cuts in the unfolded fronds or spears (Fig. 1.1b). In young palms, where the spears are narrower and penetration may occur lower down, the effects of the damage can be much more severe than in older palms (Wood 1968) (Fig. 1.1c).

Risks: The larvae are capable of surviving in floating logs transported by ocean currents (Lever 1969).

1.3.3 *Scapanes australis* Boisduval 1832 (Coleoptera: Scarabaeidae)

This large beetle (up to 5 cm long and 2.5 cm in diameter), the New Guinea rhinoceros beetle, is sex dimorphic: males bear three long prothoracic horns (Fig. 1.2a), whereas the females do not. Males bore directly into the stem of the palm from the side for food and shelter (Bedford 1976). They call mates by emitting an aggregation pheromone during characteristic behavior at the entrance of their gallery at night (Prior *et al.* 2000). A male can be attracted to the caller. The latter and the newcomer then fight for possession of the gallery. Females are rare in the galleries but more frequent in dedicated organic matter heaps, where the larvae develop for at least 1 year outside the plantations (Beaudoin-Ollivier *et al*. 2001).

Distribution: Oceania and Eastern Asia: Papua New Guinea and the Solomon Islands (Bedford 1976; Waterhouse and Norris 1987), Indonesia (Kalshoven and van der Laan 1981), Philippines (Lepesme 1947; FAO 1966), and Singapore (APPPC 1987).

Host palms: *C. nucifera*, *E. guineensis*, *Areca catechu* (betel nut palm), *Musa* sp. (banana).

(a) (b)

Figure 1.2 (a) *S. australis* adult (male). (b) Damage due to *S. australis* attack.

Harmful stage of the pest and damage: The adults, which feed on the juices from the bored tissues. Attack by *S. australis* is usually restricted to young palms, from just past the seedling stage to about 5 years of age. Owing to the large size of the borer and replicated attacks, fatal damage is extremely frequent. If the growing point is not destroyed, the fronds show typical V-shaped cuts or varying degrees of deformation (Fig. 1.2b): fronds are truncated, notched, or twisted, with the leaflets compressed and crumpled together (Bedford 1976).

Risks: *S. australis grossepunctatus*, from the northeastern islands of Papua New Guinea and the Solomon Islands, could pose a phytosanitary risk if it was accidentally transferred to the main island of Papua New Guinea (Beaudoin-Ollivier, personal communication). In this area only, *S. australis grossepunctatus* lives and is not a pest, for undetermined reasons. Local use and production of hybrid mature nuts and seedlings lower the phytosanitary risk of seedling transport between the islands.

S. australis attacks create sites that are highly propitious for the attraction and development of *Rhynchophorus bilineatus* (Beaudoin-Ollivier *et al.* 1999).

1.3.4 *Rhynchophorus ferrugineus* Olivier 1790 (Coleoptera: Dryophthoridae)

R. ferrugineus (red palm weevil or RPW) infests and kills palm species of high economic value, particularly coconut in Monsoon Asia, and more recently date palm and Canary Island date palm in the Middle East and Mediterranean Basin (Fig. 1.3a) (see Chapter 4, this volume). Both the larva and the adult feed on palms. Males emit an aggregation pheromone that attracts RPW in synergy with the odor of wounded palms or decaying fruit. The adult is a good flyer and prolific: 100 to 250 eggs/female (see Chapters 4 and 5, this volume).

Origin: Indo-Malaysia (Monsoon Asia), from eastward to the Philippines (Rugman-Jones *et al.* 2013).

Distribution: Today RPW is present in most countries from southwestern Europe (Portugal) to the Mediterranean and Black seas (see Chapter 4, this volume) and to the Middle East up until Pakistan plus the Canary Islands, Madeira, the Caribbean (Curacao and Aruba), Taiwan, and China (EPPO website for updated reports 2008; Abe, Hata,

(a) (b) (c)

Figure 1.3 (a) Damaged *P. dactylifera*. (b) *R. ferrugineus* adult. (c) *R. ferrugineus* larva.

and Sone 2009; El-Mergawy and Al-Ajlan 2011). RPW originating from tropical and subtropical areas has settled in temperate areas with a Mediterranean or arid climate, and has adapted to palms species that are not present in its native range.

Host palms: Chapter 4 and in particular Table 4.3 provides a critical and comprehensive list, an overview of which is given here:

- *with obvious susceptibility:*
  Sixteen species growing in the native tropical area: *Areca catechu*, *Arenga pinnata*, Borassus flabellifer, two *Caryota* spp., *C. nucifera*, two *Corypha* spp., *E. guineensis*, two *Livistona* spp., *Metroxylon sagu*, *Nypa fruticans*, two *Oncosperma* spp. and *Roystonea regia* are original RPW hosts; two species adapted to drier climates and common in northwestern India: *Phoenix sylvestris* and *P. dactylifera*.
- *less susceptible with obvious resistance:*
  These include *Chamaerops humilis*, *T. fortunei*, *Washingtonia robusta*, and *W. filifera*, which are common in the EU, and the Aegean *Phoenix theophrasti*.
- *susceptible with insufficient information:*
  Two *Brahea* spp., *Butia capitata*, *Howea forsteriana*, *Jubaea chilensis*, *P. theophrasti*, *Sabal* spp., and *Syagrus romanzzofiana* have all been naturally infested with RPW, resulting in death of some palms.
- *other potential hosts:*
  - *Non-palm:* Larvae can be bred on banana fruit (Salama and Abdel-Razek 2002), agave (Malumphy and Moran 2007), and sugarcane (Rahalkar, Harwalkar, and Rananavare 1972).
  - *Palm:* Larvae can develop in *Livistona decora* if artificially infested (Barranco *et al.* 2000), and Liao and Chen (1997) reported larval infestation of *Bismarckia nobilis* seedlings in Taiwanese nurseries.
  - *Potential non-host palm species:* There are no reports of natural infestations of *Archontophoenix alexandrae*, *Nannorrhops ritchiana*, or *Phoenix rupicola*. Furthermore, larvae did not develop to pupation under laboratory conditions on stem tissues of *N. ritchiana* (Farazmand 2002).

RPW has long been reported as a severe pest on coconut and date palm and, to a much lesser extent, as a regular pest on African oil palm as well as other palm species with traditional uses, such as the sago palm (Wattanapongsiri 1966; Faleiro 2006; El-Mergawy and Al-Ajlan 2011; Jacquemard 2011). *P. canariensis* and *P. dactylifera* are highly susceptible hosts in the invasion area (Faleiro 2006). *P. dactylifera* appears less susceptible than

P. canariensis. However, date palm and Canary Island date palms have shown differences in susceptibility within varieties, sexes, and hybrids (Rochat 2006; Salama, Zaki, and Abdel-Razek 2009). For example, more male than female *P. canariensis* and *P. dactylifera* are infested by RPW in Italy and Spain (Uribarrena 2013). Various other palm species with high patrimonial value, such as the endemic *P. theophrasti*, *J. chilensis*, or *Washingtonia* spp., can also be killed by the pest.

Harmful stages and damage: Both adults and larvae (Fig. 1.3b, c) are the most damaging stages by far. Once they reach the growing point, they kill the palm. Visible damage symptoms due to low to moderate attacks are similar to those observed for palm rhinoceros beetle attacks in tall specimens: characteristic cuts in the unfolded fronds and missing parts of adjacent leaflets eaten during frond formation. Under high attack, the entire crown dries up and collapses (see Chapter 9, this volume). Palm mortality is reported to be high on coconut palms in native areas and on *P. canariensis* and *P. dactylifera* in invaded areas (see Chapter 4, this volume).

Risks: Palms damaged by *O. rhinoceros* (Section 1.3.2) are often attacked by RPW where the two species co-habit. Similarly, *P. archon* (Lepidoptera: Castniidae) (palm borer moth; PBM, Section 1.3.6) could provide favorable cues for RPW host detection, thereby facilitating palm colonization in a new spot. Major attention should be paid to these risks to the southern and southeastern shores of the Mediterranean, where PBM is currently absent but may well adapt to using the date palm as a host.

1.3.5 *Castnia daedalus* Cramer 1775 (Lepidoptera: Castniidae)

Castniid adults have been named butterfly moths due to their diurnal activity and morphological resemblance to some butterflies, although they belong to the Cossoidea, a group that is well separated from the Papilionoidea (butterflies). *Castnia* (syn. *Eupalamides*) *daedalus* is one of the largest insect borers of palm stems and fruit bunches (Fig. 1.4a). The female can lay around 500 eggs (Ohler 1984). The larval stage lasts 315 days, as the caterpillars continuously feed and grow to the considerable size of about 13 cm in length and the diameter of a fat thumb (Huguenot and Vera 1981; Yaseen 1981).

Distribution: Amazon valley through the Guianas to Panama (Rai 1973), Venezuela, Surinam, Guyana, Brazil (northeast), Colombia, Ecuador, and Peru (Genty *et al.* 1978).

(a)

(b)

Figure 1.4 (a) *C. daedalus* adult. (b) Holes as a result of *C. daedalus* caterpillar boring into the stem at the leaf bases of oil palm.

Host palms: *C. nucifera*, *E. guineensis*, genera *Euterpe*, *Pritchardia*, *Livistona*, *Mauritia*, *Maximiliana*, *Oenocarpus*, and *Roystonea* (Lepesme 1947; Lever 1969; Ferreira, Warwick, and Siqueira 1994), banana, sugarcane, and pineapple (Howard *et al*. 2001).

Harmful stage and damage: Caterpillars, especially due to their large size and long life. On hatching, the caterpillars bore into the stem at the leaf bases and form deep tunnels under the leaf bases and fruit bunches, causing them to wilt and fall due to lack of support (Fig. 1.4b). Feeding for almost 1 year can lead to considerable losses in fruit production (Rai 1973). Older caterpillars tunneling the trunk may cause large cavities under the stem apex and kill the palm (Schuiling and Dinther 2009). As the caterpillars continue feeding throughout this period, they may cause considerable damage to the stem of the palm. Significant reductions in fruit production have been reported in plantations infested by *C. daedalus* (Huguenot and Vera 1981).

1.3.6 *Paysandisia archon* Burmeister 1880 (Lepidoptera: Castniidae)

P. archon (PBM; Fig. 1.5a) is another butterfly moth, which has not been reported as a pest in its native region (South America), with the exception of reports from Buenos Aires (Bourquin 1930; Montagud Alario 2004; Sarto i Monteys *et al*. 2005). In contrast, in France, Italy, and Spain, it is an invasive pest, which causes serious damage and palm mortality (Fig. 1.5b), especially in nurseries of ornamental palms (Montagud Alario 2004; Riolo *et al*. 2004; EPPO/OEPP 2008). The life cycle of this palm borer has been described by Sarto i Monteys *et al*. (2005) and Sarto i Monteys (2013). The adult is in flight from May to September in Europe. It flies between the hours of 1100 and 1600. Mating peaks between 1400 and 1500 and 87% of the females are fertilized and start laying eggs 1.25 (±1.14) days after mating (Delle-Vedove *et al.* 2012). Vision is sophisticated and plays an important role in adult behavior (see Chapter 7, this volume). Chemical communication in the PBM remains controversial, but it certainly does not use the long-range female-attractive sex pheromone typical of moths (see Chapter 7, this volume).

Origin: Argentina, Brazil, Paraguay, and Uruguay (Miller 1986; Lamas 1995; Sarto i Monteys 2002; González, Domagala, and Larysz 2013).

Distribution: Introduced in Cyprus, Denmark, France, Greece (including Crete), Italy (including Sicily), Slovenia, Spain (including Balearic Islands), the United Kingdom (isolated occurrence), Belgium, Bulgaria, and Croatia in Europe, as well as in Switzerland. It is still unknown in the other Mediterranean countries (Reid 2008; Buhl *et al*. 2009;

(a) (b) (c)

Figure 1.5 (a) *P. archon* adult. (b) *P. archon* last-instar larva. (c) *T. fortunei* killed by *P. archon* caterpillars.

EPPO 2014 version 5.3.1. accessed June 26, 2014; Psirofonia and Niamouris 2013) (see Chapter 6, this volume).

Host palms:

- In the native area: *P. canariensis*, *Butia capitata*, *C. humilis*, *Livistona chinensis*, *Syagrus romanzoffiana*, *Trithrinax campestris*, and *Butia yatay* (Sarto i Monteys 2013) (see Chapter 6, this volume).
- In the Mediterranean: the above-mentioned palm species, as well as *Brahea armata*, *B. edulis*, *Livistona australis*, *L. decora*, *L. saribus*, *P. dactylifera*, *P. reclinata*, *P. roebelenii*, *P. sylvestris*, *P. theophrasti*, *Sabal mexicana*, *S. minor*, *S. palmetto*, *T. fortunei*, *T. wagnerianus*, *Washingtonia filifera*, and *W. robusta* (see Chapter 6, this volume).

T. fortunei, *C. humilis* and *P. canariensis* are by far the most attacked palm species by PBM in France, Italy, and Spain (Drescher and Jaubert 2003; Riolo *et al.* 2004; Chapin 2006; André and Tixier Malicorne 2013; Sarto i Monteys 2013).

Harmful stage and damage: Damage is entirely inflicted by the larvae, whose feeding activity can cause deformation of the crown (Fig. 1.5b). If the larvae reach the apical bud, the palm dies (Fig. 1.5c). The eggs are laid in the fibers in the crown or in the upper part of the stem. The neonate larvae penetrate rapidly into the stem. Larvae excavate galleries until pupation. They can be found tunneling in different parts of the palms: early instars in the stem and fruit of *C. humilis*, or within the leaf rachis (especially in *P. canariensis* and *W. filifera*). In *T. fortunei*, the first-instar larvae can bore into the young packed fronds. Large larvae are found in the stem of 2- to 10-year-old *T. fortunei* and *C. humilis* and tend to bore into and remain within the very core of these structures, where humidity is higher and temperature more stable (Riolo, Isidoro, and Nardi, 2005; Sarto i Monteys *et al.* 2005).

Risks: The PBM is listed as a quarantine pest in EPPO member countries. Galleries produced by the larvae can facilitate secondary infestation by pathogens as *Talaromyces erythromellis* (Frigimelica *et al.* 2012). Damage by PBM may attract RPW and provide suitable sites for females to lay eggs and colonize palms as secondary pests.

1.4 Defoliators of Fronds (= Leaves)

1.4.1 Pest Ecology, Damage, and Management

These insects consume the leaflets of the fronds, essentially reducing photosynthesis. As many defoliators are subject to intense outbreaks, these species can seriously stress the palm trees and reduce fruit yield. They generally do not cause direct death of the palms. However, important feeding activity of defoliators favors attacks by palm-pathogenic fungi such as the tropical *Pestalotiopsis* spp.

Most pest defoliators on palms are caterpillars from various Lepidoptera families (mainly Coleophoridae, Hesperiidae, Limacodidae, Lymantriidae, Noctuidae, and Psychidae) and beetles, both larvae and adults (Chrysomelidae). They are either quite generalist herbivores on arboreal or shrub plants, or much more specialized species that are dependent on Arecaceae, such as many hispine beetles or some Nymphalidae species. Some small species are leaf miners, such as the larvae of *Coelaenomenodera lameensis* (Section 1.4.4), and some larger larvae can show some borer activity, such as the *Sesamia* caterpillars (Section 1.4.6). In addition, there are a great variety of occasional palm defoliators, but sometimes with a severe impact, belonging to various orders and families, such as long-horned grasshoppers (Orthoptera), and stick insects (Phasmida).

As they live in the crown in the open air, they can be controlled using various types of insecticides, either synthetic or biological. The management of outbreaks in large plantations is nevertheless costly due to the need to treat wide areas and the crown at the top of the plants, which requires dedicated (e.g. aerial) means. Despite some research, no biocontrol on a large scale has ever been implemented against such pests.

1.4.2 *Pistosia dactyliferae* Maulik 1919 (Coleoptera: Chrysomelidae)

P. dactyliferae, a small (5–6 mm) Indian species, was observed for the first time in the southeast of France in 2004, and was thought to have been eradicated after action had been taken against it. Then, in 2006, it was recorded in a nursery in Italy (Tuscany), and again in France in 2012 in the Botanical Garden of Saint-Jean-Cap-Ferrat (Besse, Panchaud, and Gahlin 2013; Panchaud and Dusoulier 2013, 2014). Larvae live in groups. The life cycle is short, about 1 month, and under laboratory conditions, there are 5–6 generations per year (Besse, Panchaud, and Gahlin 2013).

Origin: India.

Distribution: Introduced in Europe: France (Alpes-Maritimes) and Italy (Tuscany).

Host palms: *P. canariensis*, *Washingtonia* sp., *C. humilis* (Drescher and Martinez 2005), *Syagrus romanzoffiana* (Chapin and Germain 2005), *Sabal minor*, *S. palmetto*, *S. causiarum*, *T. fortunei*, *Rhapidophyllum hystrix*, and *Butia* sp. In the Saint-Jean-Cap-Ferrat botanical garden, *Trachycarpus* and *Phoenix* were the more susceptible genera to *P. dactyliferae* attack.

Harmful stages and damage: Both larvae and adults feed on the external tissues of the rachis and prefer the dark parts of the crown (Drescher and Martinez 2005) (Fig. 1.6a, b). They may concentrate on the central fronds of young palms, which dry up. Severe attacks can kill the palms. Adults seem to be nocturnal. Damaged rachises are covered by sawdust and show brown spots due to feeding activity by the larvae (Fig. 1.6a).

Risks: *P. dactyliferae* is a threat to Mediterranean nurseries and horticultural areas and is potentially invasive due to its nocturnal activity, small size, and rapid multiplication. It may provide favorable conditions for RPW oviposition and hence colonization by the weevil, as well as for pathogenic fungi.

1.4.3 *Brontispa longissima* Gestro 1885 (Coleoptera: Chrysomelidae)

There are several species of *Brontispa* (coconut leaf beetles) specialized on palms, of which *B. longissima* is the most harmful. The adult is a small (8–9 mm), elongate, flattened beetle (Fig. 1.7a). The larva is elongated as well, and bears lateral expansions and setae typical of the hispine group. Larvae inhabit the closely packed central cluster spear of fronds (Fig. 1.7b, c).

Origin: *B. longissima* was originally described in the Aru Islands. It is native to Melanesia, from Java to Vanuatu (Indonesia, possibly Irian Jaya, and also Papua New Guinea, including the Bismarck Archipelago).

Distribution: Widespread in Southeast Asia and the Pacific. Most islands of the Pacific, and also present in Malaysia, Indonesia, Vietnam, Philippines (EPPO 2014), and northern Australia (Fenner 1984; EPPO 2014).

(a) (b)

Figure 1.6 (a) *P. dactyliferae* larva. (b) *P. dactyliferae* adult.

(a) (b) (c)

Figure 1.7 (a) *B. longissima* adult. (b) and (c) Damage on coconut palms in the nursery.

Host palms: *C. nucifera*, *Areca catechu* (betel nut palm), *Metroxylon sagu* (sago palm), and some other native and ornamental palms are also attacked.

Harmful stages and damage: Damage is caused by the larvae and adults, which feed on leaflet tissues of the coconut palm (Manciot 1965; Maddison 1983) (Fig. 1.7a). Larvae feed mostly on the epidermis of the young growing fronds. All stages are found between the leaflets or within folded leaflets. *B. longissima* mostly affects the seedlings and palms within the first year in nurseries, killing young spears and eventually the whole plant. When attack is severe, complete defoliation of the palms may result and older palms can also be seriously damaged.

Risks: Neglected palms are more heavily attacked than those kept free from undergrowth (Frogatt and O'Connor 1941; Kalshoven and van der Laan 1981; Maddison 1983). If palms are young or suffering from poor growing conditions, death will occur. Vietnam has experienced a widespread outbreak of *B. longissima* since 2001, whereas prior to that, it was not a serious pest of coconut. It has been estimated that there are now 1 million infested coconut palms in that country (Batugal, personal communication).

1.4.4 *Coelaenomenodera lameensis* Berti 1999 (Coleoptera: Chrysomelidae)

C. lameensis (leaf-mining hispine) is considered the most economically important hispine pest of plants in West Africa (Wagner, Atuahene, and Cobbinah 1991). It feeds on the leaf tissue between the two epidermal layers, causing the formation of a "blister-like" mine. Four generations are possible in one year. The number of eggs laid by one female varies considerably, from about 100 to more than 400 (Morin and Mariau 1971). Outbreaks induce considerable defoliation of cultivated palms, such as oil palm (Fig. 1.8a).

Distribution: Central and Western Africa: Benin, Cameroon, Ivory Coast, Ghana, Nigeria, and Sierra Leone (Hargreaves 1928; Jover 1950; Cachan 1957) including Madagascar.

Host plants: *C. nucifera*, *E. guineensis* older than 3–4 years, *Borassus* sp., *Raphia* sp., ornamental palms (Cotterel 1925).

Harmful stages: Both the imaginal and larval stages mine the leaflet chlorophyllous parenchyma (Fig. 1.8b, c). The adult causes less serious damage (Fig. 1.8d). Leaflets of younger (central) fronds appear withered, gray-brown with rolled edges. Thousands of larvae per leaf lead to the direct destruction or complete desiccation of the frond. The ravages are visible on the lower leaves first, and then move to the crown. When attacks are severe, the palms can be completely defoliated (Mariau *et al*. 1981).

Risks: Radiating out from the initial focus, *C. lameensis* can rapidly contaminate a whole plantation if no method of control is applied.

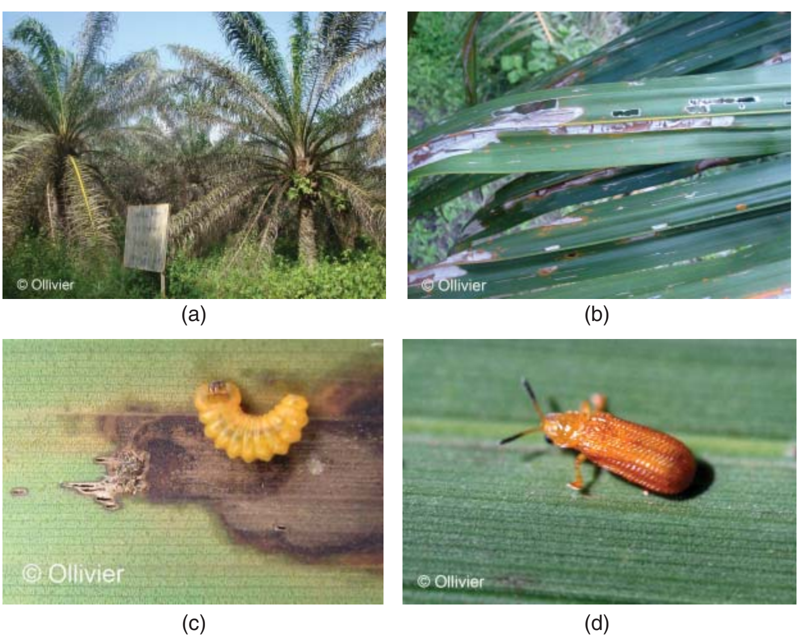


Figure 1.8 (a) Outbreak of *C. lameensis* on oil palm trees. (b) Tunnels within the foliar tissue. (c) *C. lameensis* larva. (d) *C. lameensis* adult.

(a) (b) (c)

Figure 1.9 (a) *S. nitens* caterpillar showing urticating spines. (b) Defoliation on oil palm due to *S. nitens*. (c) Damaged leaf.

1.4.5 *Setora nitens* Walker 1855 (Lepidoptera: Limacodidae)

Of the dozen or so most common and most dangerous species of leaf-eating Lepidoptera, *S. nitens* is the major oil palm and coconut leaf-eating pest in Southeast Asia. Periodically, it explodes into a major pest, causing severe damage to coconut and oil palm plantations. The caterpillars are quite polyphagous but particularly appreciate palm fronds. Together with the larvae of Zygaenidae, they are called slug caterpillars due their globose and fattened body shape and hidden head and legs, sometimes with large tentacle-like points at each extremity of the body, as in *S. nitens* (Fig. 1.9a). They are brightly colored. The moth is stocky and brown.

Severely damaged palms are almost entirely defoliated (Fig. 1.9b, c). The body of the caterpillars is armed with urticating spines that cause considerable discomfort and may endanger the health of laborers employed in the plantations (Lever 1969); this characteristic has led to its other common name of nettle caterpillar (Fig. 1.9a).

Distribution: Malaysia, Singapore, Burma, Vietnam, China, India, and Indonesia (Lepesme 1947; Ohler 1984; Cock, Godfray, and Holloway 1987).

Host palms: *C. nucifera*, *E. guineensis*, *Nipa* sp. Also, *Nephelium lappaceum*, cocoa, banana, tea, tobacco, coffee, and citrus (Lepesme 1947; Cock, Godfray, and Holloway 1987).

Harmful stages and damage: The larvae form windows on the leaf undersurface epidermis, which, particularly on coconut, allows access to the *Pestalotiopsis* fungus (Cock, Godfray, and Holloway 1987). Severe outbreaks can cause considerable defoliation (Fig. 1.9b, c). *S. nitens* attacks the older fronds then moves progressively to the younger ones. The larvae attack oil palms of all ages but the consequences are most important on those aged 2–8 years (Cock, Godfray, and Holloway 1987).

Risks: If regular quantitative monitoring is not undertaken and a critical number of young caterpillars per frond is not detected, the outbreak can be devastating.

1.4.6 *Sesamia nonagrioides* Lefèbvre 1827 and *Sesamia cretica* Lederer 1857 (Lepidoptera: Noctuidae)

The stem borers *S. nonagrioides* and *S. cretica* are considered the most important pests of maize and sorghum in many countries in the Mediterranean region (Anglade 1972; Commonwealth Institute of Entomology 1979). *S. cretica* is a pest of maize and sugarcane mainly in eastern Mediterranean countries.

Distribution: The geographic origins of *S. nonagrioides* and *S. cretica* are most likely Africa and Asia (Commonwealth Institute of Entomology 1979; CABI 2015). The distribution of both species includes southern Europe, Africa, the Middle East (east, west, and northwest), and some Atlantic islands (Eizaguirre and Fantinou 2012; CABI 2015).

Host plants: Although both species are mainly found on Poaceae, they are highly polyphagous pests with a fairly wide range of hosts other than those reported above, which comprise millet, rice, grasses, melon, asparagus, palms, banana, plus various ornamental and wild plants (Riolo *et al.* 2007; Eizaguirre and Fantinou 2012; CABI 2015). In central-eastern Italy (Marche region), young plants of *T. fortunei* and *W. filifera* in nurseries have been infested by one or the other species (Riolo *et al.* 2007).

Harmful stage and damage: On palms, the caterpillar causes damage to the fronds on either the foliage or the rachis. The larvae of these species can bore into the young packed fronds and feeding damage to leaves becomes obvious as the frond develops, opens, and expands, showing a series of consecutive perforations on a circular sector (Fig. 1.10a, b). In some cases, these larvae have also penetrated into the leaf rachis (Fig. 1.10c, d, e). These symptoms are similar to those caused by young larvae of *P. archon* (see Chapter 9, this volume).

Risks: The two species may spread in the Mediterranean and northern Europe with global warming and worsening of the sanitary situation in palm nurseries.

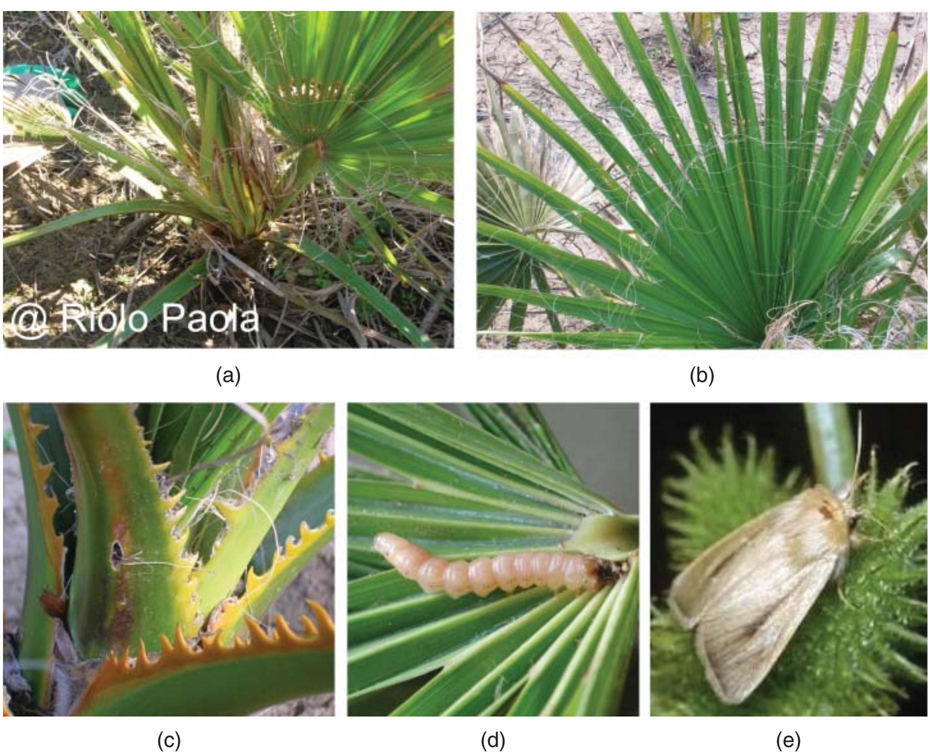


Figure 1.10 Damage of *S. nonagrioides* on *W. filifera*. (a) and (b) Presence of perforated leaves. (c) Presence of larval gallery hole within leaf rachis. (d) *S. nonagrioides* larva and (e) adult.

1.5 Sap and Frond (= Leaves) Feeders?

1.5.1 Pest Ecology, Damage, and Management

These insects have piercing-sucking mouthparts and feed mainly on fronds, including the rachis and base. Immature and adult forms share the same feeding habit and contribute to additional damage on cultivated plants. A few species are strictly dependent on palms. They belong to the order Hemiptera. The main pest species are from the Auchenorhynccha, with species from various families related to the plant hoppers, and from the Sternorrhyncha, comprising aphids, scales, and whiteflies, together making up the former Homoptera group (Howard *et al.* 2001). Many species of Sternorrhyncha are typically capable of parthenogenetic reproduction and very high multiplication rates. These features enable them to cause very severe outbreaks, favored by physiological stress to the palm species. The latter is frequent in date palms due to abnormal climatic conditions with unusually hot periods and drought, an imbalance in the mineral nutrition, or damage by other pest herbivores.

The very large colonies of sap feeders may totally cover the foliage, leading to exacerbated damage, both direct by insect feeding and indirect due to the excretion of honeydew, which covers the leaves and fruits and favors the development of sooty mold. The palm trees then suffer due to an important reduction in photosynthesis due to the screen effect of the organisms and feces and to the necrosis of the leaflets due to the injection of salivary toxins. The whole crown can dry, leading to yield reduction. The fruit value can be severely downgraded due to fouling by the sap feeders.

The management of sap feeders is particularly difficult, especially in village farming with low economic capabilities. Preventive sanitary measures are important, based essentially on healthy management of the plantations with regular palm and land cleaning and appropriate watering and fertilization practices, but so is a cropping system that favors natural biological control. Chemical control is challenging because of the need to treat the entire canopy, added to the worldwide increase in sap-feeder resistance to many insecticide families and the environmental and human health concerns.

1.5.2 *Ommatissus binotatus* Fieber 1876 (Hemiptera: Tropiduchidae)

O. binotatus (dubas bug, plant hopper, or date palm leafhopper) infests date palm. The palms are weakened and photosynthesis is reduced (Fig. 1.11a). Honeydew dripping from the palms soils the fruit bunches and causes fruit atrophy, resulting in downgrading of dates.

Origin: Iberian Peninsula.

(a) (b) (c)

Figure 1.11 (a) *P. dactylifera* affected by *O. binotatus*. (b) *O. binotatus* immature stages. (c) Damaged axils of leaflets on rachis.

Distribution: Sicily (Guglielmino 1997), south of France (Labonne and Bonfils 1998; Howard *et al.* 2001), Israel (Klein and Venezian 1985), Iraq, Iran, Libya, the United Arab Emirates, Saudi Arabia, Kuwait, Bahrain, the Sultanate of Oman, Egypt, Algeria, and Sudan (El-Haidari and Al-Hafidh 1986). Large populations have been found in Egypt and Libya (Talhouk 1977).

Host palms: *P. dactylifera* (common), *C. humilis*.

Harmful stages and damage: All stages (Fig. 1.11b) attack all of the green tissues that are easily accessible in the axils of leaflets on the rachis but also in frond midribs, the bunch stalks, and the pedicels and fruit themselves (Fig. 1.11c). Sap that exudes from the feeding points and the honeydew excreted by the insect ferment and encourage the development of microorganisms (bacteria, fungi) on the leaflets, which turn yellow and dry out (Fig. 1.11a, c).

Risks: Infestation is spread through the transfer of seedlings or offshoots at the foot of mother palms, which contain eggs in the petioles.

1.5.3 *Aspidiotus destructor* Signoret 1869 (Hemiptera: Diaspididae)

A. destructor (coconut scale, transparent scale) is a highly polyphagous diaspid scale insect. It is the most widespread and destructive sap-feeding species on coconut palm, wherever it occurs. It is also an important economic pest of mangoes in Asia and Africa, and of bananas in most tropical areas. However, *A. destructor* appears to be naturally controlled in most regions, and few major outbreaks have been recorded in recent years.

Distribution: Of unknown origin, it was described from La Réunion and reported from Madagascar by Lepesme (1947). It is now reported from most tropical and subtropical regions worldwide and present in nearly all countries where coconuts are grown (Anon 1966).

Host palms: *C. nucifera*, *E. guineensis*, *Phoenix* spp. (Lepesme 1947).

Its range of host plants is very wide, including many tropical trees and other tropical crops, as well as many wild plants. Its hosts are typically perennial species and include many species of fruit trees, such as avocado, breadfruit, mango, guava, and papaya, *Actinidia*, banana, and mango.

Harmful stages and damage: The scales form a crust over the lower surface of all leaflets, which become yellow due to heavy loss of sap. The scale-feeding activity also blocks the stomata, causing fronds to die (Fig. 1.12a, b, c). On coconut palms, frond stalks, flower clusters, and young fruit can also be affected. In extreme cases, the leaves dry up, entire fronds drop off, and the palm dies. The intensity of the attack depends on local ecological conditions: older trees (over 4 years) or trees on well-drained soil are

(a) (b) (c)

Figure 1.12 (a) *A. destructor* scales. (b) Dry coconut leaves. (c) Yellow coconut leaves.

seldom seriously infested. In turn, neglected plantations and densely planted palms are particularly susceptible. Dry weather favors this pest. Wind and various animals—such as insects, birds, and bats—assist in disseminating this pest (Menon and Pandalai 1958). Mariau and Julia (1977) reported that mineral nutrition of the palm may affect the dynamics of *A. destructor* population.

1.5.4 *Parlatoria blanchardi* Targioni, 1868 (Homoptera, Diaspididae)

P. blanchardi (date white scale or Parlatoria date scale insect) is a sap-feeder on palm hosts.

Origin: Arabian Gulf countries.

Distribution: Spain, Italy, France (Foldi 2001), and Sudan. It has spread into India and central Asia, the Middle East, North Africa, Turkey, Australia, and North and South America (Smirnoff 1957).

Host plants: *P. dactylifera*, *P. canariensis*, *P. reclinata*, and *W. filifera* (Lepesme 1947), *Hyphaene thebaica* (Howard *et al.* 2001).

Harmful stages and damage: The scales are hidden by the sheath of fibers that wrap the frond base, where they prefer to live. When the population develops and infestation increases, the colonies tend to occupy the whole frond, concentrating first on the hardest parts: rachis and petioles. Feeding on fronds causes necrosis of the tissues. Heavily infested fronds turn yellow and die prematurely. Damage is very serious on young palms between 2 and 8 years of age, but even under severe attack the palm and its offshoots do not die (Zaid *et al.* 1999). The scales first infest the older foliage and then move to the younger foliage and finally the fruit (Howard *et al.* 2001). Fruits attacked by the insect shrivel up, and remain small and unmarketable.

Risks: The date palm cultivars show differential susceptibility to *P. blanchardi* (Dabbour 1981). This pest is usually spread by trade of the offshoots.

1.5.5 *Aleurotrachelus atratus* Hempel 1922 (Hemiptera: Aleyrodidae)

Although not commonly known as a serious pest of coconut, since 2002 in the Comoros Islands, the white fly, *A. atratus*, has caused considerable damage to coconut palms through sap feeding (Streito, Ollivier, and Beaudoin-Ollivier 2004; Borowiec *et al.* 2009) (Fig. 1.13a, b). The sooty mold that develops on the honeydew excreted by whiteflies worsens the damage, significantly affecting palm growth and yield (Fig. 1.13a). The feeding habit and the resultant damage are somewhat similar to those of the coconut scale *A. destructor*. It is considered a typical invasive pest.

(a) (b) (c)

Figure 1.13 (a) Coconut affected by *A. atratus*. (b) *A. atratus* affecting coconut in the nursery. (c) *A. atratus* puparium.

Origin: Tropical America (Brazil) (Lepesme 1947; Mound and Halsey 1978).

Distribution: In the Neotropics: Most of the Caribbean Islands, Brazil, Colombia, Guyana, Mexico, Puerto Rico, Venezuela, and Florida in the USA (Evans 2007; Delvare *et al*. 2008). It has recently been reported from the Palaearctic region: Canary Islands (Hernandez-Suarez *et al*. 2003), the Pacific region: Hawaii (Wong *et al.* 2006) and Samoa, and the Afrotropical region: Sao Tomé (Martin 2005), and Saint Helena (Howard *et al.* 2001). It also occurs on various islands in the southwestern Indian Ocean: La Réunion, Seychelles, and Comoros, and in glasshouses in Paris (France) (Streito, Etienne, and Balmès 2007; Borowiec *et al*. 2009), Madagascar, Mozambique, and Mauritius (Beaudoin-Ollivier *et al*. 2004).

Host palms: *C. nucifera* is the major host (Mound and Halsey 1978); nine other species of Arecaceae—among them *Syagrus schizophylla*, *E. guineensis*, and *Adonidia merrillii*—are commonly attacked (Howard *et al*. 2001; Evans 2007). In the Indian Ocean and Paris greenhouses (France), *A. atratus* was recorded on 56 palm species (Borowiec *et al*. 2009).

Harmful stages and damage: All three immature instars, the third corresponding to the fourth or "pupal" stage (Howard *et al*. 2001) (Fig. 1.13c) feed on fronds. Observation of palms reveals a depigmentation of the leaflets related to the whitefly activity, which interferes with normal cell functioning. Plasmolysis symptoms on leaves characterize very serious weakening. In addition, feeding whiteflies secrete excess sugars—honeydew—which is the food source for a number fungal species called "dark sooty mold" or "fumagine." This sooty mold causes black spots that prevent gas exchange and, therefore, photosynthesis (Streito, Ollivier, and Beaudoin-Ollivier 2004) (Fig. 1.13a, b).

Risks: *A. atratus* is well adapted to surviving tropical storms. Dissemination risk is high due to exchanges of coconut material. It is a risk in greenhouses and for ornamental palms in urban areas. The wide host range may facilitate this whitefly's spread.

1.6 Inflorescence and Fruit Borers

1.6.1 Pest Ecology, Damage, and Management

There are many insect pollinators on palms, which are mostly pollinated by beetles with remarkable co-evolution (e.g. by Coleoptera: Curculionidae) (Henderson 1986). In contrast, there are quite a limited number of pests that focus on feeding on palm fruits or flowers, as compared to the diversity of palm defoliators and borers. Damage to the inflorescences and fruit bunches may be important by crown borers such as *C. daedalus*, which severely spoil the forming bunches.

Palm fruit and their nutritious mesocarp, such as of dates, are attacked by several generalist species, mostly moths (Pyralidae) and beetles (Nitidulidae), as well as some bugs and mites. Damage is severe when the insect feeding leads to fruit abortion (e.g. mites or *Aphomia sabella* for dates) or directly compromises the fruit's market value and storage. Many pest moths of dates damage the fruit, both during growth on the palm and post-harvest in warehouses. There are a few species that cause economic damage to the seeds.

Effective management of moth pests relies largely on adequate sanitation and cultural practices at the plantation level, and benefits from methods that favor natural biocontrol based on the many parasitoids or predators present in the environment (Lepesme 1947; Moore 2001). Physical protection of date bunches using dedicated nets, which prevent egg-laying, have been recommended. Today, chemical protection in the field is difficult as the larvae spend most of their time in the fruit and efficient insecticides have been banned. Fumigation is efficient in warehouses, but methyl bromide is in the process of being banned and alternative solutions, such as using modified atmosphere or cold, require costly dedicated facilities.

1.6.2 *Batrachedra amydraula* Meyrick 1916 (Lepidoptera: Batrachedridae)

B. amydraula (lesser date moth) is by far the most serious pest of developing date fruit, which may cause more than 50% loss of the crop. Heavy infestations reduce the yield considerably, with losses of up to 75% recorded in some locations (Carpenter and Elmer 1978). It damages fruit in both the field and in storage (Dowson 1982).

Distribution: Egypt (Badawi, Kamel, and Saleh 1977), Israel, Bangladesh to western Saudi Arabia, Yemen, Iraq and Iran, Libya and United Arab Emirates, as well as most of North Africa (Sayed *et al*. 2014).

Host plants: *P. dactylifera* and *Derris trifoliata* (Fabaceae).

Harmful stage and damage: The imago oviposits on and near inflorescences (Fig. 1.14a). The larvae bore into the inflorescences and the bases of immature date fruit. They sometimes consume the seeds in tender seed varieties (Howard *et al.* 2001) (Fig. 1.14b). Larval attack on the young dates usually stops fruit growth (Fig. 1.14c). The larva can move from one fruit to another, causing more damage. Damaged fruit wither and are shed.

Risks: In Israel, most date varieties are susceptible to the pest.

1.6.3 *Tirathaba rufivena* Walker 1864 (Lepidoptera: Pyralidae)

This moth has a few names: the oil palm bunch moth, the coconut spike moth, and the greater spike moth (Eloja and Abad 1981). It causes serious damage in Southeast Asia and the Pacific region. Various other *Tirathaba* spp. cause similar damage. Young palms are more heavily damaged than older palms, due to their compact crown.

Distribution: Asia from Sri Lanka to New Guinea and possibly eastward to Vanuatu (Waterhouse and Norris 1987; Howard *et al.* 2001).

Host plants: Palms: *C. nucifera*, *E. guineensis*, *Areca catechu*, *Nypa fruticans*, *Plectocomia* spp., *Pritchardia pacifica*, *Roystonea regia* (Lepesme 1947; Howard *et al.* 2001); non-palm: Musa, Phaseolus, and Coix (Lepesme 1947).

(a) (b) (c)

Figure 1.14 (a) *B. amydraula* adult (Source: Lepesme 1947). (b) *B. amydraula* larva boring into date fruit. (c) Damage on immature date fruit.

(a) (b)

Figure 1.15 (a) *T. rufivena* caterpillar damaging coconut flowers. (b) Dry inflorescences of coconut due to *T. rufivena* caterpillars.

Harmful stage and damage: Caterpillars: When the egg hatches, the young larvae begin feeding on newly opened male flowers. The later instars also bore into the female buttons, causing them to shed prematurely (Fig. 1.15a). The attacked female buttons soon decay and drop to the ground, often with fully grown larvae inside (Waterhouse and Norris 1987). The species is harmful by causing extensive premature nut fall (Fig. 1.15b).

Risks: Loss of nut production has to be sustained before consideration is given to this problem.

1.6.4 *Ectomyelois ceratoniae* Zeller 1839 (Lepidoptera: Pyralidae)

This moth, commonly known as the "carob moth," is a considerable agricultural pest, recognized as the most economically damaging pest of the date industry in California (Warner 1988; Nay and Perring 2005), and of high-value nut and fruit commodities.

The adult moth has a wingspan of 22–24 mm and is creamy white to gray, brownish, or even dark brown. The shade also varies according to palm date variety as related to date color (Idder *et al*. 2009). Eggs are laid on the dates and hatching begins within 3–7 days. The larval period is about 3 weeks in warm months and 8 weeks in colder months. The adult lives only 3–5 days, during which time the female may lay 60 to 120 eggs. Three or four generations are produced annually (Carpenter and Helmer 1978). Taking into account the moth's life cycle, it is recommended to protect the fruit bunches, to clean the plantation of wind-fallen fruit and to fumigate harvested and stored dates. The use of pheromone traps will not only help determine the emergence of moths but also estimate their population level. The rate of infestation could be lowered by spraying the infested fruit with *Bacillus thuringiensis* (Djerbi 1994).

Distribution: Widespread in the Mediterranean areas of Europe, North Africa, and Asia (Carpenter and Helmer 1978), Iran, and Israel (Rochat, personal communication). It has been reported in Spain, Italy, Greece, and France (Le Berre 1978).

Host plants: *P. dactylifera*, *Ceratonia siliqua*, *Punica granatum*, citrus fruit, *Pistacia vera*, *Juglans regia*, *Prunus dulci*, *Macadamia integrifolia*, *Acacia farnesiana*, *Caesalpinia sappan*, *Cassia bicapsularis*, *Ricinus communis*, *Erythrina monosperma*, *Haematoxylum campechianum*, *Prosopis juliflora*, and *Samanea saman.*

(a) (b) (c)

Figure 1.16 (a) *C. cautella* adult. (b) and (c) Damage on date fruit by *C. cautella* larva. Reproduced with permissions of HP Aberlenc.

Harmful stage and damage: The larva of the carob moth attacks dates in plantations, packinghouses, and storage. It attacks maturing fruit, especially the drier ones, and causes damage by feeding and by accumulating grass.

Risks: Through introduction in dried fruit. It is the main constraint for export (Doumandji 1981; Doumandji-Mitiche 1983; Idder 1984; Raache 1990; Haddad 2000). If fruit is not fumigated promptly and stored properly, serious losses can occur (Carpenter and Helmer 1978).

1.6.5 *Cadra cautella* Walker 1863 (Lepidoptera: Pyralidae)

The moth *Cadra* (= *Ephestia*) *cautella* is known as the almond moth or tropical warehouse moth. It is one of the most destructive insect pests attacking date palm fruit in the field, and infestation continues in storage post-harvest (Fig. 1.16a). Ali, Metwally, and Hussain (2003) stated that semi-dry dates are the most injured by *C. cautella* during storage, with approximatively 50% of stored dates being lost after 6–7 months of storage.

Distribution: In all tropical and warmer temperate areas of the world.

Host plants: It attacks dried dates, carob, and almonds (Gough 1917). A range of stored foods, especially cereal (maize, rice, wheat, sorghum, millet, oats) flours, and other cereal products, dried cassava, groundnuts, cocoa beans, dried mango, dates, nutmeg, mace, cowpeas, and other dried stored products (Bondar 1940). Polyphagous species (Lepesme 1947).

Harmful stage of the pest: Larvae feed on the pulp of the date fruit (Fig. 1.16b, c).

Organ damaged: Dried fruit post-harvest, male and female flowers of coconut palms (Bondar 1940).

Risks: Adults do not feed during their short lives but stored food is contaminated with dead bodies, frass, excreta, and larval webbing.

1.6.6 *Aphomia sabella* Hampson 1901 (Lepidoptera: Pyralidae)

Aphomia (= *Arenipses*) *sabella* (greater date moth) is found inside flowering/fruit bunches as well as fruit (Fig. 1.17a). There are two generations a year with overwintering of the larvae of the second generation. The caterpillars (23 mm at maximal growth) spend most their lives inside the inflorescences or fruit, living for a while externally in silken tubes (Hussain 1974). Pupation occurs in the crown.

Distribution: Throughout the date-growing regions of North Africa, the Middle East, and northern India (Lepesme 1947). It was first recorded in Spain in 1999 (Asselbergs 1999; Chapin and Germain 2005).

Host palms: *P. dactylifera*, *P. canariensis* (Kehat and Greenberg 1969).

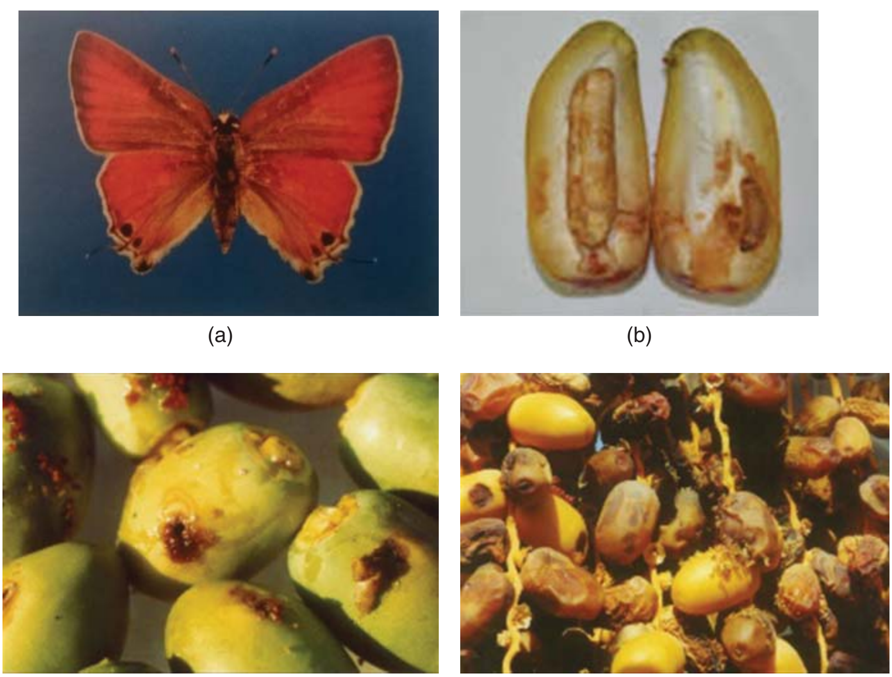
(a) (b)

Figure 1.17 (a) *A. sabella* adult. (b) *A. sabella* damages the peduncle of the inflorescence.

Harmful stage of the pest: The neonate caterpillars bore into the unopened spathes or just blooming female inflorescences. The larvae can also attack more developed inflorescences and the petioles of young fronds, but also inside developing fruit (Fig. 1.17b) (Balachowsky 1972; Howard *et al.* 2001).

1.6.7 *Virachola livia* Klug 1834 (Lepidoptera: Lycaenidae)

V. livia (pomegranate fruit butterfly) causes significant damage to date palm (Mashal and Albeidat 2006) in several Middle-Eastern countries (Fig. 1.18a). This species has



(a) (b) (c) (d)

Figure 1.18 (a) *V. livia* adult. (b), (c), and (d) Damage on fruit due to *V. livia* caterpillar.

the same capacity as the carob moth, *E. ceratoniae* (Lepidoptera: Pyralidae), to damage pomegranate and date fruit.

Distribution: Egypt (Willcocks 1922), Arabian peninsula, Jordan, Sultanate of Oman, and Tunisia (Abbas *et al*. 2008).

Host palms: *P. dactylifera*; also pomegranate (*P. granatum*) orchards.

Harmful stage and damage: The neonate larvae perforate the fruit. Caterpillars further tunnel for feeding until pupation (Fig. 1.18b, c, d). This is generally accompanied by an invasion of saprotrophic fungi and bacteria, making the fruit unmarketable. In Egypt, the Sewi and Mathour date varieties are seriously damaged by this pest.

Risks: Sanitation of the traditional orchards where both pomegranate and date palms are cultivated should be recommended to remove as many of the fallen fruit, which shelter larvae, as possible.

1.6.8 *Coccotrypes dactyliperda* Fabricius 1801 (Coleoptera: Scolytidae)

Eleven species of *Coccotrypes* have been described by Lepesme (1947). *C. dactyliperda* is 1.5 mm (males) to 2 mm (females) (Fig. 1.19). Adults are shiny reddish-brown with a convex shape, covered with hairs on the dorsal surface. The species uses the haplodiploid sex-determination system. The sex ratio in the field is strongly female-biased (Blumberg and Kehat 1982). In Africa, four species (*C. dactylifera*, *C. congorus*, *C. nigripes*, and *C. perditor*) are found on the fallen fruit of *E. guineensis* (Alibert 1946; Mariau, 2001).

C. dactyliperda (= date seed beetle or date stone beetle) is considered a primary pest of date palm worldwide (Blumberg and Kehat 1982; El-Shafie 2012).

Distribution: Middle East region, North Africa, Indian subcontinent, North America (Lepesme 1947; Carpenter and Elmer 1978), and Israel (Kehat *et al.* 1966; Avidov and Harpaz 1969).

Host palms: *Phoenix* spp., including the date palms *P. dactylifera* and *P. canariensis*. *Areaca catechu*, *C. humilis*, *Livistona chinensis*, *W. filifera*, *E. guineensis*, *Sabal bermudana* (Lepesme 1947).

Harmful stages and damage: All stages. The female beetle tunnels into the kernels (stones) of green unripe date fruit and lays its eggs there. The larvae and pupae develop and the adults leave the date host through a circular hole that they bore, after which they attack new fruit, specifically green unripe ones. A single date is able to support as many as 70 individuals. Each beetle can damage several fruit. Damage by *C. dactyliperda*

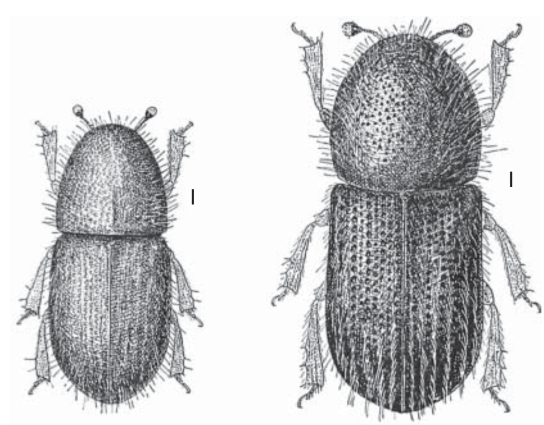


Figure 1.19 *C. dactyliperda* L., male (left side) and female (right side) (35× magnification) (from Lepesme 1947).

ultimately results in both reduced yield (fruit drop) and lower fruit quality (fruit infestation by sap beetles) (Blumberg and Kehat 1982).

Risks: The dropped and rotting dates serve as hosts for nitulid beetles such as *Carpophilus* spp. that attack ripe fruit in late summer.

1.6.9 *Carpophilus hemipterus* L. 1758 and *Carpophilus mutilatus* Erichson 1843 (Coleoptera: Nitidulidae)

Sap beetles of the genera *Carpophilus* (e.g. *C. hemipterus* and *C. mutilatus*) and *Epuraea* (= *Haptoncus*) *luteola* are pests of several agricultural crops, including dates, throughout the world. They are minute (1.5–5.5 mm) beetles with short truncate, black-brown or black bodies. The larvae are whitish or yellowish with a brown head, final length 5–7 mm.

C. hemipterus adult length is 1.8–2.1 mm with obovate to subparallel body. It may be distinguished from other *Carpophilus* spp. by the presence of two pale humeral and apical patches on the elytra (Leschen and Marris 2005) (Fig. 1.20a). The adults are strong fliers, covering several kilometers a day in search of food. Mature larvae emerge from the fruit to overwinter as pupae in the soil.

C. mutilatus is 1.5–1.8 mm length with a parallel body, variable color, or unicolored light tan to brown. The antennal segment is three times less than 1× the length of segment 2; the male mandibles are asymmetrical with the right mandible strongly elbowed (Leschen and Marris 2005). This species has been described from western India, and the first record of it in New Zealand was by Hutton (1904). *C. hemipterus* (dried fruit beetle) and *C. mutilatus* (confused sap beetle) were re-described by Gillogly (1962), Audisio (1993), and by El-Shafie (2012) in a review on insect pests identified worldwide on date palm.

At least four species have been reported to occur abundantly in date orchards, in both the USA and the Middle East (Lindgren and Vincent 1953; Mashal and Albeidat 2006). In date orchards, sap beetles are considered primary pests, damaging the ripening fruit on palms and then later in storage (Bitton *et al*. 2007). Several species of nitidulid beetles attack ripened dates (Howard *et al.* 2001).

Distribution: Native area unknown. Present in California, North Africa, and the Middle East (Carpenter and Elmer 1978), including Egypt (Lepesme 1947). Also included is Australia (except for Arctic and colder temperature regions) (Connell 1991; Williams

(a) (b) (c)

Figure 1.20 (a) *C. hemipterus* (10× magnification) (from Lepesme 1947). (b) Dates damaged by *Carpophilus*. (c) Date infested with *Carpophilus* larvae.

et al. 1983) and New Zealand, where it has been introduced and has become established (Leschen and Marris 2005).

Host palms: *C. hemipterus* have been observed on rotting *Elaeis* and *Bactris* bunches in the Congo (Lepesme 1947; Mariau 2001). Ripening fruit of many commercial trees, especially those that have been previously damaged, and other fermenting plant material.

Harmful stage of the pest: Essentially the larvae, which typically feed on the pulp of dried fruit, such as ripening dates on the palm tree and on the ground (Fig. 1.20b, c). The eggs are laid in damaged fruit on the date palm or in rotting fruit lying on the ground in the shade. Mature larvae emerge from the fruit and complete their development in the soil.

Risks: The drop of green date fruit caused by *C. dactyliperda* enhances *Carpophilus* populations and increases their damage. Pest penetration into the fruit facilitates the development of microorganisms, resulting in rot and fruit fermentation that downgrade the date fruit.

1.7 Roots

1.7.1 Pest Ecology, Damage, and Management

Some insect species, mostly scarabs and moths, feed on palm roots. Damage is caused by the larvae, which consume either the aerial roots or those growing in the soil, or both equally. A few species are pests, and still fewer attack roots exclusively. For instance, the date palm beetle, *Oryctes agamemnon*, has been reported to feed on aerial roots in Tunisia as well as in Israel and the Arabian Peninsula (Soltani, Chaieb, and Ben Hamouda 2008), but it more generally feeds on old leaf bases where the dead and living tissues meet, as moist woody material is available there. Extensive feeding on the roots leads to weakening of the palm, which spends much energy in renewing the spoiled organs, with a potentially severe slowdown of growth and fruit production. Another consequence is toppling of the palms, particularly in windy areas or during storms. Control of these pests can be achieved using conventional insecticides when the pest is aerial, but is much less difficult when the larvae live exclusively underground.

1.7.2 *Sufetula sunidesalis* Walker (Lepidoptera: Crambidae)

Oil palm is affected by several Lepidopteran root miners, which can sometimes damage the root system to such an extent that palm development is slowed and the palm tree topples (Desmier de Chenon 1975). *S. sunidesalis* is a moth with a wingspan of 15–20 mm. The male presents a dark color overall, and the wings vary from yellowish to black-brown and are decorated with several more or less complete sawtooth stripes. In the female, the body is shorter and thicker. The wings appear darker and are less clearly marked by transversal stripes (Desmier de Chenon 1975). *S. sunidesalis* is a typical species of these pest moths.

Distribution: Southeast Asia: Indonesia (Mariau, Desmier de Chenon, and Sudharto 1991), Malaysia.

Host palms: *C. nucifera* and *E. guineensis*.

Harmful stages and damage: The caterpillar (Fig. 1.21a) destroys root extremities growing out from the base of the stem into the open air when the palm has been

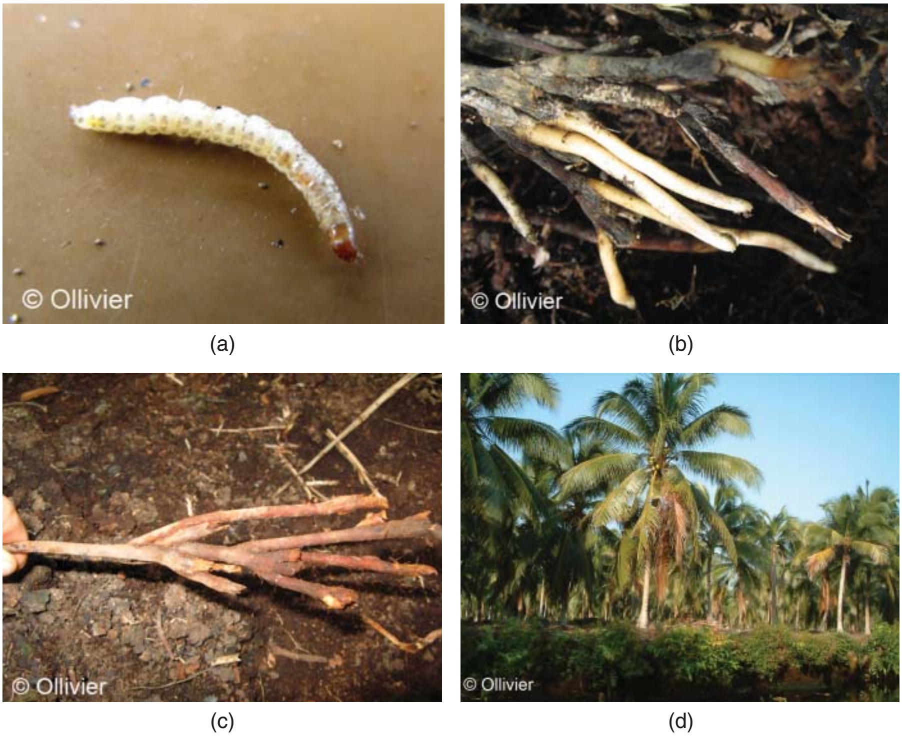


Figure 1.21 (a) *S. sunidesalis* last-instar larva. (b) Repeated reiterations of oil palm root system. (c) Typical symptoms on oil palm primary roots attacked by *S. sunidesalis*. (d) Coconut palms affected by *S. sunidesalis*.

incorrectly planted, or the roots underground. The attacks cause successive and repeated iterations of the root system (Fig. 1.21b). The most severely attacked plots on peat displayed very typical symptoms of highly branched root tips (Fig. 1.21c). The primary roots become stumped, delaying palm growth and resulting in loss of production (Fig. 1.21d).

Risks: Plantations on peat soil and neglected plantations.

1.8 Conclusion

This chapter describes the many insect species that are common to palms. They are classified into groups based on their preferred palm organ. However, some species are not highly specific to a particular organ. They may infest more than one part at the same time, and can attack foliage as well as fruit or inflorescences, depending on the severity of the infestation and prevailing weather conditions (*A. destructor*, for example). Damage is worse on young palms and rare on palms older than 3–4 years, although damage has been recorded on palms 15 years after planting and on isolated palms.

The interactions between palm pests, such as *S. australis* (or *O. rhinoceros*) and the weevil *Rhynchophorus*, or between *P. archon* and *R. ferrugineus*, must be seriously considered. The damage inflicted to the palm by the first pest is often exacerbated by the effects of a secondary pest (e.g. *P. archon* attacks create sites that are highly propitious for weevil reproduction).

Specific insect problems vary with geographic area and location. Particular conditions may dispose palms to infestation by insect pests, such as weakened palms, presence of other insects, poor management or field sanitation, lack of or excess irrigation, and fertilization. The nature and severity of the attacks also vary with cultivar, weather, and cultural practices, and may also aggravate the situation and lead to an increase in a specific pest population. Effort should be made to prevent invasive pests from causing outbreaks and becoming established.

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2

Morphology and Physiology of Palm Trees as Related to *Rhynchophorus ferrugineus* and *Paysandisia archon* Infestation and Management

Yuval Cohen

Department of Fruit Tree Sciences, Institute of Plant Sciences, Agricultural Research Organization, The Volcani Center, Rishon LeZion, Israel

2.1 Introduction

Only a few palm species are native to Europe and the Mediterranean region. However, palm trees are culturally important, with natural and planted palm groves having historical significance in Europe. These include the date palm groves in Elche, Spain, and the natural groves of Canary and Cretan date palms in the Canary Islands and Crete, respectively. Palm species are important ornamental plants that play a fundamental role in landscaping and gardening throughout southern Europe and the Mediterranean. The recent appearance and spread of the destructive palm borer pests the red palm weevil (RPW, *Rhynchophorus ferrugineus*) and the palm borer moth (PBM, *Paysandisia archon*), threatens the existence of palms and their associated culture. These two pests are obligatory palm borers (i.e. they develop only on palm species). Therefore, their spread is completely dependent on palm distribution and is affected by horticultural/gardening practices. Methods and techniques for early detection of these pests (see Chapter 10, this volume) and their management (see Chapter 12, this volume) are still being developed. To be efficient, these tools need to consider the special morphological, structural, and physiological characteristics of palms.

2.2 Palms in Europe and the Mediterranean Basin

2.2.1 Palms and their Global Distribution

Palms are a unique group of plants forming very diverse taxa with approximately 2500 species (Tomlinson, 1990, 2006; Dransfield *et al.*, 2008; Broschat, Elliott, and Hodel 2014). Palm trees symbolize the tropics and most palm species are distributed in the tropical regions of the world. Absence of physiological dormancy together with the inability to withstand freezing temperatures restrict palms to the tropics and sub-tropics, and prevent their spread into temperate regions (Tomlinson 2006). Only a few palm species have adapted to somewhat temperate weather conditions, and several others to dry and arid conditions. Therefore, only a few palms are native to the

Handbook of Major Palm Pests: Biology and Management, First Edition.
Edited by Victoria Soroker and Stefano Colazza.

European and Mediterranean flora. The only palm species that grows naturally on the European mainland is the European fan palm (*Chamaerops humilis*). However, even the distribution of this palm is restricted to coastal areas of the western Mediterranean (in both Europe and North Africa), on sandy and rocky ground on hills and cliffs near the sea (Merlo *et al*. 1993; Dransfield *et al*. 2008).

Although several palms are well adapted to warm and arid conditions, they still require a stable supply of groundwater for their survival. The common arid palms occurring in the Mediterranean region are the date palms (*Phoenix dactylifera*). The other local drought-resistant palm is the doum palm (*Hyphaene thebaica*) that inhabits a few oases in southern Israel and North Africa. The *Washingtonia* species (*W. robusta* and *W. filifera*), native to southern California and Mexico, have natural habitats similar to that of the date palm. The two *Washingtonia* species are very common ornamental palms in many countries.

Three palms of the genus *Phoenix* are native to the Mediterranean region. The date palm (*P. dactylifera*) is an important tree in desert oases. It is a very important fruit crop in the Middle East and North Africa. The Canary palm (*P. canariensis*) is native to the Canary Islands, where it forms natural groves. It is also one of the most important palms in landscaping worldwide. The Cretan date palm (*P. theophrasti*) is endemic to Crete, as well as to several additional islands in the Mediterranean, where it forms natural groves.

2.2.2 Palms in Horticulture

Some of the palm species have been domesticated, and serve as important fruit crops. The coconut palm (*Cocos nucifera*), the African oil palm (*Elaeis guineensis*), and the date palm (*P. dactylifera*) are globally important agronomic crops. All three are extremely important to the economy of tropical and arid regions worldwide. Many additional palm species serve as a food source, or have other uses (such as for wood or fibers) in many tropical regions of the world. Some palms also hold important cultural significance. For example, the date palm is important in the culture of three main religions—Christianity, Islam, and Judaism—and its organs (fruit and fronds) are used in some religious ceremonies.

2.2.3 Palms in Gardening and Landscaping

The unique nature of palms is advantageous for landscaping. In fact, although palms are mostly tropical and are very limited in their tolerance to cold, they are very common and popular in landscaping (Hodel 2009). Some palm species originating in subtropical (or even warm temperate) regions are better adapted to cool conditions, making them suitable for landscaping in subtropical and even some temperate areas (Hodel 2009; Broschat, Elliott, and Hodel 2014). The palm's size, straight stem of equal diameter, and lack of side branches make it ideal for landscaping (Sayan 2001; Hodel 2009; Broschat, Elliott, and Hodel 2014). The adventitious root system makes transplanting of large trees more efficient (Sayan 2001; Pittenger, Hodel, and Downer 2005; Hodel 2009; Hodel, Downer, and Pittenger 2009). They are impressive in the vertical line formed by a symmetrical crown of large leaves on a long and thick stem. Therefore, palms are very common for landscaping along avenues, streets, or paths, in squares and plazas in public areas, as well as private gardens (Sayan 2001). Although most palms are not part of the natural flora, palm species are very common throughout southern Europe and the Mediterranean Basin. A large industry of nurseries is active in propagating and supplying palms for ornamental use. Moreover, large volumes of palms are imported into Europe to satisfy the high demand. Palm species planted in Europe include mainly those palms that are relatively well adapted to moderate cold conditions. They include the local *Chamaerops*, Canary, and date palms and the two *Washingtonia* species. The *Trachycarpus* genus is specifically important since it is more cold-tolerant than other palms, and is able to survive cooler habitats in wider regions of Europe. Many additional palms species are grown in various gardens and parks, and used for landscaping throughout southern Europe and the Mediterranean.

2.3 Palm Morphology and Anatomy

Since palms are perennial monocots, their structural biology resembles that of other monocots, like grasses, more than that of typical dicotyledonous trees. Palms have several characteristic structural features that differentiate them from other trees. In general, palms are large trees with a solitary stem (the stem is sometimes called a stipe, or pseudo trunk, to distinguish it from the structurally different "true" dicotyledonous tree trunk) bearing a crown of large composite (usually palmate or pinnate) leaves on its apex. In some palm species, more than a single stem develop into a multi-stem plant. Typically, there is only one growing point per palm stem that produces the leaves and inflorescences (Tomlinson 1990; Hodel 2009). This growing center is called the palm apical meristem.

During development, a palm tree passes through several developmental stages: (1) seedling, (2) establishment stage, (3) adult vegetative stage, and (4) adult reproductive stage (Tomlinson 1990; Dransfield *et al.* 2008; Broschat, Elliott, and Hodel 2014). At the seedling stage, the seed germinates and its first roots and juvenile leaves are formed. These are usually structurally different from the mature organs. Throughout the establishment stage, the palm width increases, growing more and more leaves until its stem reaches the maximal diameter. During this period, which can last several years, the palm does not grow vertically. At this stage, leaf structure changes from the juvenile leaf type to the species-typical palmate or pinnate forms. Together with the increase in stem width, the number of vascular bundles increases. Only then, in the mature vegetative phase once the stem diameter is maximal, does the palm start to grow vertically to form a tree and the leaves gradually adopt the mature shapes and sizes. At the mature reproductive stage, very few changes are observed, except for the development and emergence of inflorescences that turn into fruit bunches. These inflorescences will continue to develop until senescence and eventual death of the entire palm stem (Tomlinson 1990; Broschat, Elliott, and Hodel 2014). Palms are divided into two groups according to their flowering habit. The first is palms that flower recurrently once they enter the mature reproductive stage. These palms continue to generate new leaves after flowering (pleonanthy). The second group includes palms that only flower once. They have determinate inflorescences, will not create new leaves after flowering, and die after flowering and fruiting (hapaxanthy) (Tomlinson 1990; Dransfield *et al.* 2008). Most palms that are used for ornamentals and are common in Europe and the Mediterranean region are of the pleonanthy type.

Since both RPW and PBM infest mainly palm trees in the adult phase, with their significant stems, the present summary will focus mainly on the structural aspects of the mature (vegetative or reproductive) stages of palm development.

2.4 The Palm Crown

All of the photosynthetic (leaves) and reproductive (inflorescences) organs of palms aggregate into a few, but very large, organs, constituting the crown which is situated at the top of the large stem (Tomlinson 1990; Dransfield *et al*. 2008).

2.4.1 Leaf Development, Structure, and Phyllotaxis

Palm leaves are usually very large and can reach up to several meters. The largest palm leaf, of *Raphia regalis*, can grow 25 m long and 3 m wide (Hallé 1977). The palm leaf is composed of three main parts: the petiole, the blade, and the sheath. Most palm leaves are either pinnate (feather-like, when the blade extends into the petiole as a rachis) or palmate (fan-like). The petiole is strong and fibrous, as it must support the large blade. The leaf sheath completely encircles the stem and encloses younger leaves (Tomlinson 1990; Dransfield *et al*. 2008).

All leaves of a single stem develop sequentially from the single apical meristem. The leaves develop in a helical order and their phyllotaxis (arrangement of the leaves on the stem) follows the Fibonacci sequence. Most small palms have a 2/5 phyllotaxy (five leaves generated in each of two spirals around the stem), but in larger palms, the orthostichy (the arrangement of leaves at different heights in the phyllotaxis so that their median planes coincide) can be 4/13 (as in *P. dactylifera*) or 5/21 (in *P. canariensis*) (Ferry 1998; Elhoumaizi, Lecoustre, and Oihabi 2002; Dransfield *et al.* 2008).

The emerging leaf (spear leaf) grows horizontally from the center of the crown. Therefore, the younger leaves are always situated at the top and center of the crown, while older leaves are gradually pushed down and to the sides of the crown canopy. While some palms have dozens of leaves, others have only a few. The rate of new leaf emergence is dependent on both the species and the environmental conditions. The leaves usually develop faster under warmer conditions. Under European conditions, most leaves will develop during the warmer season, and almost no growth will occur during the winter.

2.4.2 Palm Inflorescences

Palm flowering is relatively less important for understanding RPW and PBM biology and infestation, and will only be briefly described. Palm flowers are usually small, but are organized in very large clusters termed inflorescences. The inflorescence develops from the axillary meristem. In most (pleonanthy-type) palms, these meristems are located at the base of each leaf at the "heart" of the palm, deep in the center of the crown. Sexuality varies in different genera of the palm family. Many palm species have hermaphroditic flowers with functional male and female organs; others are monoecious—having separate male and female flowers on the same plant (in the same or different inflorescences)—or dioecious—where staminate (male) and pistillate (female) flowers develop on different individual plants (Dransfield *et al*. 2008). While the *Washingtonia* species are hermaphroditic, the *Phoenix* species are dioecious. This may be relevant to RPW infestation of Canary palms (*P. canariensis*) because most infestations occur at the tree's crown. Previous reports have suggested increased infestations of male trees. Male pollen, or flower clusters, may better attract the weevils to the crown of the male trees during the flowering season.

2.4.3 The Single Apical Meristem and "Palm Heart" Organization

The leaves, inflorescences, and fruit bunches develop at the crown from a single growing point or apical meristem, located deep within the developing leaves (Tomlinson 1990; Broschat, Elliott, and Hodel 2014). Sometimes this meristem can be positioned inside the stem as much as 1 m below the apex, where the spear leaf is emerging. The meristematic region, the "heart" of the palm, is very small, only several hundred micrometers in size. Owing to the importance of the apical meristem, several studies have focused on its structure and on changes in its organization during development (Ball 1941; Jouannic *et al*. 2011). This meristematic tissue is active throughout the life of the palm stem. Damage caused to this meristem will result in cessation of new leaf generation, resulting in the palm's inevitable death (in multi-stem palms, this will result in the death of the specific stem, but not the death of the entire palm). A description of the palm heart's organization is presented in Fig. 2.1.

The ontogeny of palm leaves is slow and the process of leaf development is very long. The palm leaves develop continuously, resulting in a developmental gradient through the palm heart (Tomlinson 2006). Leaf primordia are generated by the apical meristem; they enlarge and develop through the phyllochron, until their emergence as spear leaves. Only then does the tightly packed blade of the newly exposed leaf expand. The developmental process of a single leaf continues for several years. Date palm leaves can take as many as 4 years to complete their development and expansion (Bernstein 2004). During that time, the leaves are nested and enclosed one within the other in a structure

(a)
(b)
(c)


(d) (e)

Figure 2.1 Organization of the palm "heart." (a) Scanning electron micrograph of the apical meristem of a 4-year-old date palm surrounded by the three youngest leaf primordia. (b) Developing leaves within the palm heart. (c) A small developing leaf showing the developing petiole and blade attached to the circular leaf sheath. The empty center is the place where younger leaves have developed. (d, e) Cross-section through the center of the crown of a mature date palm. The developing leaves and the apical meristem region (black dot) can be seen. The region below the meristem will differentiate into the upper stem.

very similar to that of geophyte bulbs—like the scales of an onion: the apical meristem is situated at the center, covered by numerous layers of developing leaf sheaths, each completely encircling all of the smaller and younger leaves (Fig. 2.1). In some palms, such as date, up to 100 developing leaves are sequentially arranged within the palm heart (Tomlinson 1990; Bernstein 2004; Cohen *et al*. 2013).

2.4.4 Implication of Crown Structure for RPW/PBM Symptom Development

2.4.4.1 Visible Pest Symptoms

Both RPW and PBM are palm borers, developing and actively damaging the palm tissues. In Europe, their two most common targets are the Canary palm (*P. canariensis*) and the European fan palm (*C. humilis*), respectively, although many other palm species are also infested. Both borers tend to mainly develop in and damage the palm crowns. The larvae do not feed or develop in the exposed leaf blade or petiole, but rather within the leaf bases and the numerous layers of leaf sheaths at the heart of the palm.

Much effort has been invested in defining and describing symptoms of infected palms. Visible symptoms are described in detail in Chapter 9. In the crown, the major symptoms are damaged or missing fronds. Detectable damage by both RPW and PBM to the leaf blade occurs mainly on growing, developing leaves, while they are still within the palm heart, and not on the exposed leaves. Early symptoms on the leaf blades include characteristic "sewing," "perforation" holes, or "L-shaped" cuts in localized regions of the leaf petioles and leaflets. These traces of RPW or PBM larval feeding always occur early in leaf development, when they are still within the palm heart. In the folded developing blade, all leaflets are close together. The larvae tunnel through the crown and chew through the growing leaf sections. Since this damage cannot be reversed, the symptoms will remain and become visible once the leaves expand fully. The specific position of the damaged leaves relative to the spear leaf can indicate the time of infestation, occurring months earlier.

Missing leaves is another symptom of infested crowns. This can occur if the larvae damage the entire leaf petiole, rachis, or blade. Often, growth of the spear leaf is completely arrested in infested trees, since its base, within the crown, has actually been cut through. It will later dry out and fall, once newer emerging spear leaves push up its dead parts.

Both RPW and PBM inhabit the larger leaf bases, and their cocoons are very commonly located in these bases. Palm leaves do not tend to wilt. Even though infested and sometimes mostly or completely separated from the stem vasculature, the leaves may remain green for weeks, and infestation will be hard to detect. The structural elements, designed to support the very large leaves through storms and wind with their very fibrous rachis and thick leaf cuticle, make them very resistant to wilting. The ability of many palms to efficiently close their stomata and reduce their leaf water loss makes leaf drying a lengthy process. This is one of the reasons it is hard to detect early infestation of both pests. However, once significant damage occurs, the frond may detach from the crown, again disrupting the crown's symmetry and suggesting the suspected infestation.

2.4.4.2 The Importance of an Active Apical Meristem to the Palm's Survival

Since only a single meristem is active in generating new leaves on a single stem, once it is damaged, new organs will not form, and eventually the tree will die. The meristem is very small and well protected deep at the base of the crown. For RPW in Canary palms, damage at or near the meristem occurs only in very advanced stages of the infestation, usually when a large number of larvae are already infesting the entire crown. In smaller palms, even a few larvae can tunnel all the way through the crown to the meristem and kill the palm.

2.4.5 Implication of Crown Structure for Chemical and Biological Treatments

Palm borers tunnel through the palm heart. Several treatments, including various pesticides, have been developed (see Chapter 12, this volume). These include systemic treatments and local treatments applied specifically to the crown. The systemic treatments involve chemicals that penetrate the vascular system and move with the xylem flow toward the crown at the top of the tree. These are either applied as a soil drench or injected into the stem below the infested area (Dembilio *et al*. 2014; Ferry and Gomez 2014) (see below). Local application of pesticides to the crown is also common. Application of biological agents—mainly nematodes and entomopathogenic fungi—has also been tested (see Chapter 8, this volume) and some have been developed into commercial products. To efficiently cure infested palms by either pesticides or biological treatments, these agents need to spread through the entire crown tissue. Application of large doses of solution as a crown drench with special telescopic poles allows controlled dispersion among all leaf bases of the crown. The applied solution slowly diffuses between the leaf sheaths down to the inner parts of the crown, and some of it probably penetrates into the soft, inner leaf sheath tissues themselves. On the other hand, the "onion-like" structure of the crown, with many leaf sheaths completely encircling one another, restricts penetration of sprayed material through the sheaths into the innermost layers. Thus, low application rates are important to enable better penetration of the active agents between the leaf sheaths. Moreover, such treatments may not be efficient at reaching the innermost crown center, where the very young developing leaves and the apical meristem are located. The dispersion of pesticides and biological agents from the top of the crown is based on local penetration between the leaf sheaths. This is not a systemic treatment, and it does not efficiently reach the stem below the crown. Therefore, crown drench applications cannot protect the stem from infestation.

2.4.6 Implication of Crown Structure for Sanitation and Crown Dissection to Rescue Infected Palms

Tree sanitation by dissection is a relatively simple method to save infected palm trees. In general, during dissection, infested and damaged organs are removed. The exposed tissue is very vulnerable and sensitive to both insects and pathogens. Therefore, to protect the tissue from infection, following dissection it is immediately treated with both insecticides and fungicides. After the treatment, the tree recovers by generating a new set of leaves. This method can result in recovery of the trees within several months of their treatment (Fig. 2.2c–e). As a rule, as long as the apical meristem is still functional, it will continue to generate new leaves and the tree can usually be saved (Ferry and Gomez 2008; Ferry and Gómez Vives 2008).

The meristem cannot be evaluated prior to dissection. During crown dissections, the infected area is gradually removed, and the condition of the crown heart is inspected. As long as the heart cross-section displays the characteristic "kaleidoscope" pattern of leaf sheaths and blades (Fig. 2.2a, c), the dissection level is still above the apical meristem.

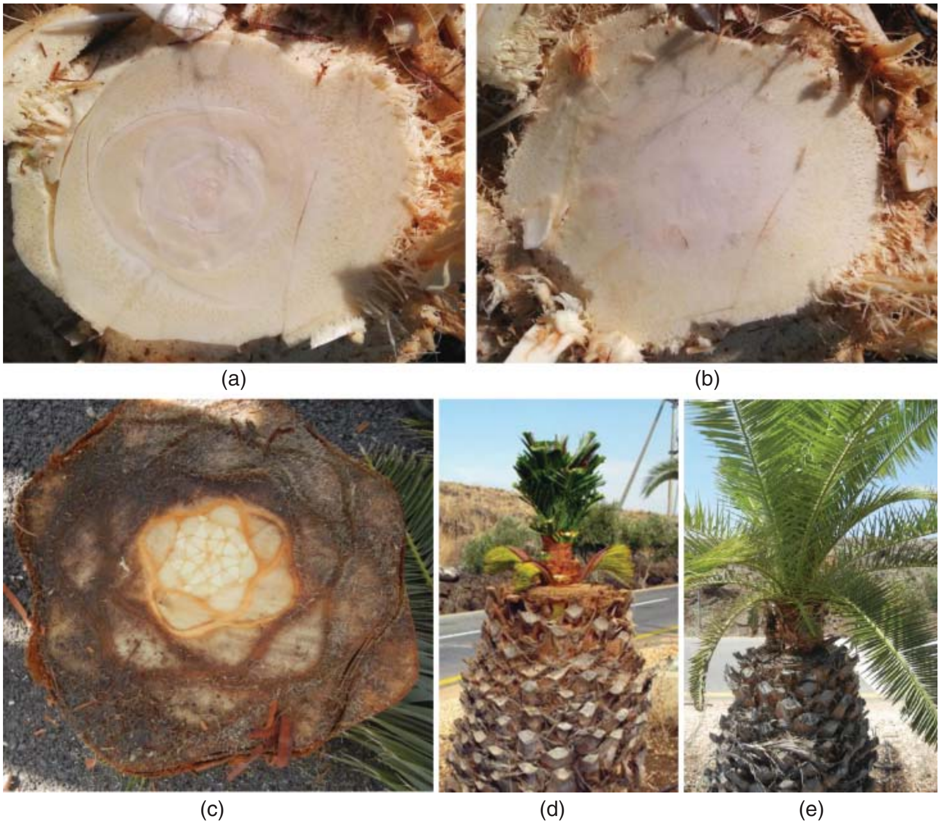

Figure 2.2 Dissection through the palm heart and the apical meristem. (a) Dissection above the apical meristem of a young, 4-year-old date palm. The organization of the leaf sheaths (outer leaves) and rachis and petioles (younger, inner leaves) is clearly visible. (b) Dissection through the same palm heart, approximately 5 mm lower. Since the cut is below the meristem, no structural organization of leaves is detected. (c) Dissection through the crown of a RPW-infected Canary palm to rescue the tree. The "kaleidoscope" pattern of leaf sheaths, rachis and blades confirms that the dissection level is above the meristem. (d, e) Recovery of the same Canary palm tree, 45 days and 11 months, respectively, after the treatment.

Once this pattern disappears, dissection has gone below the meristematic region, indicating that the palm cannot be recovered (Fig. 2.2b).

2.5 The Structure of the Palm Stem

The palm stem provides transport and storage of water, minerals, and carbohydrates, and mechanical support for the crown (Tomlinson 1990, 2006; Hodel 2009). The palm stem can be extremely long. In "climbing" rattan palms, a single stem can reach up to 200 m (Tomlinson 1990, 2006). Different species may be either solitary or with several stems (Tomlinson 1990; Dransfield *et al*. 2008). Aerial branching of palm stems is rare, and occurs naturally in only a few species, such as the doum palm (*Hyphaene*) (Dransfield *et al.* 2008).

2.5.1 Organization of the Stem through Cross- and Longitudinal Sections

The outer part of the stem is covered by old leaf bases, or by scars of shed leaves. In transverse section, the palm stem has a narrow cortex surrounding a central cylinder that fills most of the stem's volume. The central cylinder has numerous vascular bundles embedded in ground tissue, which is mainly composed of parenchyma cells. The stems' parenchyma cells store water and carbohydrates (usually starch) that are important to the palm's physiology and survival. While no annual thickening of the stem occurs, other processes, such as fiber and parenchyma cell-wall thickening, provide increased strength to the lower (older) part of the stem while enabling flexibility of its higher (proximal) parts (Tomlinson 1990; Tomlinson and Huggett 2012).

2.5.2 The Palm Vasculature

Palms lack a cambium layer and thus do not have secondary stem growth. Therefore, the stem diameter is usually constant (Tomlinson 1990; Dransfield *et al*. 2008; Broschat, Elliott, and Hodel 2014). Unlike other trees that increase their transport capacity with age, the palms' "strategy" is different. The palm builds its entire vasculature at the establishment phase, when it still has a small crown; thus, the vascular system is in essence "overbuilt." Once the tree matures, its stem diameter is fixed and the size of the crown also remains relatively constant. Therefore, the vascular system is suited to the mature tree dimensions.

Like other monocots, the palm's vasculature is based on vascular bundles. Each bundle includes both phloem and xylem elements, and is associated with, and many times enclosed in, a fibrous sheath (Tomlinson 1990; Broschat, Elliott, and Hodel 2014). These bundles are dispersed throughout the stem. This is in contrast to the vascular tissue of most trees, which has two concentric rings of phloem and xylem with a narrow layer of cambium between them.

The vascular bundles of the palm stems are not independent. They are interconnected by numerous junctions and bridges. In most palms, the vascular bundles are concentrated toward the periphery of the central cylinder, and are interconnected with each other by bridges and with leaves and inflorescences by traces (Zimmermann and Tomlinson 1972; Tomlinson 1990; Tomlinson and Huggett 2012). The stem parenchymatic tissue has a large water capacity. It has been suggested that palm stems serve as a water reservoir, and constant interaction and water flow between the vascular bundles and the ground parenchyma play a major role in the palm's water balance (Holbrook and Sinclair 1992a, b; Sperling *et al*. 2015).

Whereas in most trees, the cells of the vasculature are active for a limited time and are replaced by seasonal division and differentiation of cambium cells, in palms, the same vascular elements retain their activity throughout the lifespan of the plant. This unique characteristic of the palm vasculature makes for extremely long cell longevity. As there are no annual rings, it is hard to estimate the age of palm trees except by their height. However, since documented individual palms are known to have lived for at least 150–200 years (Zona and Maidman 2000) and much longer lifespans have been estimated (summarized in Tomlinson and Huggett 2012), their vasculature has been functioning for the same duration. This is in contrast to most dicotyledonous trees, in which the center of the trunk is composed mainly of dead cells; in the palm stem, the entire tissue is alive and biologically active.

2.5.3 Offshoots

Most palms do not branch in their aerial sections. Vegetative branching is limited because the hydraulic capacity of the stem base is fixed by primary vascular development and cannot support an ever-expanding crown (Tomlinson and Huggett 2012). If branching occurs, it is usually restricted to the base of the stems, at or close to ground level, where development of a new root system to support the new stems (and developing crowns) can occur (Tomlinson 1990; Tomlinson and Huggett 2012).

Propagation of most palms is performed from seeds. Palms with multiple stems can be propagated by splitting. This practice is very common in date palms, where clonal propagation of important cultivars is traditionally and practically performed from offshoots. The offshoot bases are covered with wet soil to induce rooting, prior to splitting the offshoots from the main palm's stem (Zaid and De Wet 2002a, b; Hodel and Pittenger 2003a, b).

Date palm (*P. dactylifera*) and Canary palm (*P. canariensis*) are two related species of the same genus. They differ in their trait of offshoot generation. Canary palms do not make offshoots, while date palms do. It seems that in date palms, the site of offshoot development is specifically vulnerable to RPW infestation. While RPW usually infest Canary palms at the crown, date palms are almost always infested at their bases, at or near the sites of the offshoots (Fig. 2.3a). In particular, the infestation site occurs specifically at the junction between the offshoot and the larger stem. From this site, the larvae burrow into either the offshoot or the larger mature stem. These sites are probably more vulnerable to infestation. The developing offshoots break through the protective dead

(a) (b)

Figure 2.3 Infestation of date palm with RPW at the base of the stem. (a) No symptoms, except a dry offshoot, were detected. Removal of the offshoot reveals a very large cavity at the base of the stem. (b) An infested date palm with a large cavity filling most of the stem interior. Adventitious roots have formed and are growing into the cavity.

leaf sheaths that might otherwise be impassable to the weevils. Thus, these sites may provide an easy path for the pest to penetrate into the palm stem tissue. Other breaks in the stem tissue, such as wounds and cavities, add to the plant's susceptibility.

2.5.4 Implications of Trunk and Vasculature Organization for RPW Symptom Development

One of the major challenges in palm borer infestations is their early detection. While infestation in the crown is detected by damaged leaves that hamper its symmetry, infestation at the stem is much harder to detect. Since damage to the stem is internal, it is rarely detectible at early stages. In date palms, drying offshoots is therefore a very indicative symptom of infested date palms, occurring at the site of the infestation itself. The active connection of the offshoot to the mother plant is usually small. Therefore, when dry offshoots are detected, their vascular elements are often already severely damaged, completely separating them from the main stem's vasculature. When identified, their internal tissues have usually also been largely eaten by the larvae.

Indirect effects of stem damage can generate symptoms of drought at the crown. However, since palm leaves do not wilt, such effects are not easily observed. Reduced water transport to the crown can be detected by the altered physiology of the leaves. Physiological parameters such as leaf photosynthesis and evapotranspiration will be reduced and can be detected using special equipment. Leaf water stress can also be detected in palms using thermal imaging (Cohen *et al*. 2012) (see Chapter 10, this volume). However, the high water capacity of the palm stem serves as a reservoir: the water is transferred to the leaves at the crown and utilized during the warm hours to enable photosynthesis, and storage is slowly replenished during the evening and night hours (Sperling *et al.* 2015). This mechanism enables the constant flow of water above damaged regions within the stem. The large number of inter-connections in the vasculature can bypass discontinuities in vascular bundles eaten by larvae and even large cavities in the stem, enabling continued efficient water transport throughout the stem to the crown. Despite the limitations, recent experiments have shown that thermal remote sensing can assist in identifying infested potted Canary and date palms, and point to suspected infested date palms in commercial orchards (Golomb *et al*. 2015). This approach is promising since it does not require manual assessment of each individual palm, but rather enables screening large areas and automatic detection of suspected palms (see Chapter 10, this volume). However, as discussed above, the organization of the stem vasculature limits the sensitivity and uses of these approaches for palms with significant internal damage.

2.5.5 Implication of Stem and Vasculature Organization for Chemical Treatments and their Application

Stem injection is a very common treatment practice in trees. It is also used for the treatment of different palm diseases and pests (Wood, Liau, and Knecht 1974; Nadarajan and Channabasavanna 1981), including preventive and curative treatments against RPW (Abd-Allah and Al-Khatri 2000; Azam and Razvi 2001). In a recent review, the potential and risks of stem-injection treatments against the RPW were discussed (Ferry and Gomez 2014). Injection procedures involve drilling deep into the stem and applying pesticides into the generated hole. Since palm stems do not have secondary growth, holes, similar to larger cavities, will not be filled by regenerated tissue. However, after the injection, a narrow barrier is formed isolating the healthy tissue from the wounded and damaged cells. This efficient sealing occurs in neighboring parenchyma cells, with the deposition of chemicals such as phenols, suberin, and tyloses. Damaged vascular vessels are specifically clogged by gums, enabling their isolation from the rest of the vascular system. However, this efficient sealing of the internal tissue prevents multiple uses of the same drilled holes for repeated pesticide applications. The distribution of many vascular bundles throughout the cross-section of the stem reduces the chances of the drill damaging the water and sap flows (this resembles cases occurring in many infected palms with large cavities in their stems, sometimes made by hundreds of RPW larvae, which survive and continue with vegetative and reproductive growth).

The large number of junctions and interconnections in the palm's vascular system, and the flow of water to the parenchyma cells, confine the damage of injection to a very limited region in the stem, without any effects on the crown parts. Moreover, these numerous interconnections enable even distribution of injected insecticide in the palm, especially throughout the crown and in the leaves, even with a small number of injection points (Ferry and Gomez 2014). Since the treatment involves active drilling into a living tissue, fungicide treatments should be added to prevent internal microbial and pathogen contamination.

Development of protocols using pesticides with long-term activity can reduce the damage of recurring injections. Although such protocols are efficiently used, a further understanding of the local two-directional flow between the vessels and the parenchyma, and the systemic spread of different pesticides, both acropetally (from the base to the top of the plant) through the xylem sap and basipetally (from the top toward the base) through the phloem sap, will enable improvement of these techniques. This is especially important in palms with offshoots, like date palms, in which the infested regions are not in the crown at the top of the stem, but rather in the lower stem itself and at the connected offshoots. In these cases, the injection must be applied as low as possible to allow even insecticide translocation that will also reach all offshoots. Moreover, chemicals and protocols allowing a lower rate of spread are probably needed to retain the active insecticides locally, in the lower stem regions were most infestations occur.

2.5.6 Palms Roots: Adventitious Root System and its Possible Role in Recovery after RPW Infection

The palm root system is adventitious. The roots arise from a zone at the base of the stem. They can be rather long, but they have a constant diameter, because, like the stems, they lack a mechanism of secondary growth. The primary roots split into narrower secondary, tertiary, and sometimes quaternary levels. Because of the palm's adventitious root system, large field-grown specimen palms can easily be transferred with a small root volume and transplanted (Hodel 2009; Broschat, Elliott, and Hodel 2014). This enables the industry to grow or import large trees and replant them on site.

Apparently, roots are not a target for either the RPW or the PBM. However, the lower portion of the stem is a common site for RPW infestation, especially in young, offshoot-bearing date palms. The damage can consist of large cavities in the lower stem that reduce the strength of the tree, threatening its collapse. These can also interfere with water flow from the root system through the stem to the crown. As palm roots are adventitious, trees can regenerate new roots at their lower stems. This has important implications for the recovery of palms that are damaged at their bases. Regrowth of roots, at or above the cavities, can stabilize the plant and allow it to retain its strength, as well as to rebuild its water-transport capacity. In several cases, root development and growth into internal cavities in the center of the stem have been detected (Fig. 2.3b). In general, to rescue palms with cavities in their stems, the damaged tissue is removed, the holes and cavities are filled with soil, and the lower stem is covered with a large pile of soil. Following this treatment, many infected trees develop new sets of roots that help them to survive and continue to grow (and even yield) for many years.

2.6 Conclusion

Palms are unique organisms, with distinct differences from other trees. A single apical meristem, located in the palm heart deep within the crown, generates all leaves and inflorescences. Damage to the apical meristem thus results in the palm's death. The vascular system is made up of thousands of interconnected bundles. Unlike dicotyledonous plants, damaged vascular elements in palms cannot be regenerated. Holes and cavities in the stems will remain throughout the palm's life, reducing its strength and affecting its water-transport capacity.

Successful treatment of infested palms, such as their rescue by crown dissection and sanitation, or by treatment of damaged stems, efficient systemic application of pesticides using direct stem injections, or as a soil drench, and local application of pesticides or biological agents to the crown are all dependent on the palm's structure and physiology. Understanding the unique structural biology, morphology, and physiology of palms is therefore essential for both the effective detection of palm borer infestation and efficient curative treatments.

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3

Economic and Social Impacts of *Rhynchophorus ferrugineus* and *Paysandisia archon* on Palms

Alan MacLeod and Mohamud Hussein

Food and Environment Research Agency, Sand Hutton, York, N. Yorkshire, United Kingdom

3.1 Introduction

The international trade of plants and plant products is a major pathway for the spread of plant pests and other invasive alien species (IAS) (Perrings, Williamson, and Dalmazzone 2000; Pimentel 2011). Following the spread of the red palm weevil (RPW) into Egypt where it was first reported by Cox (1993), it subsequently spread to Spain via the import of thousands of *Phoenix* palms from Egypt (Barranco *et al.* 1996; Ferry and Gomez 1998). Adults emerging from infested palms were able to establish themselves in Spain and the pest subsequently spread further, with the weevil becoming regarded as an invasive species.

The introduction into Europe of the palm borer moth (PBM), a native of South America, is most likely to have occurred via the import of infested palms from Argentina (EPPO 2005; Reid and Moran 2007). As non-European species, both RPW and PBM can be regarded as IAS and they add to the suite of such pests that are primarily introduced into new ecosystems through human activities (Vitousek *et al.* 1997; Hulme 2009; Roy 2010). Researchers have reported a correlation between access to new markets (e.g. for plants and plant products) and the introduction of new pest species, and between increases in international trade and the number of species incursions (Dalmazzone 2000; Vila and Pujadas 2001; Levine and D'Antonio 2003; Smith *et al.* 2009; Tatem 2009; Dehnen-Schmutz *et al.* 2010).

The impacts of invasive plant pests can be negative and costly. Plant pests not only cause direct damage to their hosts but also can have additional effects, such as imposing significant additional costs as a result of management interventions to mitigate the impact (e.g. USDA 2015). Palms infested by RPW or PBM are often not recognized as infested until the first symptoms of the attack appear, by which time the larval burrowing can be so serious that, in the case of RPW, the damage generally results in the palm's death (Ferry and Gomez 1998; Faleiro 2006). In such cases, management action to inhibit pest spread includes felling and removal of infested and nearby palms, which is often very expensive.

Around the Mediterranean, palm trees have become an essential component of the urban landscape. They are planted in large numbers along streets, in public parks, on hotel grounds, and in private gardens. Palm trees provide a variety of benefits to people

Handbook of Major Palm Pests: Biology and Management, First Edition.
Edited by Victoria Soroker and Stefano Colazza.

and, while not all of these benefits are easily valued in financial terms, any degradation of palms due to RPW or PBM will affect them. The concept of "ecosystem services" can be used to describe and categorize the types of benefits provided by natural systems, and individual species therein, such as palms.

This chapter outlines the ecosystem services provided by palms in the Mediterranean region so as to establish what is at risk from RPW and PBM; it further provides examples of the value of some of those services. It then describes the damage caused by the palm pests before providing examples of incurred costs of control measures in trying to limit the spread of RPW. The chapter concludes by highlighting the lessons to be learned from the European experience with RPW.

3.2 Ecosystem Services Provided by Palms

The terminology of ecosystem services and the principle of placing an economic value on biodiversity were given significant impetus by the Millennium Ecosystem Assessment (MEA) in 2005. Ecosystem services are most simply regarded as the benefits humans obtain from ecosystems.

The benefits of ecosystems are directly or indirectly enjoyed, consumed, or used to provide for human well-being (MEA 2005; Boyd and Banzhaf 2006; UK National Ecosystem Assessment 2010). The driving purpose for the development of the concept of ecosystem services was the need for decision-makers to more fully consider the value of nature where human activities impact on ecosystems. By providing a better understanding of what nature provides directly and indirectly, decisions on its use, management, and protection can be improved. Ecosystem services matter because changes in them affect human well-being through impacts on security, the necessary material for a good life, health, and social and cultural relations. These in turn influence people's freedom and choices (MEA 2005).

Just as the framework of ecosystem services can be used to describe the benefits that man derives from ecosystems, it can also be used to describe the human impacts on ecosystems resulting in the consequent loss or reduction of ecosystem services (EFTEC 2005). Similarly, the impact of IAS can also be described using the ecosystem service framework.

We begin with an outline of the three broad themes of ecosystem services following the terminology proposed in the Common International Classification of Ecosystem Goods and Services (Haines-Young and Potschin 2010):

1) **Provisioning services** such as the provision of food through the plants and plant products that we eat, as well as the fish and other animals we consume; provision of resources such as wood fuel and fiber;
2) **Cultural services** such as ecosystems from which non-material benefits are obtained but which, for example, provide cultural heritage or are of spiritual or religious importance, or which are inspirational or aesthetic;
3) **Regulating services** performed by ecosystems, such as climate regulation and water purification and regulation.

Palms provide a variety of ecosystem services within these three themes. The precise ecosystem services provided by palms depend upon the palm species and their location. Below we provide descriptions of the ecosystem services provided by palms, focusing on the Euro-Mediterranean area. Ecosystem services provided by palm species are summarized in Table 3.1.

Table 3.1 Ecosystem services provided by palms as grouped following the Common International Classification of Ecosystem Goods and Services (CICES) categories.

Theme	Class	Group	Palm examples
Provisioning	Nutrition	Terrestrial plant and animal foodstuffs	Dates and palm oil[a]
		Freshwater plant and animal foodstuffs	—
		Marine plant and animal foodstuffs	—
		Potable water	—
	Materials	Biotic materials	Ornamental plants
		Abiotic materials	Palm oil
	Energy	Renewable biofuels	Palm oil
		Renewable abiotic energy sources	—
Regulation and maintenance	Regulation of wastes	Bioremediation	—
		Dilution and sequestration	Carbon sequestration
	Flow regulation	Air-flow regulation	Wind-sheltering and sun-shading effects in urban areas
		Water-flow regulation	Canopy intercepts rainfall and effects on drainage
		Mass-flow regulation	—
	Regulation of physical environment	Atmospheric regulation	Air-pollution abatement
		Water-quality regulation	—
		Pedogenesis and soil-quality regulation	—
	Regulation of biotic environment	Life-cycle maintenance and habitat protection	—
		Pest and disease control	—
		Gene-pool protection	Plant biodiversity
Cultural	Symbolic	Aesthetic, heritage	Landscape amenities and historic palm groves
		Religious and spiritual	Palm leaves for religious ceremonies
	Intellectual and experiential	Recreation and community activities	Public gardens and parks
		Information and knowledge	Educational activities

a) Dates are mostly produced in the Middle East and the eastern Mediterranean. Palm oil is produced in other parts of the world.

3.2.1 Provisioning Services

The primary provisioning ecosystem service provided by palms in the Mediterranean region is in the production of edible dates, with date plantations centered around the eastern part of the Mediterranean, in the Middle East, and North Africa, where date palms are the primary tree crop due to their thermophilic character and drought tolerance (Manickavasagan, Mohamed Essa, and Sukumar 2012; Fig. 3.1). Dates are a major food source and have a significant impact on the economy of many countries in these regions (Botes and Zaid 1999). Several million tonnes of date fruit are produced annually in the area, and date production is a significant economic activity, with countries producing dates for both domestic and export markets. Egypt is the single largest producer of dates in the world, and its production is increasing. Since 2000, Egypt has grown its production of dates from just over 1 million tonnes to almost 1.5 million tonnes in 2013 (FAO STAT 2015). Annual production is now worth in excess of $400 million. Date production in Egypt is largely for domestic consumption, whereas a significant proportion of the dates produced by Algeria, Tunisia, and Israel are exported. These countries have developed a specific export strategy to grow top-quality varieties such as Medjool and Deglet Nour, and target the higher-priced European markets (Al-Saoud 2010). Almost 70% of EU date imports come from these three countries, with the dominant supplier being Tunisia, which regularly exports over 350,000 t of dates annually to the EU. Where date production is an important feature of agriculture, thousands of people make their living from labor related to date production. A relatively small quantity of dates is now produced within the EU in palm groves in Spain (4000 t from 700 ha) (FAO STAT 2015).

Figure 3.1 Plantation of date palms in the Jordan Valley, Israel. Reproduced with permissions of Neil Audsley, Israel, 2012.

In the past, such date production was larger, but the agricultural and economic interest in the Spanish date palm has decreased significantly since 1950 due to the high costs of production, largely due to the expense of irrigation and low cost of imported dates, leading to their low profitability (Ferry and Greiner 1999).

Outside of date-producing areas, palms are grown and traded commercially for ornamental purposes, and such activity can be regarded as a provisioning ecosystem service that is also an economic activity generating income and providing employment in Europe.

3.2.2 Cultural Services

The clearest benefits provided by palms, outside of date-growing areas around the Mediterranean, concern their cultural services, through which people relate to, appreciate, and enjoy nature and the environment. Palms provide considerable landscape amenities and have cultural significance in the form of heritage palm groves, botanical gardens, and in public parks and other urban environments and private gardens (Ferry and Greiner 1999; Pintaud 2002; Manachini, Billeci, and Palla 2013).

3.2.2.1 Urban Palms

Numerous palm species have long been planted in town and village squares and along promenades around the Mediterranean. Compared to rural environments, urban areas have limited green space and access to it may be unequally distributed. Urban forests can add significantly to the beauty of an urban landscape and enhance both residents' quality of life and the urban tourist's experience (Deng *et al*. 2010; Majumdar *et al*. 2011).[1] In addition to the aesthetic benefits provided, palms, along with other urban forest trees, provide numerous benefits, such as the provision of habitat for wildlife, an increase in property values, a sense of place and community, and stress reduction (Chaparro and Terradas 2009; Nowak 2010; Escobedo *et al*. 2011). Furthermore, as part of the urban forest, palms also provide opportunities for outdoor learning and many kinds of recreation; exposure to so-called green infrastructure can have benefits, including aesthetic satisfaction, improvements in health and fitness, and an enhanced sense of spiritual well-being (Tzoulas *et al.* 2007).

3.2.2.2 Heritage Palm Groves

In the European Mediterranean countries, there are three major heritage palm groves. They are in Elche in Spain (Fig. 3.2), Bordighera in Italy, and Crete in Greece (Gimenez Peon 1998). However, there are hundreds of other historical gardens containing palms. For example, in Sicily alone, 35 different species of palm are found in 113 Sicilian historical gardens (Manachini, Billeci, and Palla 2013). Palmeral of Elche was listed as a UNESCO[2] World Heritage Site in 2000 because its groves represent a remarkable example of the transferal of a characteristic landscape from one culture and continent to another, in this case from North Africa to Europe. *Phoenix dactylifera* has been cultivated since at least the 16th century in Bordighera, near the Italian–French border, for religious purposes, with palm fronds and leaves being processed for both Christian Palm Sunday and Jewish New Year ceremonies (Castellana 2001). The date palm groves

1 Urban forests include natural and planted trees in streets, gardens, recreational areas, and parks, unused public and private lands, transportation and utility corridors, and watershed lands around urban areas.
2 The United Nations Educational, Scientific and Cultural Organization.

Figure 3.2 View of the palm trees within the city of Elche, Spain. Reproduced with permissions of Alan Macleod, Spain, 2013.

are established on a succession of terraces maintained by dry stonewalls built on the steep slopes of the Sasso Valley, and irrigated by a complex network of canals and tanks. Although the number of palms has dropped over the last 100 years, the visual effect that they provide to the Sasso Valley remains distinctive. Palms and palm landscapes have long been acknowledged as symbols of exoticism and, as such, contribute greatly to attracting people, especially tourists, to Mediterranean regions such as the French Riviera and the Italian Adriatic coast (Palm Riviera) (Pintaud 2002). The historic date palm groves of Crete attract over 200,000 visitors a year (European Commission 2003) and are of sufficient size to be called a "forest", for example the Vai palm forest spreads over 2 km along a beach in eastern Crete.

3.2.2.3 Botanical Gardens

The historic palm groves of Spain, Italy, and Greece have contributed to highly valued plant collections in a number of botanical gardens, which also attract visitors. These collections also fulfill a very important role in the conservation of a number of threatened palm species. There are a number of important botanical gardens with sizeable palm collections in Europe. Palm collections have long been an important part of botanical gardens worldwide (Griffith, Lewis, and Francisco-Ortega 2011). In the 19th century, major gardens invested heavily in the acquisition and care of palm collections. Palms are now prominent and a popular component of their collections—forming part of the "exotica" visitors expect to see in botanical gardens—whilst also holding an important genetic pool for many palm species (Maunder *et al.* 2001). The genetic diversity maintained in botanical gardens is important for the survival of a species because plants that are genetically identical are likely to be vulnerable to the same pests and diseases (Cartwright 2000). The value of palm collections held in botanical gardens is linked to their multiple functions, for example in providing a sense of community and opportunities for research and conservation, education, and leisure activities.

3.2.3 Regulating Services

In urban environments, palms and other urban forest trees provide numerous benefits that can improve environmental quality and consequently human health. These benefits include improvements in air and water quality, the provision of shade (Fig. 3.3), leading to lower ambient air temperature, reductions in ultraviolet radiation, the production of oxygen and reduction of carbon dioxide, and lower levels of noise and dust (Chaparro and Terradas 2009; Nowak 2010; Escobedo *et al*. 2011). Studies have estimated economic values for some of the regulating ecosystem services provided by urban trees, including palm species. In a study of the regulating services provided by urban trees in Barcelona, Spain, Chaparro and Terradas (2009) found that, of 1.4 million trees, just over 2% were palms, with *Phoenix canariensis* being the most common species. They used USDA software by Nowak and Crane (2000) that considers species composition and diversity and takes into account structural characteristics, such as tree density and health, leaf area and leaf biomass, to generate results estimating volatile organic compound emissions (emissions that contribute to ozone formation), total carbon stored, and net carbon sequestered annually, as well as pollution removal. They reported that Barcelona's trees and shrubs depurate 305.6 t of pollution from the air, worth an estimated €1.12 million per year, a proportion of which was due to palms. They also estimated sequestration of 5422 t of carbon each year, and that *P. dactylifera* was second only to *Eucalyptus camaldulensis* in sequestering and storing the most carbon per year per mass of individual species. Working in Florida, Escobedo *et al.* (2011) collected field data on composition, structure, and canopy cover to estimate the value from carbon sequestration and air

Figure 3.3 Palm trees providing shade in a resort closed to the city of Catania, Italy. Reproduced with permissions of Alan Macleod, Italy, 2014.

pollution removal for trees, including palms, in Miami-Dade County. The removal of air pollutants (CO, NO_2, O_3, PM_{10}, and SO_2) was assessed to be of the highest value, worth approximately $20 million per year in health benefits. As seen in the study from Barcelona, palms in the Mediterranean also provide similar health benefits.

Having recognized the variety of benefits provided by palms, as well as some partial value estimates, we next provide examples of the damage reported as a result of the introduction and spread of RPW and PBM around the Euro-Mediterranean area. Although damage is not reported in terms of lost ecosystem services, it is reasonable to conclude that ecosystem services are impaired when large numbers of palms are killed or destroyed.

3.3 Impacts and Costs of Mitigation

The life cycles of RPW and PBM are described elsewhere (see Chapters 6 and 7 this volume). The cryptic tunneling larval life stages cause the most damage and explain why both RPW and PBM are highly damaging palm pests. The widely planted ornamental palm species *P. canariensis* and *P. dactylifera* are in particular very suitable hosts in which the pests can multiply. Infested palms can be killed within 6 months to a year. Regarding RPW, more than a thousand offspring can disperse from an infested palm and go on to infest other palms in less than 1 year (Ferry 2010). As a consequence of the pests' fecundity and dispersal ability, RPW can damage a large number of palm trees in a relatively short period of time.

Although RPW is less damaging to oil and date palms than it is to some ornamental palm species, in date-producing countries, the economic losses due to the eradication of severely infested palms and knock-on effects can still amount to tens of millions of dollars per year (El-Sabea Faleiro, and Abo-El-Saad 2009). In southern and eastern Mediterranean countries, RPW infestation threatens the economic viability of the production of palm dates (Faleiro 2006). RPW destroys palms wherever they occur, along roads and in public squares, as well as in public and private gardens (Sacchetti *et al.* 2005). Outside of date-producing areas, RPW has killed tens of thousands of amenity palms and has resulted in the destruction of hundreds of thousands of them as a consequence of official control measures (European Commission 2014). For example, in Spain, over 50,000 palms have been destroyed in Andalucía, with an estimated 100,000 destroyed across the entire country (Suárez 2010; Jacas, Dembilio, and Llácer 2011). In Italy, RPW has caused widespread damage to palms in Sicily (Conti *et al.* 2008) and on the mainland in Tuscany, Campania, Puglia, and Lazio (Bariselli and Via 2008), where thousands of palms have been killed. RPW has destroyed thousands of palms in urban landscapes and plant nurseries in a number of regions of France, including Provence-Alpes-Côte d'Azur, Corsica, and Languedoc-Roussillon (Ministère de l'Alimentation de l'Agriculture et de la Peche 2010). In France, the direct cost for removing and replacing dead palms has been estimated at more than €500 million (Ferry 2010). The first outbreak of PBM in the La Croix Valmer region of France resulted in an estimated 80% loss of *Phoenix* species, and significant impacts can be expected in famous tourist resorts and destinations, such as St Tropez, Cannes, and Monaco. In Greece, RPW has caused extensive damage to thousands of palms on the mainland, where *P. canariensis* is the most common palm used for ornamental purposes (Kontodimas *et al.* 2006).

Given that RPW has killed thousands of ornamental palms as it has spread around the Mediterranean, impacts would be expected to be significant. In 2011, the value of destroyed palms was estimated at €65–€195 million, while perhaps €96–€288 million worth of palms were infested but not destroyed (FCEC 2011). However, these figures can be regarded as an underestimate of the total economic value of the affected palms as the estimates do not account for all aspects of the ecosystem services they provide.

For the maintenance of human well-being, it is in the interest of societies as a whole to strive to maintain ecosystem services and avoid any diminution of the level of services provided. Hence, interventions are employed. Biosecurity surveillance can identify pest threats, which can then be evaluated with regard to the risk they present (MacLeod 2015). To mitigate damage and protect the ecosystem services provided by threatened palms, the EU has introduced phytosanitary legislation against RPW. The primary legislative framework for the EU phytosanitary regime is referred to as the Plant Health Directive (Anon 2000). The legislation lists many harmful organisms assessed as a threat to plants in the Community (MacLeod *et al.* 2010). Although the original directive did not specifically include RPW as a harmful organism, legislation allows EU member states to take temporary emergency measures to protect plants from any harmful organism not included in the Directive. Following a pest risk assessment that concluded that RPW could cause significant mortality to members of the Palmae, the EU adopted emergency measures in May 2007 (Anon 2007). The measures aimed to inhibit the entry and spread of RPW into and within EU member states. The measures included specific requirements for the import of palms into the EU and for their internal movement within the EU, as well as surveys to monitor for the presence of the pest. They also specified the official measures to be taken when an infested palm is detected. The program required that an infested zone (the area within 200 m of an infested palm) and a buffer zone extending to 10.2 km around the infested zone be designated. Within these zones, competent national authorities were required to take mitigating actions to eradicate RPW, or at least inhibit its spread. Actions included prompt felling and controlled destruction of severely damaged infested palms and sanitation of partially damaged palms to remove infested potential hosts, prevention of new infestation by pre-emptive treatment of potential hosts around the infested specimens, and continued surveillance within the buffer zone, including inspections of palms and installation and monitoring of pheromone traps.

Recognizing that taking such actions against a harmful organism can be expensive, and that large-scale eradication programs by EU member states might be difficult without EU support, the EU has a solidarity fund to which member states can apply for financial assistance in combating IAS. Financial contributions corresponding to a percentage of the eligible expenditure for eradication programs against RPW have been notified in the *Official Journal of the European Union* (Anon 2000, 2007). Such notification indicated that, between 2008 and 2011, Malta incurred eligible costs of €2.18 million. Cyprus incurred costs of at least €0.48 million between 2010 and 2012, while in France, between 2009 and 2012, expenses of €3.46 million were incurred. EPPOs (European and Mediterranean Plant Protection Organization) often face difficulties in implementing compulsory measures against RPW promptly, because private citizens may not comply with the regulations (Nardi *et al.* 2011). Therefore, despite ongoing control efforts, RPW continues to spread and damage a large number of palms across the region. The cost of containment and eradication measures against RPW in the EU was estimated to have reached at least €50 million and to have involved the destruction of at least 65,000 palms, but this was considered only a fraction of those infested (Pimentel 2011).

3.4 Conclusion

We showed that palms provide a variety of ecosystem services within the themes of provisioning services, cultural services, and regulating services. In principle, a partial estimate of the value of some ecosystem services provided by palms can be determined by a direct measure of the economic benefits from, for example, reduced environmental pollution through valuing abatement cost of air pollutants, savings in energy costs due to shading during the summer months, and the value of carbon sequestration by palms via photosynthesis (Sander, Polasky, and Haight, 2010). However, to date, there have been relatively few studies specifically examining and valuing amenity trees around the Mediterranean, and while we recognize that value is provided by palms, quantifying the total value by a few species over a large area is a significant challenge. Estimates to date are in the order of tens to hundreds of millions of euros. We further recognize that, although the benefits are not easily valued in economic terms, any degradation of the palms due to the harmful effects of RPM and PBM will impact on the very significant benefits provided.

In addition to the losses of ecosystem services through pest damage, there are significant public and private costs associated with the implementation of official EU control measures, felling and destroying severely damaged palms, or sanitizing and restoring them if the damage is more limited. Although action by authorities could be supported by solidarity funds, the EU has not co-financed losses incurred by private citizens resulting from the destruction of plant material ordered as part of official control measures. This is in contrast to the EU policy for culled animals within the EU animal health regime. It has been argued that there is therefore little incentive for owners of affected plants to notify authorities of outbreaks of regulated harmful organisms or to comply with the measures (Pluess *et al.* 2012). Additional factors that contribute to the difficulties in controlling RPW as it spreads around Europe include the high density of susceptible host species in some areas, the pests' high fecundity and long dispersal distance (see Chapter 10, this volume), and the limited ability to detect infested palms before damage occurs. Each of these challenges is addressed in subsequent chapters (see Chapters 9, 10, and 13 this volume). In addition, prior to regulations imposed in 2007, trade in ornamental palms continued relatively freely and could have facilitated the spread of infested plants within the region. For example, in the Canary Islands, several companies supplied large palms to Spain and continental Europe. As problems with RPW became recognized, these companies suffered losses of around €3 million a year due to cancelled orders, but the businesses adapted such that most of the palms that are grown and traded are now of species that are not susceptible to RPW (van der Ploeg 2008).

It has been acknowledged that RPW spread rapidly and that the management strategies in Europe were not effective at controlling the pest. This was partly due to the practical difficulties of accessing infested palms on private land and of applying more vigorous control methods, such as insecticide injections or sprays in urban environments where chemical usage was unacceptable (Pinhas *et al.* 2008; Guarino *et al.* 2011; Jucker and Lupi 2011). It is also partly due to the time lag between a palm becoming infested and the onset of symptoms caused by the pest and removal of damaged trees to prevent further spread of the pest (Ferry 2010; Bariselli and Via 2008). However, more importantly, it must be recognized that there are weaknesses in the EU Plant Health Directive of 2000. For example, any plants not regulated by the Directive are allowed entry into the EU with minimal regulation. Hence, trades and pathways with which there is no prior experience develop with little scrutiny, posing plant health risks, and sometimes it is only after those risks are realized and new pests have become established that risk-management measures are applied (MacLeod *et al*. 2010). This was the case with palms from third countries in the late 20th and early 21st century. Prior to 2007, RPW was not officially regarded as a harmful organism within the EU and no specific action was required to prevent its introduction or spread. When damage was first reported in Spain in 1992, it was not recognized as a sign of an emerging issue. Consequently, there was a long delay until 2007, when emergency measures were eventually introduced, despite the fact that the European and Mediterranean Plant Protection Organization had highlighted the possible threat from RPW in 1999. Plant-protection authorities are now more engaged in horizon-scanning activities and seek to employ methods to detect threats from emerging plant pests (EFSA 2011). Such activities are intended to prevent the widespread and damaging impacts caused by pests such as RPW or PBM from occurring again on palms and other plants.

Recognizing the benefits provided by palms, and the magnitude of the impacts caused by the pests that harm them, there is a great and urgent need to develop and implement alternative efficient pest-control methods to inhibit the spread of harmful palm pests and prevent such huge losses. This is the subject of future chapters.

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4

Rhynchophorus ferrugineus: Taxonomy, Distribution, Biology, and Life Cycle

Didier Rochat[1], Oscar Dembilio[2], Josep A. Jaques[2,], Pompeo Suma[3], Alessandra La Pergola[3], Rachid Hamidi[1], Dimitris Kontodimas[4] and Victoria Soroker[5]*

[1] *Institute of Ecology and Environmental Sciences of Paris (UMR 1392), INRA, Versailles, France*
[2] *Universitat Jaume I, Department of Agricultural and Environmental Sciences, Campus del Riu Sec, Spain*
[3] *Department of Agriculture, Food and Environment, Applied Entomology Section, University of Catania , Italy*
[4] *Department of Entomology & Agricultural Zoology, Benaki Phytopathological Institute, Athens, Greece*
[5] *Department of Entomology, Agricultural Research Organization, The Volcani Center, Rishon LeZion, Israel*

4.1 Introduction

The red palm weevil (RPW), *Rhynchophorus ferrugineus* (Olivier, 1790), has been known as a pest for more than one century in its native area. It was accidentally introduced into the European Union (EU) about 20 years ago, where it has adapted to the climate and the palm species available, especially in the Mediterranean Basin but also at several places at the Atlantic shores. Since then, RPW together with PBM, *Paysandisia archon* (Burmeister, 1880), have killed more than 150,000 palms in this area and more than €100 million have been allocated to control them (Palm Protect estimates). RPW has been a regulated quarantine pest in the EU since 2007 (EC 2007). Circulation of palm trees has consequently been subjected to strict regulations to prevent RPW spread (EC 2008, 2010). This is fully justified because RPW is a specialized insect, remarkably adapted to live on palm trees where it is very difficult to detect and to remove.

In spite of important investment in research, and advances to detect and control RPW (e.g. review in Giblin-Davis *et al*. 2013), the pest is not currently under control in the Mediterranean and the EU. One of the main reasons for such a situation is the life confined in the host plant at almost all stages. Adults are difficult to observe on the palm trees. Larvae feed and live in the plant, which protects them from harmful weather conditions. They cannot be easily detected and observed unless the palms are dissected. The hidden life style, often at the top of large tall plants, makes observation and experimentation particularly difficult. Many studies have been carried out and published, particularly since the spread in Middle Eastern date palms. However, many aspects of its ecology and behavior have remained controversial or undetermined, particularly under temperate conditions.

This chapter is thus reviewing current knowledge, recent advances, and yet undetermined features regarding the life cycle and the host plants of RPW with the view of

*J.A. Jaques was formerly J.A. Jacas

Handbook of Major Palm Pests: Biology and Management, First Edition.
Edited by Victoria Soroker and Stefano Colazza.

understanding how the species has adapted to temperate climate. We will (1) present the current systematic position and typical morphology of the species; (2) describe the main traits of the life cycle; (3) thoroughly review the host plants to show the strict relationships to palms, with a tentative critical ranking of the susceptibility of the species grown under the Mediterranean and reference to the species from the native area; and finally (4) review the fundamentals of RPW adaptation to the temperate climates and provide thermal thresholds, which rule RPW reproduction, development and flight. Information will be discussed with consideration of the buffer effect of living deep in palm tissues and the possibility of simulating the risk of further spread of RPW to mild Atlantic climate. The behavior of RPW and behavioral ecology are detailed in Chapter 5.

4.2 Taxonomy and Distribution

4.2.1 Systematic Position and Morphology

The RPW is a weevil (Insecta, Coleoptera, Polyphaga, Curculionoidea) from the Dryophthorine subgroup, sometimes considered a family (Thompson 1992; Alonso-Zarazaga and Lyal 1999). An evolutionary trait of the Dryophthorine is the strict larva and adult feeding on stems of monocots. Only a few species evolved feeding on seeds or dicots (Thompson 1992; O'Meara 2001). The RPW host plants are Arecaceae or palms (see Chapter 1, this volume) (Wattanapongsiri 1966) and *Rhynchophorus* spp. are the so-called Palm weevils. Most Dryophthorine weevils, as RPW, ancestrally shelter symbiotic enterobacteria in a specific organ (bacteriome) at the larval stage and further as an adult connected to the ovaries. The endosymbionts produce metabolites that supplement the plant diet (O'Meara 2001; Lefèvre *et al.* 2004). Such an endosymbiosis is typical of various groups of insects that feed on nutritionally deficient diet such as phloem, wood, seed, or blood lacking metabolites necessary to the insect development.

RPW adults are typical weevils: the head extends with a long thin rostrum that holds the antennae and tiny mandibles. In addition, the adults of all Dryophthorine share two distinctive traits: first, the distal articles of the antennal club are fused. Second, the elytra do not cover the tip of the abdomen (pygidium) (Fig. 4.1A and C). RPW has a pair of functional membranous wings, which make it an excellent flyer (see Chapter 5, this volume).

RPW are sex dimorphic. Typical males bear a patch of setae on the dorsal side of the rostrum, which is absent in the female but also in tiny or worn males. The setae serve for slow release of the aggregation pheromone (see Chapter 5, this volume) in *Rhynchophorus palmarum* L. (Sánchez *et al*. 1996). The rostrum is thinner and longer in the female. The fore tibiae are sex dimorphic too: with a comb-like brush of tightened long hairs in males and only some scarce hairs in females. This latter feature is more constant than the rostral setae and should be checked on the small specimen for secured diagnostic.

The size of RPW greatly varies from 15 to 40 mm (rostrum tip to abdomen tip) and from 7 to 15 mm in width. Most individuals in the Mediterranean are around 30 mm long. The mass ranges from 0.8 to 1.2 g. In general, females are about 10–15% larger and heavier than males (Wattanapongsiri 1966; Martín and Cabello 2005). RPW has become the largest weevil in the European and North African fauna.

RPW adults are known for a large phenotypic variability: the body color ranges from entirely orange-red to all black with all intermediates regarding the number and size

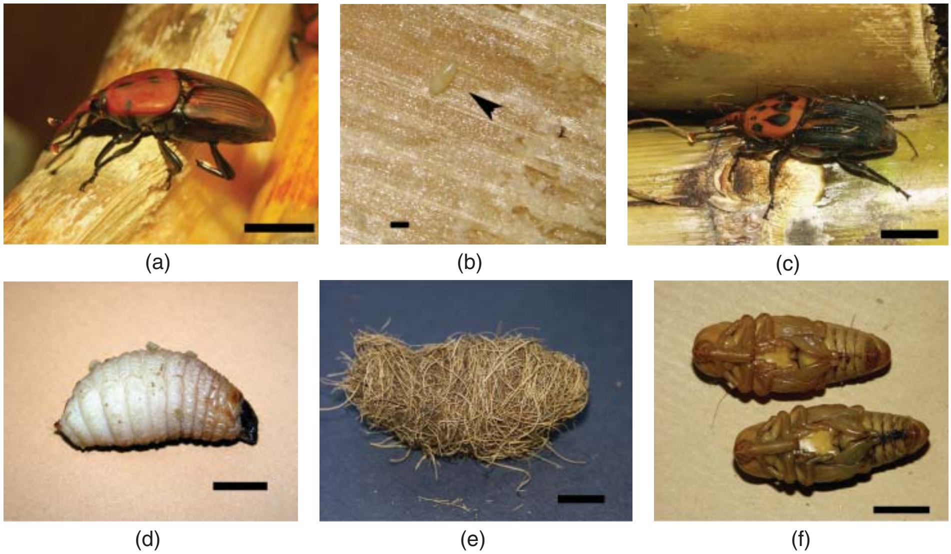

Figure 4.1 The main forms of the life cycle of the red palm weevil. Adults: A. Female with a thin, long, and glabrous rostrum and C. male with a stockier rostrum bearing a patch of setae at the distal part. The pictures illustrate two morphs: a red one and a dark one, with a few and strong black markings, respectively. Note the extremity of the abdomen not covered by the elytra and the truncated antennal club made of fused segments, which are typical of the Dryophthorine weevils. B. Egg (arrow) removed from the substrate where it was inserted by the female. Note the same colors of the eggs and of the substrate. D. Mature larva bearing a large and hard head with powerful mandibles but without legs, which are typical features of weevils' larvae. E. Cocoon made by the larva with palm fibers which protects the pupa. The rounded end (right) corresponds to the starting point and the truncated end (left) to the termination point. The cocoon has been withdrawn from the palm frond where it was inserted. F. Pupae extracted from their cocoons. The upper and lower individuals correspond to a male and a female, respectively, based on the length of the rostrum sheath: the tip goes beyond the sheath of the fore tibiae in the female but not in the male. The horizontal black bar in the pictures represents 1 cm (A, C–F) or 1 mm (B). (All pictures by Didier Rochat; INRA, France)

of the black marks. This led to describe several different species latter synonymized (Wattanapongsiri 1966) as *Rhynchophorus vulneratus* (Panzer, 1798) by Hallett, Crespi, and Borden (2004). Recent genetic studies using various markers showed an important genotype variability with a unique haplotype (DNA sequence of the mitochondrial cytochrome oxidase subunit I (COI) gene) in the Mediterranean with the exception of Syria and several different types in the other Asian populations, which did not include individuals from original Monsoon countries (Gadelhak and Enan 2005, El-Mergawy *et al*. 2011a, b, c; A'Hara *et al*. 2012). A more comprehensive study with specimens from the native area concluded that *R. ferrugineus* and *R. vulneratus* are two separate species that do not occupy the same territories (Rugman-Jones *et al*. 2013) and *R. bilineatus* Montrouzier, 1857 a third one. It is finally suggested that several cryptic *Rhynchophorus* species may exist within the populations studied. RPW would obviously deserve more comprehensive investigation to establish the distribution maps of the genetically separated populations (possibly species) in correlation to eco-ethological adaptations, especially to host palm species.

The egg, whitish with a smooth chorion, is elongated Ø × L: *ca.* 1.0 × 2.5 mm (Fig. 4.1B). Larvae, whitish or yellowish, are also typical of the weevils: they have a large hard brown head with powerful mandibles and no legs (Fig. 4.1D). The size ranges from 2 mm upon hatching up to 5 cm at full growth in length for a weight from about 1 mg up to 4 g. The pupa is protected in a solid “cocoon” (See Section 4.3.1) made of palm fibers (Fig. 4.1E). After the cocoon is formed the larva enters a pre-pupal stage: its body contracts and it does not crawl any more. The future adult organs are well apparent in relief on the pupa (Fig. 4.1 F). The sex can be determined from the relative position of the rostrum and of the tibiae of the forelegs: in females the tip of the rostrum extends clearly (1 mm or more) beyond the tibiae, placed perpendicular to the body axis; in males it ends at the same level or even slightly before. Similarly in the adult female, the tip of the rostrum juts the clubs of the antennae naturally extended in a walking weevil while it does not in males.

4.2.2 Past and Present Distribution

Based on several comprehensive reviews and particularly the genetic study by Rugman-Jones *et al.* (2013), RPW is a common Indomalayan species (i.e. a tropical species from Monsoon Asia, which typically occupies the northern and essentially continental part of this area, from India eastward to the Philippines). RPW-like populations in the Indonesian islands are of *R. vulneratus*. The presence of RPW in the Australasian area, particularly north of Australia, is therefore dubious, and RPW-like weevils may correspond to *R. bilineatus* from Papua New Guinea. The ancient report from Mesopotamia is dubious (Wattanapongsiri 1966; Faleiro 2006; EPPO/OEPP 2008; El-Mergawy and Al-Ajlan 2011; Fiaboe *et al.* 2012). Abe, Hata, and Sone (2009) reported the first presence in a new country out of this range in Japan in 1975. From 1985 and due to the boom of ornamental palm trade, RPW rapidly spread to many countries from Pakistan, where it should have been native, to the Arabic Peninsula, then the eastern Mediterranean and Spain in the 1990s, and more recently in increasingly farther territories, including the Canary Islands and Madeira, the Caribbean (Curacao and Aruba), Taiwan, and China. The presence in the USA (California) initially attributed to RPW is now attributed to *R. vulneratus* (Rugman-Jones *et al.* 2013). In 2015, 18 countries out of the 21 with a shore on the Mediterranean Sea have reported RPW (El-Mergawy and Al-Ajlan 2011; Fiaboe *et al.* 2012; CABI 2015; EPPO/OEPP 2015). In the EU, RPW is officially present in Croatia, Cyprus, France, Greece, Italy, Malta, Portugal, Slovenia, and Spain. On the African coast, RPW has been chronologically reported from Egypt, Libya, Morocco, Tunisia, and possibly Algeria (Fiaboe *et al.* 2012). The other concerned Mediterranean countries are Israel, Lebanon, Syria, Turkey, and Albania plus Georgia and Russia (Karpun, Zhuravleva, and Ignatova 2014) on the Black Sea.

With the exception of the official positive reports, the areas actually occupied by RPW are imprecisely or even conflictingly reported in many countries. The EPPO/OEPP database (2015) indicates many cases with no precision. The situation is rapidly evolving due to the pest hidden multiplication, which leads to the sudden collapse of large population of palms. This has been due to the underestimation of the threat because of the difficulty to detect the symptoms with sufficient accuracy and before an irreversible damage is visible (see Chapter 9, this volume). The chronology of spread of RPW in the Mediterranean is schematized in the map Fig. 4.2. It illustrates the quasi-total invasion of the Mediterranean shores between 1999 and 2011. The yet-RPW-free

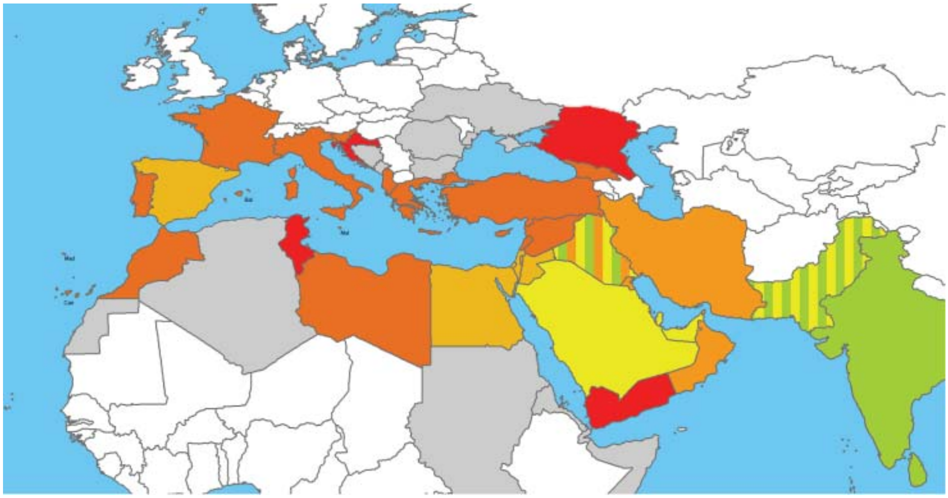

Figure 4.2 Western distribution area of the RPW, with chronology of invasion from 1985. Caribbean and Far Eastern areas are not illustrated. The entire concerned countries are colored according to the date of first report irrespective of the actual zones where outbreaks occurred. Green: native area, established before 1980. First reports from: 1980–89 (yellow), 1990–99 (pale orange), 2000–2009 (bright orange), and 2010–2015 (red). Striped coloring with same coding as above indicates an uncertain situation: Pakistan: RPW should be a native species originally growing on local *Phoenix dactylifera* and *Phoenix sylvestris*. Iraq: an ancient dubious report suggests RPW possibly native on date palm. Current presence has been reported but without precise dating for first outbreak. Russia: only a portion of Russia is colored with an arbitrary northern limit. Gray: areas under high threat due to proximity of infested countries and reports of palm movements. (*See color plate section for the color representation of this figure.*)

countries (Fig. 4.2 in gray) should be concerned because of ongoing urban planting and uncontrolled palm movements, particularly in Africa.

Thus, RPW that lived under tropical and subtropical climates settled in territories with temperate climates characterized by the rhythmic occurrence of low temperatures and the presence of palms species naturally absent from its native range. Regarding the explosive plantings of palms worldwide and the RPW customs, the probability of acclimation of RPW to the Black Sea and the mildest Atlantic northern shores is extremely high.

4.3 Biology and Host Plants

4.3.1 A Borer Species that Lives only on Palms

4.3.1.1 What is a Host Plant? Field Surveys versus Experimental Results

A host plant for an insect should only be a plant species where it can complete its development and reproduce under natural conditions. In the most evolved cases this involves the active location and selection of the plant by the insect, especially by the female to lay eggs, the overcoming of the plant defenses, and profitable feeding by the immature stages, which can complete their development (Bernays and Chapman 1994).

In the case of plant borers, when an egg or a larva has been artificially introduced into the plant (forced infestation) and then develops into an adult, to describe the plant as a host would be a misnomer. If there is no evidence about the natural capability of the insect to get access to the nutrients and to overcome the antixenotic and/or antibiotic properties of the entire plant growing outdoors (Painter 1951; Kogan and Ortman 1978; Wiseman 1999), the plant species should only be noted as a "potential host plant."

Table 4.1 therefore separates (1) the reports of larvae that develop in palms naturally from (2) a development observed under semi-field conditions with eggs laid by females confined with the palms, and from (3) a development observed under artificial conditions after forced infestation.

Several comprehensive reviews have been published (e.g. Wattanapongsiri 1966; Murphy and Briscoe 1999; Barranco *et al.* 2000; Martín and Cabello 2005; Faleiro 2006; EPPO/OEPP 2008; El-Mergawy and Al-Ajlan 2011; Fiaboe *et al.* 2012). Most of them aggregated under the term "host plant" species naturally infested, either commonly or occasionally, or that made larval development possible irrespective of natural egg-laying or forced infestation, and until adult or not. Almost all the experiments that studied development in living palms used small specimens. Transposition to mature specimens is unknown. Experimental evidence of the unsuitability of species evaluated is rarely reported in host plant reviews.

We therefore revisited the literature including earlier and new experimental reports both with positive and negative RPW development. The host palms reported from the different EU countries have been documented separately. We clearly separate "potential host" that means successful under experimental conditions yet without confirmed natural infestation and possibly death of the host palm.

4.3.1.2 RPW: A Borer that knows to Locate Palms Where it Exclusively Lives

RPW host plants as discussed above are all members of the Arecaceae (=Palmae) family (see Chapter 1, Section 4.3.2, and Table 4.1): we did not find documented reports of natural infestation and complete development in other plants. In particular, in the native area sugar cane has never been reported as damaged by RPW, whereas the crop can adjoin attacked coconuts. The same within the invasion area where no reliable report of infestation on yuccas, cycas, or *Agave americana* L. 1753 could be found. Consistently with the field situation, many assays to breed RPW proved sugar cane, fruits, and other diets not to be optimal for complete development as compared to palm tissue (Martín and Cabello 2005; Dembilio and Jacas 2011).

Large-scale RPW dissemination since 1985 has been of pure anthropic origin due to the transport of infested palms (Fiaboe *et al.* 2012). However, RPW infested palms are highly clustered (Faleiro, Ashok Kumar, and Rangnekar 2002), which suggests that most adults from one palm are essentially colonizing palms close to their site of emergence. This is likely linked to the high olfactory sensitivity of RPW, which can efficiently detect and orient toward palms and conspecifics odors with the help of visual cues (see Chapter 5, this volume). Indeed, RPW males produce an aggregation pheromone (Hallet *et al.* 1993). This should be an adaptive trait to signal a dispersed resource since palm densities are low in natural tropical moist forest where most RPW host palms grow and to optimize locating mates and food, thanks to an important flight capability (Abbas *et al.* 2006 and Chapter 5, this volume) to reach remote host palms.

The attraction is synergized by the odor emanating from freshly cut palm tissues, which are also attractive per se. Synergy is maximal when the cut tissues ferment (review in Vacas *et al.* 2014). The attraction to wounded palms has long been described for *Rhynchophorus* spp., which are known as wound insects meaning that they come after an

Table 4.1 List and status of RPW host plants: Literature revisited with focus on invasion area.

Taxonomic position within Angiospermae, Monocotyledonae					Common names	Main features					Infestation - Conditions and amplitude				
											Natural		Semi-natural or artificial		
						Originating									
Clade, Order	Family	Sub-family	Genus	Species		Area	Climate Biotope [a]	Economic Value [b]	Host and susceptibility status	Abundance in Med and EU	< 1980 Native area	> 1985 Invasion area	Natural egg-laying	Forced larval infestation	Laboratory
Lilianae, Asparagales	Asparagaceae	Agavoidea	*Agave*	*A. americana* L. 1753	Century plant, maguey, American aloe	North and Central America	Trop dry forest	Orn	PH / NH?	++					? [8]
Commelinids, Arecales	Arecaceae	Calamoideae	*Metroxylon*	*M.* (=*Coelococcus*) *sagu* Rottb. 1783	Sago palm	Asia	Trop moist forest	Cult	H	0	[1]				
		Nypoideae	*Nypa*	*N. fruticans* Wurmb 1779	Nipa palm	Asia	Trop moist forest mangrove	None	H	0	[1]				
		Arecoideae	*Archontophoenix*	*A. alexandrae* (F. Muell.) H. Wendl. & Drude 1875	(King) Alexander palm, Alexandra palm, King palm, Northern Bangalow palm	Australia	Trop moist forest		NH?	r			(-) [PP]		
			Areca	*A. catechu* L. 1753	Betel tree or palm	Asia	Trop moist forest	Cult	H	0	[1]	[13]			
			Howea	*H. forsteriana* (C. Moore and F. Muell.) Becc., 1877	Kentia palm, Thatch palm	Australia	Trop moist forest	Orn	H?	r		C? [13, 21]			
			Oncosperma	*O. horridum* (Griff.) Scheff., 1871		Asia	Trop moist forest		H	0	[1]				
				O. tigillarium (Jack) Ridl., 1864		Asia	Trop moist forest		H	0	[1]				
			Butia	*B. capitata* (Mart.) Becc., 1916	Jelly palm	South America	Trop dry forest		H?	r		C? [21] [11]			
			Cocos	*C. nucifera* L., 1753	Coconut palm	Asia panTrop	Trop moist forest	Cult	H+	0	[1]				

(*Continued*)

Table 4.1 (Continued)

Taxonomic position within Angiospermae, Monocotyledonae					Common names	Main features					Infestation - Conditions and amplitude				
						Originating					Natural		Semi-natural or artificial		
Clade, Order	Family	Sub-family	Genus	Species		Area	Climate Biotope[a]	Economic Value[b]	Host and susceptibility status	Abundance in Med and EU	< 1980 Native area	> 1985 Invasion area	Natural egg-laying	Forced larval infestation	Laboratory
		Coryphoideae	*Jubaea*	*J. chilensis* (Molina) Baill., 1895	Chilean wine palm	Chile	Med forestland scrub	Orn	H?	r		[11, 16, PP]			
			Syagrus	*S.* (=*Arecastrum*) *romanzoffiana* (Cham.) Glassman, 1968		South America	Trop dry forest	Orn	H?	r		C? [11] (-) [21]			
			Elaeis	*E. guineensis* Jacq., 1763	African oil palm	Africa panTrop	Trop moist forest	Cult	H	0	[1]				
			Roystonea	*R. (=Oreodoxa) regia* (Kunth) O. F. Cook, 1900	(Cuban or Florida) royal palm	North and Central America	Trop moist forest	Orn	H	0	[1]				
			Bismarckia	*B. nobilis* Hildebr. and H. Wendl., 1881		Madagascar	Trop dry forest	Orn	PH	0		C? [3]			
			Borassus	*B. flabellifer* L., 1753	Asian palmyra palm, toddy palm, sugar palm, Cambodian palm	Asia	Trop moist forest	Trad Use	H	0	[1]				
			Arenga	*A. pinnata*(Wurmb) Merr. 1917 (=*saccharifera* Labill. ex DC.)	Sugar palm, Arenga palm	Asia	Trop moist forest	Cult	H	0	[1]				
			Caryota	*C. cumingii* Lodd. ex Mart., 1853 (=*urens* L.)	Philippines fishtail palm	Asia	Trop moist forest	Trad use	H	0	[1]				
				C. maxima Blume ex Mart., 1838		Asia	Trop moist forest		H	0	[1]				
			Nannorrhops	*N.ritchiana*(Griff.) Aitch., 1882		Asia Middle-East	Med Forest and Scrub	-	NH?	0		(-) [5]			(-) [5]
			Corypha	*C. utan* Lam.,1786 (=*elata* Roxb., =*gembange* Blume, =*gebanga* Mart.)		Asia	Trop moist forest		H	0	[1]				
				C. umbraculifera L., 1753	Talipot	Asia	Trop moist forest		H	0	[2]				
			Livistona	*L. australis* (R.Br.) Mart., 1838	Cabbage-tree palm	Australia	Med forest and Scrub		PH	r		? [13]			

	L. chinensis(Jacq.) R.Br. ex Mart., 1838 (=subglobosa (Hassk.) Mart.)	Chinese fan palm, fountain palm	Far East Asia	Med forest and Scrub		PH	r		? [14, 17, 24] (-) [21]			
	L. decora (W. Bull) Dowe, 2004 (=*decipiens* Becc., 1910)		Australia	Trop dry forest		PH	r				(+) C? [4]	
	L. saribus (Lour.) Merr. ex A. Chev., 1919	Taraw palm		Trop moist forest		H	0	? [14]				
Chamaerops	*C. humilis* L., 1753	European fan palm, Med. dwarf palm, dwarf fan palm	Med basin	Med forest and scrub	Pat Orn	H-	+++		min [11, 18, 20]	(-) [9] min C? [PP]	(-) [4] min C+ [9]	
Trachycarpus	*T. fortunei* (Hook.) H. Wendl., 1861	Chusan palm, windmill palm, Chinese windmill palm	Asia China	Temperate mixed forest	Orn	H-	++		min [16, 20]	(+) C? [PP]	min C? [4]	C+ [10]
Brahea	*B.* (=*Ertythrea*) *armata* S. Watson, 1876	Mexican blue palm, blue hesper palm	North and Central America	Desert and xeric shrubland	Orn	H?	r		[11, 20]		(-) [4]	C+ [10]
	B. edulis H. Wendl. ex S. Watson, 1876	Guadalupe palm	North and Central America	Desert and xeric shrubland	Orn	H?	r		[16, 20, 23]			
Copernicia	*C. alba* Morong, 1893	Caranday, Wax palm Ananachícarí	South America	Trop dry forest	Orn Trad Use	H?	r		C+ [25]			
Washingtonia	*W. filifera* (Linden ex André) H. Wendl. ex de Bary, 1879	Desert fan	North America	Med forestland scrub	Orn	H-	++		min [16, 20] [21]	(-) [9]	(-) [9]	C+ [10]
	W. robusta H. Wendl., 1883	Mexican fan palm	North America	Desert and xeric shrubland	Orn	H-	++		min [20] [21]	(+) C? [22] (-)[PP]	(-) [4]	
Phoenix	*P. canariensis* Chabaud, 1882	Canary Islands date palm	Canary Islands	Med forestland scrub	Pat Orn	H+	+++		(+++) [11, 12, 16, 20...]			C+ [10]
	P. dactylifera L., 1753	Date palm	Asia Middle East	Med forestland scrub	Cult	H+	+++	[1, 12]	(+++) [6, 11, 13, 16, 20...]			
	P. dactylifera L., 1753	Date palm	Asia Middle East	Med forestland scrub	Cult	H+	+++	[1,12]	(+++) [6, 11, 13, 16, 20...]			
	P. reclinata Jacq., 1801	Wild date palm, Senegal date palm	Africa	Trop dry forest		NH?	r		(-) [20]			
	P.roebelenii O'Brien, 1889	Pygmy date palm, miniature date palm	Far East Asia	Med forestland scrub	Orn	NH?	r		? [24]	min C? [PP]		

(*Continued*)

Table 4.1 (Continued)

Taxonomic position within Angiospermae, Monocotyledonae					Common names	Main features					Infestation - Conditions and amplitude				
						Originating					Natural		Semi-natural or artificial		
Clade, Order	Family	Sub-family	Genus	Species		Area	Climate Biotope [a]	Economic Value [b]	Host and susceptibility status	Abundance in Med and EU	< 1980 Native area	> 1985 Invasion area	Natural egg-laying	Forced larval infestation	Laboratory
				P. rupicola T. Anderson, 1869	Cliff date palm	Asia India	Med forestland scrub		NH?	r			(-) [PP]		
				P. sylvestris (L.) Roxb., 1832	Silver date palm, Sugar date palm	Asia	Med forestland scrub		H+	r	[1]	C? [3, 13] [12, 24]			C+ [10]
				P. theophrasti Greuter, 1967	Cretan date palm, Phoenix of Theophrastus	Med basin Greece Turkey	Med forestland scrub	Pat	H?	r		(+)	(+) C? [PP] (-) [11] [7, 9]	(+) C? [PP] min C? [9, 11]	
			Sabal	*S. palmetto* (Walter) Lodd. ex Schultes and Schult.f., 1830 (=*umbraculifera* Mart.)	Cabbage palm, palmetto (palm), Cabbage palmetto	North America	Med forestland scrub	Orn	H?	r		(+) [13, 16] ? [20]			
Commelinids, Poales	Poaceae	Panicoidea	*Saccharum*	*S. officinatrum* L., 1753	Sugar cane	Asia panTrop	Trop dry forest	Cult	PH	r			(-) [19]		C+ [2, 19, PP]

Originating Area, Climate and Biotope: Med Mediterranean and Trop Tropical.
Economic/patrimonial value: Cult: cultivated for fruits; Orn: ornamental; Pat: patrimonial for biodiversity as locally native in one of the EU territory; Trad: traditional use: beverage, sugar…
Host and susceptibility status: H: host in originating area; H+: susceptible host with major economic impact; H-: host with low mortality as compared to abundance and evidence for resistance; H?: host but with insufficient/conflicting data to establish degree of susceptibility; NH: non-host: no field infestation and all experiments with no development; NH?: likely non-host: no infestation in the field, experimental development possible but no evidence for complete cycle; PH: potential host (development possible under laboratory condition with no reliable field data)
Abundance in Mediterranean area and EU: 0 absent (extremely rare specimens essentially in greenhouses); +++ (group 1 in text) Very abundant and widely distributed; ++ (group 2 in text) locally abundant as avenue or park trees but much less than in group 1); r (group 3) rare and scattered in parks and gardens as compared to group 2.
Infestation: Conditions and degree
The number refers to the reference in the reference list below. ? X indicates citation from reference X without detail and not verified.
Infestation amplitude and evidence for complete cycle are given as follows: (-) no report of infestation from survey or trial; min weak larval development as compared to number of documented cases/replicates; (+) larval development and some dead palms due to it; (+++) very high mortality due to positive development; C+ vs. C? adults obtained versus no evidence for complete cycle.
References: 1. Wattanapongsiri 1966; 2. Rahalkar, Harwalkar, and Rananavare 1972; 3. Liao and Chen 1997; 4. Barranco *et al*. 2000; 5. Farazmand 2002; 6. Faleiro 2006; 7. Kontodimas *et al*. 2005-2006; 8. Malumphy and Moran 2007; 9. Dembilio, Jacas, and Llácer 2009; 10. Ju *et al*. 2009; 11. Nardi *et al*. 2011; 12. Cobos Suárez 2010; 13. Pete 2010; 14. El-Mergawy and Al-Ajlan 2011; 15. Dembilio *et al*. 2011; 16. Longo *et al*. 2011; 17. Fiaboe *et al*. 2012; 18. Giovino *et al*. 2012; 19. Abbas and El Sebay 2013; 20. Raciti *et al*. 2013; 21. Uribarrena 2013; 22. Llácer, Negre, and Jacas 2012; 23. Rochat 2014, personal observation, Antibes city, France; 24. Wang *et al*. 2015; 25. Suma 2014, personal observation. Sicily, Italy; PP: Palm Protect data, to be published.

injury has been made to the palm, frequently by rhinoceros beetles or rodents (Lepesme 1947; Nirula 1956; Faleiro 2006) and possibly by birds and after PBM attack in Europe (Palm Protect, unpublished; Longo *et al*. 2011).

Under conditions where a suitable host plant is available females lay eggs individually into tissues accessible to their ovipositor, which cannot perforate hard tissues (Lepesme 1947; Nirula 1956; Salem *et al*. 2012; Abbas and El-Sebay 2013). They drill a hole using the rostrum then insert the ovipositor in the prepared hole (Ince, Porcelli, and Al-Jboory 2011). RPW can lay eggs deeper in the plant tissues after tunneling, thanks to an adapted tapered body shape. The death due to RPW of palms species that could not or hardly be infested under artificial conditions by females strongly suggests that natural infestation was made possible only due to wounds or galleries in the soft tissues that became exceptionally accessible to the female. Dissection showed that eggs are generally laid at the base of the living fronds, including these of small offshoots. As shown by field dissection and breeding on various substrates, larvae are present essentially in the softest and most irrigated living tissues (growth areas) with a low to moderate proportion of fibers (see Section 4.4.1). Owing to the specific morphology of the palms, direct or indirect (microbial massive attack on damaged tissues) destruction of the apical bud will lead to the death of the plant (see Chapter 1, this volume), which makes all large palm borers very harmful insects.

There are regular reports of infestation at the base of the palm where aerial roots can develop abundantly in date palms and in *Washingtonia* spp., which can create cavities in the stem (Avand-Faghih 2004, Longo *et al*. 2011, Uribarrena 2013). Similar cavities have been observed at the base of the crown in date palms. The cavities weaken the palm, which can break and die (see Chapter 9, this volume). To date there are no experimental reports which demonstrate preferential attraction to a palm species and scarce data about differential egg-laying success correlated to a palm species under choice controlled conditions (Rochat *et al.*, unpublished).

4.3.2 Critical Review of the Host Plants

The RPW hosts belong essentially to the sub-families Arecoideae and Coryphoideae. The palm taxa and classification used here (Table 4.1) follow the botanical reviews by APG (2009), Palmweb (2014), and eMonocots (2013), and genomic data from the NCBI (2014). Several species earlier mentioned as different RPW hosts have been synonymized.

4.3.2.1 Damage and Susceptibility: Quantitative Ranking is Very Difficult

For plant protection the status of non-, actual, or potential host plants for a pest is useful but insufficient to optimal risk evaluation and management. Determining the susceptibility of the host plants is necessary for better risk evaluation and to advise the choice of species or varieties. However, with the exception of the major cultivated and planted species (e.g. coconut = *Cocos nucifera*, date palm = *P. dactylifera*, and Canary Islands date palm = *P. canariensis*) the numbers of palms present in a given area are not but exceptionally reported. Reports typically indicate how many palms of the various species have died but rarely from how many available to the pest (e.g. Cobos Suárez 2010; Raciti *et al*. 2013; Uribarrena 2013). Longo *et al*. (2011) and Longo, Suma, and La Pergola (2011) provided quantitative information about the numbers of RPW found in ten palm species naturally infested in Sicily. This gave an indication for the potential for RPW multiplication. But for eight species the values came from a single plant. Such snapshots do not enable estimates of the actual susceptibility of these species. Our analysis will therefore be mostly based on qualitative estimates linking survey information to experimental data.

4.3.2.2 Relative Abundance and Diversity of Palm Species in the Mediterranean and the EU

With the limits stressed above but based on consistently cross-supported data from published (e.g. Longo *et al*. 2011, b; Pete 2010, Raciti *et al*. 2013) and gray information provided by palm amateurs' societies, garden keepers, and Plant Protection officers, palms species in the Mediterranean Basin and the EU (the study area, further abridged in StA) can be classified into three main groups based on their abundance and frequency in the landscapes, with a distinction between the North-Western and the South-Eastern parts of the StA, split by a line from Alicante in Spain to the Turkish – Syrian border for commodity. Each sub-region will be further referred to as NW StA and SE StA, respectively. These groups basically determine the priorities for plant protection management. These are the following ones:

Group 1: Species Highly Abundant and Widespread *P. dactylifera*, assumed to be native from the Middle East and that dominates in the SE StA, especially with the existence of orchards for date fruit production, was introduced several centuries ago and cultivated (Peyron 2000; Palmweb 2014). It is much less abundant in the NW StA due to incompatible climate with only small historical protected orchards in southeast Spain and scattered ornamental palms elsewhere in the mildest places (e.g. Sicily). *P. canariensis*, endemic of the Canary Islands, was introduced in the mid-19th century because of its remarkable ornamental value, then massively bred and planted on the Mediterranean and worldwide. This species strongly dominates urban landscapes in most of the NW StA and has also been very much planted in the newly built urban areas of the whole StA for the latest 30 years. With a much more modest size and often a shrub aspect *Chamaerops humilis*, the only common native European palm (with *Phoenix theophrasti*; see Section 4 Group 3) is likely as abundant and widespread as the aforementioned *Phoenix* sp. as it naturally occupies western Mediterranean forests and scrubs and has been planted for ornamental purposes.

Group 2: Species Widespread, Locally Abundant (thousands) but Much Less than in Group 1 *Washingtonia filifera* and *Washingtonia robusta*, and possibly the hybrid (*Washingtonia filibusta*), are quite common as avenue trees in the whole Mediterranean, where they have been regularly planted during the 20th century. The two species are often not distinguished or possibly confounded. It is therefore impossible to reliably grant certain reports to one or the other species (see Section 4.3.2.5). *T. fortunei*, a species from Chinese forests, has long been acclimatized to the NW StA, where it has become sub-spontaneous in some places and is still regularly planted. Because of its robustness and adaptation to temperate climate, it has been planted in northern European places with an Atlantic climate (e.g. Scotland, Logan Botanic Garden).

Group 3: Rare species as Compared to those in the Previous Categories and Scattered in the Environment With the exception of *P. theophrasti*, which is endemic to Crete and neighboring lands, these palms are introduced ornamental species, typically concentrated in public historical or botanical gardens, or private parks. Many of them are old patrimonial plants. Such species grow in similar gardens located far from the Mediterranean in the EU (e.g. in Brittany, Roscoff island). All these specimens account for less than 1% of total palms but are highly diverse with more than 100 taxa. Among the many species, the most frequent ones are: *Brahea* spp., *Butia* spp., *Howea forsteriana*, *Jubaea chilensis*, *Livistona* spp., *Phoenix* spp., *Sabal* spp., *Syagrus romanzzofiana*, and *Trithrinax campestris*.

4.3.2.3 Host Palms with Obvious Susceptibility

Areca catechu, *Arenga pinnata*, *Borassus flabellifer*, *Caryota cumingii*, *Caryota maxima*, *C. nucifera*, *Corypha utan*, *Corypha umbraculifera*, *Elaeis guineensis*, *Livistona chinensis*, *Livistona saribus*, *Metroxylon sagu*, *Nypa fruticans*, *Oncosperma horridum*, *Oncosperma tigillarium*, and *Roystonea regia* are RPW original hosts (see references in Table 4.1). All of them grow in tropical moist forests. None of them can grow outdoors in the StA. Rare specimens may be found in greenhouses. In addition, *P. sylvestris* and *P. dactylifera*, adapted to drier climates and common in northwestern India are RPW hosts. RPW has long been reported as a severe pest of coconut and date palm and to a much lesser extent of African oil palm and other palm species with traditional use such as sago palm (Wattanapongsiri 1966; Faleiro 2006; El-Mergawy and Al-Ajlan 2011; Jacquemard 2013).

P. canariensis and *P. dactylifera* are highly susceptible hosts in the invasion area: from 1985, date palm confirmed host status and proved high susceptibility toward RPW (Faleiro 2006). *P. canariensis* appeared by far the most severely infested and killed palm species by RPW in the StA with more than 100,000 specimens killed during the last 25 years (Palm Protect review of many sources). In the NW StA, where *P. dactylifera* is rare, 90 to > 99% of the palms killed by RPW are *P. canariensis* (Raciti *et al*. 2013). *P. dactylifera* appears less susceptible than *P. canariensis* based on the replicated observations of a much higher mortality in *P. canariensis* than in *P. dactylifera* where both *Phoenix* spp. are present in similar proportions. Among the 2700 *P. canariensis* palms present in the city of Valencia in the period 2006–2012, 16% were infested by RPW, whereas only 0.8% of the 6000 neighboring date palms had been attacked (Uribarrena 2013). Though the relative abundance of *P. dactylifera* and *P. canariensis* in Spain is not reported, Cobos Suárez (2010) indicated that 85.4% of the 49,800 palms destroyed because of RPW in Spain up to 2009 were *P. canariensis*, 14.3% *P. dactylifera*, and only 0.3% palms of other species.

4.3.2.4 Date Palm and Canary Islands Date Palm: Differences of Susceptibility within Varieties, Sexes, and Hybrids

Varieties and Hybrids There are several reports about differential susceptibility of the many varieties of date palm particularly abundant in the Middle East (e.g. Rochat 2006; Salama, Zaki, and Abdel-Razek 2009). In eastern Iran, for instance, much higher infestation in Mazafati variety was correlated to its abundance, its prevalent use for clonal multiplication via the offshoots, and a much higher proportion of young palms, which produced much more shoots than the other varieties and older specimens, less attacked by RPW. These many factors likely acted together. The basis of these differential infestations has not yet been supported by convincing correlations to simple characters, either morphological or physiological, or with sets of genes. In Saudi Arabia, Faleiro *et al.* (2014) compared the attraction of females to the odors from freshly cut petioles of seven date palm varieties, the number of eggs laid, and hatching rate on the same tissues, and the tunneling and development for one week of second or third instar larvae introduced in the frond base of 3-year-old potted palms. One variety (Khalas) attracted more females than the other six ones in a choice situation. In turn similar egg-laying, hatching, and tunneling of the larvae were recorded for all varieties. Higher RPW damage on Khalas could thus be rather correlated to higher attraction than to antibiotic factors at contact. Future investigation should focus on markers that target RPW egg-laying behavior or the feeding and the digestive physiology of the larva. Analogous possibilities have been investigated in *P. canariensis*, for which there are reports of hybrid specimens with date palms that would be less susceptible than *P. canariensis* considering that palms which had survived under severe RPW attack showed hybrid rather pure *P. canariensis* type (Raciti *et al*. 2013).

Male and Female Plants There are reports of more male than female palms infested in both *P. canariensis* and *P. dactylifera* by RPW in Italy and Spain, suggesting either a preferential attraction or a higher susceptibility (e.g. Uribarrena 2013). It has been suggested that the male flower would attract RPW. Components of the flower fragrance have been identified such as (*E*)-*β*-caryophyllene. The latter proved to be detected by RPW antenna and showed some field activity (Ortiz *et al*. 2012), which was not confirmed. Morphophysical factors could also explain the higher infestation and sensitivity of male palms: males miss the voluminous fibrous female inflorescence primordia in the crown, and therefore provide a larger volume of tissues optimal to egg-laying and larval development. Alternately, the male palms could offer a moister microclimate in the crown and more hiding places made by the litter created by the dead material fallen from the male inflorescences that accumulates at the base of the fronds and the many dead male inflorescences themselves that remain long in situ. In comparison, the female palms have a crown more aerated, thus less favorable to RPW.

4.3.2.5 Less Susceptible Host Palms with Obvious Resistance

These are *C. humilis*, *T. fortunei* (Chusan or windmill palm), *W. robusta*, and *W. filifera* that are common in the EU. The Aegean endemic *P. theophrasti*, which is locally abundant but growing in a limited area, belongs to this category. There are reports of infested and dead palms of all five species due to RPW. They are nevertheless very few as compared to the estimated abundance of these palms, particularly of *C. humilis*, *T. fortunei*, and likely *P. theophrasti* (Table 4.1 and references therein).

Under either free or forced infestation assays *C. humilis* showed very low larval development, infestation could rarely start from females, and the cycle could be completed both in Spain and Italy (Barranco *et al*. 2000; Dembilio, Jacas, and Llácer, 2009; Lo Bue *et al.*, personal observations). Time necessary to complete development is much longer than in *P. canariensis*, and less pupation is observed from the same number of females or larvae. Similar results have been reported with *T. fortunei*, where low infestation by females could be obtained on 2-year-old specimens in cages (Llácer, Negre, and Jacas 2012). The situation is different and possibly controversial with *Washingtonia* spp. because replicated trials on *W. robusta* led to no infestation either with free egg-laying or artificial infestation (Barranco *et al*. 2000, Palm Protect unpublished) or to a low rate of infestation by females (Llácer, Negre, and Jacas 2012). In *W. filifera* three trials led to no infestation both from females or larvae introduced in living palms (Dembilio, Jacas, and Llácer 2009; Llácer, Negre, and Jacas 2012) but complete development was achieved using the palm tissues as food in the laboratory (Ju *et al*. 2011). Dead palms containing all RPW developmental stages have also been reported in Sicily under natural conditions, which support the host status of both *Washingtonia* spp. (Longo *et al*. 2011; Raciti *et al*. 2013; Colazza and Soroker, personal observation). Further attention must be paid to the unambiguous determination of the damaged *Washingtonia* spp. because in many cases the species is undetermined and the relative susceptibility of the two species cannot be documented.

P. theophrasti is a susceptible species with resistance mechanisms, which likely reduce egg-laying and larval growth, based on field infestation reports in Crete in 2013 and 2014; Karamaouna, personal communication) and several experiments. Two-year-old seedlings exposed to 6 ♀ and 6 ♂ per palm for 100 days led to larval development and adult emergence, but both the infestation rate (33%) and the number of adults obtained were low and adult size was small (Kontodimas *et al*. 2005/2006), as with forced infestation by neonate larvae (Dembilio *et al*. 2011). Semi-field experiments in 2013 and 2014 by Palm Protect consortium under three pressures (3, 6, and 12 ♀/palm) confirmed none to moderate infestation of 4-year-old *P. theophrasti* after 9 days' exposure with a much slower development than in *P. canariensis* followed in the same conditions (Karamaouna *et al.* in preparation). No adult was obtained from *P. theophrasti* when many adults emerged from *P. canariensis*. Therefore, the threat to this patrimonial species is low to moderate and the slowness of development should give much better opportunity for detection and efficient control than with *P. canariensis*.

Experiments and field observations showed that *C. humilis* and *Washingtonia* spp. produce a gummy secretion at the holes drilled artificially or at the level of injury under natural situation (Barranco *et al*. 2000; Dembilio, Jacas, and Llácer 2009; Giovino *et al*. 2012). Gummy secretion was observed in both naturally and forced-infested *P. theophrasti*, indicating the existence of antibiosis in this species too (Dembilio *et al*. 2011). The secretion is thought to be detrimental to the larva either by toxicity or physical action (drowning or sticking). A mechanical and physical resistance is more likely than toxicity regarding the unsuccessful infestation trials with females and the successful development on cut tissues of *W. robusta* similar to *P. canariensis* (Ju *et al*. 2011). Natural death of *Washingtonia* spp. due to RPW suggests that the palms were injured enough to make possible successful egg-laying and further development. Alternately, resistance may decrease with aging because dead *Washingtonia* palms reported from the field are tall specimens of more than 10 years while experiments have been conducted on much younger plants.

4.3.2.6 Susceptible Host Palms with Insufficient Information

Brahea armata, *Brahea edulis*, *Butia capitata*, *Copernicia alba*, *H. forsteriana*, *J. chilensis*, *Sabal* spp. (including *S. palmetto*), and *S. romanzzofiana*: natural infestation with dead specimens due to RPW has been reported for all species (Longo *et al.* 2011). In spite of an earlier evaluation that showed negative larval development under forced infestation (young larvae placed into the stem), RPW could complete development on tissue of *B. armata* in the laboratory. Several specimens were killed in Italy and showed a possible intense multiplication of RPW as in *B. edulis* (666 individuals in one palm; Longo *et al.* 2011 where the report for *B. armata* is erroneous). The species seem suitable to RPW development at least under certain conditions, possibly after injury. Similarly specimens of *Sabal* spp. (*S. palmetto* reported) died due to RPW in Italy. No experimental data are available for the later species. With the remaining palm species, there are records of some dead specimens mostly in Italy (Longo *et al.* 2011) but also France (*J. chilensis*: Ducatillion, personal communication) with more or less brood found in the dissected palms. The degree of susceptibility cannot be established because of insufficient information, especially the absence of experimental data.

4.3.2.7 Other potential hosts

Palm Larvae developed in two out of three *Livistona decora* artificially infested (Barranco *et al*. 2000). Pupation and adult emergence was not documented. *Bismarckia nobilis* was reported to show larval infestation on seedlings in Taiwan in nurseries (Liao and Chen 1997) or as a source of adult for genetic study in China (Wang *et al*. 2015). *Phoenix roebelenii* was exceptionally infested under strong female pressure in a confined assay and naturally in Israel (Suma and Soroker, personal observation) and also reported as a source of adult in China (Wang *et al*. 2015).

Non-palm RPW larvae can be bred from banana fruit (e.g. Salama and Abdel-Razek 2002) without any report in the banana plant under natural conditions. The century plant, *A. americana* (Malumphy and Moran 2007), and sugarcane (Rahalkar, Harwalkar, and Rananavare 1972) have been reported as host plants. We could not find a reference about the outdoor presence of RPW on the century plant (Agavaceae), common in the Mediterranean. Longo *et al*. (2011) failed to breed RPW on this plant.

RPW can be easily bred on sugarcane (Poaceae) in the laboratory (e.g. Rahalkar, Harwalkar, and Rananavare 1972; Salama and Abdel-Razek 2002; Rochat and Soroker, unpublished). At the same time, RPW has no pest status on sugarcane in its native area. In Egypt, more than 40,000 ha are planted with sugarcane within 3 million date palms seriously infested by RPW. To date sugarcane is free of RPW infestation (Abbas, unpublished information). The situation reported in Australia (El-Mergawy and Al-Ajlan 2011) is confusing as *R. bilineatus* is likely the *Rhynchophorus* sp. reported there (Rugman-Jones *et al*. 2013) and citations rather refer to a threat than to a pest. The experiments by Abbas and El-Sebay (2013) support that RPW does not lay eggs on standing living sugarcane stems. Females cannot drill the cortical tissues of the stalk. In conclusion, *A. americana* and sugarcane should only be quoted as “potential host plants” for RPW.

4.3.2.8 Potential Non-host Palm Species

There are no infestation reports under natural conditions for *Archontophoenix alexandrae*, *Nannorrhops ritchiana*, and *Phoenix rupicola*. Larvae did not develop to pupation under laboratory conditions on stem tissues of *N. ritchiana* (Farazmand 2002). Palms of the other two species confined with a high density of females were not infested under semi-field conditions (Suma and La Pergola, personal communication).

4.4 Life Cycle and Adaptation to the Temperate and Desert Areas

4.4.1 Main Traits of the Life Cycle

All the stages of RPW live on palms, and more specifically in palm tissues. Dissection reveals adults in the space between the fronds, often occupied by a fibrous sheath or organic matter, and in the galleries they have burrowed in the frond bases and the stem, or those made earlier by larvae or other animals. As soon as adults have landed on the palm trees they penetrate cavities and become invisible.

Quantitative data about adult fecundity, egg-hatching, and longevity are plethoric and show considerable variations (e.g. references in Martín and Cabello 2005; Dembilio and Jacas 2011). The great majority of studies that include observation from wild pupae provide the conclusions listed in Table 4.2: adults can live over 3 months between 25 to 30 °C (Soroker and Rochat, unpublished data). Males live longer than females (e.g. Longo *et al.* 2009; Llácer, Santiago-Álvarez, and Jacas 2013) and life is shortened at higher temperatures. The extrapolation to a natural situation is not easy. Nevertheless, longevity of RPW under natural Mediterranean conditions should be reasonably estimated by means of 45 and 60 days for females and males, respectively, with a variability of 15 to 25% of the mean (standard deviation; Gaussian distribution).

Individuals mate many times during their life. Eggs are laid during almost all the life. Llácer, Santiago-Álvarez, and Jacas (2013) determined in adults from infested *P. canariensis* that oviposition steadily increased during the first two weeks of life until reaching a roughly constant rate of about 9–10 eggs/♀/day, much higher than that in earlier studies using laboratory-reared insects (2.5 eggs/♀/day; Dembilio *et al.* 2012). The high nutritional value of *P. canariensis* relative to that of semi-synthetic diets (Dembilio and Jacas 2011) could explain the difference. Again, one should be careful when extrapolating laboratory results to field conditions. Fecundity is high: the most frequent values range from 100 to 250 eggs per female. Mortality from the egg or neonate larva to the adult is high in the field: about 50% in the warmest months (mean: 31 °C) and greater than 80% in the coldest up to 100% (mean: 9 °C) (Dembilio and Jacas 2011).

From the eggs inserted in the tissues, larvae tunnel galleries in the inner living softer and juicy tissues of the palm when they are available. They are not xylophagous. The larval development comprises a minimum of 9 instars. Dembilio and Jacas (2011) determined a development with 13 instars in tall Canary Island date palms under natural conditions from precise measuring of the head capsules. The larval period can last from 1 to 10 months according to the temperature (see Section 4.4.5 and Fig. 4.3). Several hundredths of larvae can be found in large *P. canariensis* (Longo *et al.* 2011). In such cases, larvae have altered a large volume of tissues and created a cavity in the stem.

Fully grown larvae migrate at the periphery of the palms to build a solid elongated keg-shaped cocoon (up to 7×4 cm) made exclusively of palm fibers sophisticatedly rolled up. The cocoons are essentially located at the base or in the rachis of the fronds. They can be found below ground level when infestation occurs at the base of date palms or more internally in the stem in the case of severe infestation. Pupation takes place in the cocoon. The stage lasts two to three weeks at 27–28 °C. Intense dehydration hardens the cocoon, which becomes deadly for the reason that the adult cannot drill the fiber wall (Rochat, personal observation)

Table 4.2 Red palm weevil (RPW) thermal thresholds for adult activity and longevity.

			Thresholds (°C)		
Adult traits of life			**Lower**	**Optimum**	**Upper**
Feeding			11–12[6]	?[a)]	42–44[2, 6, b)]
Mobility	Walk		15–16[6]	36–40[6]	45[6]
	Flight	Body	18.5[6, b)]	30–34[6, c)]	38[6, b)]
		Air	8[3, 5, 7, b)]		
Reproduction	Mating		15[4, 6]	27–35[a)]	36–40[1]
	Egg-laying		15.5[4, 6]		
	Fecundity		15.4[1, 2]	28[1]	
Longevity (days)[d)]	Captivity		60–90 (mean with mating at 27–28 °C)		
	Nature		45 ± 15–25% (female mean ± sd[e)])		

a) Literature data show a very large variability due to many different conditions mostly under highly artificial environment (Cf. references in Martín and Cabello 2005 and Dembilio and Jacas 2011). Optimum range is provided based on literature compilation and in agreement with motion and development optima.
b) Flight has been observed during sunny winter days with mean air temperature below 10 °C (e.g. source 3 and 5 in France and Spain). Under experimental monitored conditions, spontaneous flight occurred at 18.5 °C and 42 °C extremes but more than 95% observations ($n = 132$) occurred between 27 and 38 °C (source 6) in agreement with literature compilation about pheromone trap captures.
c) Determined from measurements of vision physiology (Belušič *et al.*, personal communication).
d) As for reproduction, reported longevity shows large variability and outrun several months for RPW kept in captivity. We report consensus values for females and males respectively. For the natural situation, the values proposed are a reasonable estimate for females submitted to predation, climatic, and pathogenic pressure.
e) Standard deviation expressed as a percentage of the mean and estimated from literature review.

Sources: 1. Li *et al.* 2010; 2. Abbas 2005; 3. FREDON Corse 2008; 4. Dembilio *et al.* 2012; 5. Rochat unpublished (2011–12), 6. Hamidi *et al.* (in preparation); and 7. Longo, Suma, and La Pergola 2011.

4.4.2 Development Thermal Parameters

All stages of RPW can be found over the year under monsoon tropical climate in the Indian zone (Faleiro 2006). MYT is there around 27 °C (e.g. city of Goa). The yearly amplitude is less than 5 °C and monthly minima remain close to 20 °C. In Middle East and the Mediterranean yearly thermal amplitude generally reaches 15 °C or more with monthly minima, which can drop to 5 °C, and mean monthly temperatures mostly ranged between 10 and 15 °C during winter. The establishment of RPW in the Mediterranean has shown that winter is not an obstacle for completing development.

Though RPW had been reared under various temperature and substrate conditions for a long while (reviews in Martín and Cabello 2005; Dembilio and Jacas 2011) quantitative relationships between development rate and temperature, and thermal thresholds were

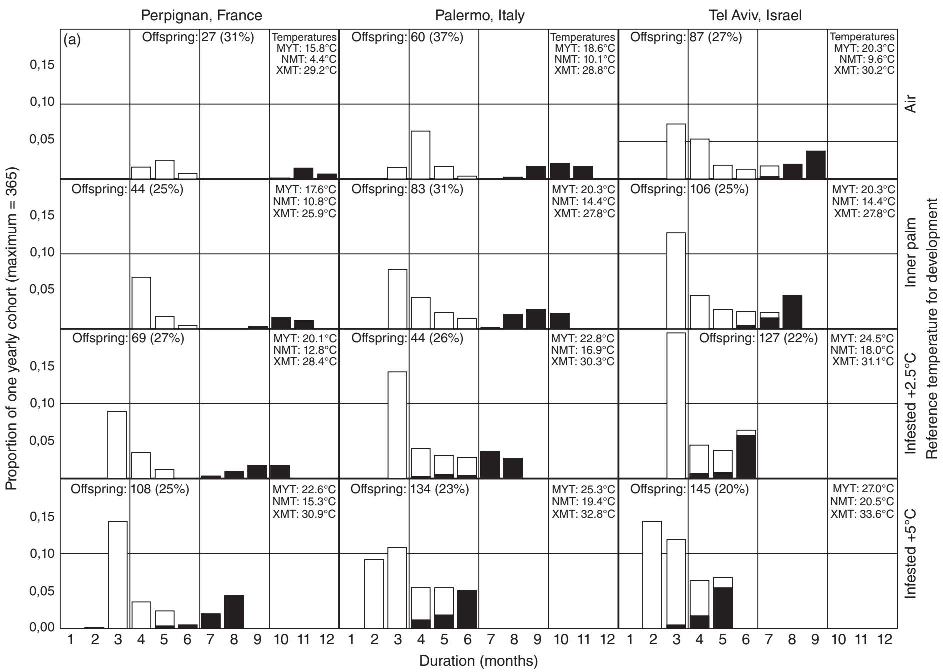

Figure 4.3 (Continued)

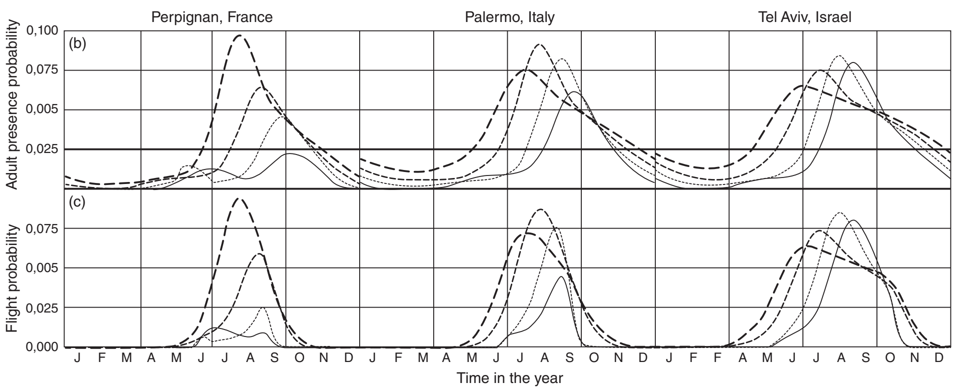

Figure 4.3 (Continued) Simulations of RPW development and adult availability based on the life parameters and standard climatic data. A. Times of development. B. Adult presence probability. C. Flight probability in three cities of the Mediterranean Basin: Perpignan, Palermo, and Tel Aviv with increasing mean yearly temperature (MYT) and decreasing winter stringency (NMT and XMT: Minimum and maximum mean monthly temperatures) under four realistic thermal scenarios of exposure: mean air temperature (thin solid lines in B and C), inner palm temperature (thin dotted lines), and RPW infestation: low to moderate (medium dotted line) and moderate to high (thick dotted line). A. Offspring: number of expected adults in 1 year based on 1 egg laid per day when the temperature is above egg-laying threshold. In brackets, the percentage that emerge the year after egg-laying (grayed bars). Parameters for simulation taken from the references in Tables 4.2 and 4.3. Mortality is based on Dembilio and Jacas (2011). Flight optimum from Hamidi *et al*. (in preparation). Flight was estimated based on 75% contribution of maximum daily temperatures and 25% by adults warmed in palm when internal palm temperature was greater than the air maximum temperature. B. and C. Curves for females based on estimates as reported in Section 4.4.4. Simulations are based on public data from Meteo France, with daily temperature values.

evaluated only from 2002 by Salama, Hamdy, and El-Din in the laboratory. This work was completed and refined by Martín and Cabello (2005) then Dembilio and Jacas (2011 and 2012).

Martín and Cabello (2005) determined development and lower lethal thresholds for most stages from a Spanish strain reared at constant temperatures on an artificial medium. The values were corroborated by some outdoor breeding in potted palms with concomitant temperature measurements (Table 4.3). Dembilio and Jacas (2011) determined the development parameters from living 7-year-old *P. canariensis* (stem: h 75 × Ø 50 cm) set outdoors in Spain after replicated artificial infestation with neonate larvae during one complete year. The latter study provided refined values for a development under natural conditions in the most commonly infested palm in the Mediterranean (Table 4.2). RPW were subjected to the plant nutritional and microbial environment and to natural thermal variation. The development parameters determined in these conditions are therefore likely much more relevant than the former ones (Terblanche *et al*. 2007) as cold stress and daily thermal fluctuation have an important impact on the insect development, which cannot be properly evaluated under constant temperature (Renault *et al*. 2004; Danks 2006; Lalouette *et al*. 2007).

The mean thermal constant established by Dembilio and Jacas (2011) for complete development was 989.5 degree days (DD) distributed into 40.5 DD (egg) plus 666.5 DD (larva) plus 282.5 DD (pupa). This work did not provide values of the corresponding variability but stressed that it was considerable. We estimate standard deviation between 25 and 33% of the mean value for the whole development. Such an amount of heat can, or cannot, be accumulated and enables a complete development cycle within the same year depending on the time the eggs are laid and on the local climate. In general, with egg-laying in spring or early summer, the adults emerge the same year. In turn, eggs laid in late summer and fall will give adults only the next year (illustrated in Fig. 4.3A from simulation). It is common to find all the developmental stages within a palm tree. Although it can correspond to eggs laid at different periods, the large variability of the development time and the impact of the cold season can also generate the mixture of various developmental stages. This trait should be adaptive and efficiently contribute to acclimatization under temperate climate.

The thermal development thresholds determined for egg, larva, and pupa are 13.1, 15, and 13 °C respectively (Martín and Cabello 2005; Dembilio and Jacas 2011). Lower lethal temperatures have been established to be 10 and 10.3 °C for the egg and the neonate larva respectively. The lower lethal thresholds confirmed to decrease with the advance of development: 4.5 °C for the latter larval stages. Hamidi *et al.* (in preparation) recently confirmed the range 3–5 °C for both pupa and adult with almost 100% mortality after 2 weeks at both 5 and 2 °C. Earlier negative data were erroneous.

Upper development thresholds and lethal temperatures have been only roughly determined. The breeding reported in the literature showed a dramatic increase in mortality of immature stages between 30 and 35 °C as compared to 25–28 °C (e.g. Martín and Cabello 2005). Higher lethal temperature would therefore be between 35 and 40 °C, the latter is lethal to the eggs and obviously out of the optimum for all stages (Abbas 2005; Abbas *et al.* in preparation; Rochat unpublished).

Direct air exposure for more than 2 days at 27 °C and 75% relative humidity (RH) of the egg and the first larval instars (young L1-4, length up to 1 cm,) is lethal (Rochat, unpublished). In turn set in paper towels saturated with water under the same climate, the eggs survive up to hatching and the larvae up to one week.

Table 4.3 Left: red palm weevil thermal thresholds for development. Right: examples of development times according to yearly mean temperatures.

Development stages		Development thresholds (°C)		Lethal temperatures (°C)		Thermal constant (DD)	Yearly mean temperature (°C) [a)]	No. cycles per year [a)]	Cycle duration (days) [a)]
		Lower	Upper	Lower	Upper				
Egg	Hatching	14[6]	?	?	?	40.5 ± 2.0[5]	< 15[*]	< 1[*]	—
		13.0[5]	35–39[3,4]	10[5]	< 40[1,3]		> 19[*]	> 2[*]	—
Larva	L1	15[4]	35–40[4]	10.5[5]	40[4]	666.5[5]	20	2.0	180
	Oldest		38[4]	4.5[5]	40[4]		25	3.9	94
Pupa		13[4]	40[4]	3–5[3,4,7]	44–45[2]	282.5[5]	30	5.7	64
Adult		—	—	3–5[3,4,7]	40[2]	—	35	7.6	48
All		—	—	—	—	989.5 ± 25–33%[3,5,b)]	38	8.7	42

Regarding the high variability of the development parameters reported by the various authors, original values (°C or DD: degree day) reported by the authors have been rounded to 0.5.

— Irrelevant

a) Standard deviation expressed as a percentage of the mean from data by the authors source 5.

b) The values with * are from source 5. below based on an average development threshold of 14 °C for all stages. The other values are calculated with the respective values for egg, larva, and pupa by the same authors (on the left) for selected constant MYTs.

Sources: 1. El-Ezaby 1997; 2. Salama and Abdel-Razek 2002; 3. Abbas 2005; 4. Martín and Cabello 2005; 5. Dembilio and Jacas 2011; 6. Dembilio *et al*. 2012; and 7. Hamidi *et al.* (in preparation).

4.4.3 Estimating the Buffer Effect of Living in Palm Tissue

The main limitation with the application of thermal development parameters is to know the amount of heat actually received by RPW present in a host palm. Two basic situations exist: healthy palms and RPW-infested palms. In healthy palms there were few measurements of the temperature in the inner palm tissues, essentially from small specimens. Living tissues of palms, particularly where RPW larvae develop, are characterized by very high water content as compared to the wood or bark of Dicot trees (see Chapter 2, this volume). Such tissues need more heat than dryer tissues, such as wood, to warm and reciprocally, keep heat longer when air temperature decreases. This situation can be compared to the seasonal cooling and heating of large bodies of water.

4.4.3.1 Healthy Palms

Conflicting information has been reported about the difference of temperature in and out the palm together with imprecise description of the protocols of recording. Abe, Hata, and Sone (2009) reported that in healthy palms the inner temperature essentially followed the air temperature with about 1 °C more in the palm at an unreported depth. Mozib El-Faki and El-Shafie (2013) indicated very similar temperatures inside and outside the palms (Saudi Arabia; mean daily temperature between 23 and 33 °C). Salama, Zaki, and Abdel-Razek (2009) indicated that the mean temperature was generally 2 to 4 °C lower in the stem (at 30 cm depth) compared with the air temperature in any given season. A minimum 12 °C and maximum 33 °C were found inside the palm, when the outside temperature was 16 °C and 40 °C respectively.

To clarify the situation, Hamidi *et al.* (in preparation) recorded simultaneously the temperature in the palm and of the air in the crown from four patrimonial Canary Island date palms (stem height from 4 to 9 m, in Perpignan, France) using precision recorders. One probe was inserted at 25 ± 3 cm into the living tissue perpendicular to the stem axis at the basal part of crown and 15 ± 2 cm into the more peripheral tissues of a frond cut for recording. The aerial one was hung from a nearby frond. Values were recorded in each situation every 15 min continuously for 1 year, successively (2012–2014).

The buffer effect of the tissues is extremely important: while the daily amplitudes were mostly of around 15 °C over one year, they were around 0.5 °C in the living tissue and reached 1 °C in the more external dryer parts. Regressions on daily mean values showed the inner temperature to remarkably follow the air temperature with significant correlation with the values of the preceding decade ($0.95 < r^2 < 0.98$; ± 1.8 °C, 95% confidence interval of the inner daily prediction; Hamidi *et al.* in preparation). Changes in the air older than 10 days did not modify the inner temperature. Thus the temperature in the palm changed with a 10-day lag with respect to the thermal evolution in the air. Seasonal variation within the palm tissue can therefore be predicted with good precision. On an average over one year, the temperature was 2.0 °C higher in the living tissue than in the air versus only 0.5 °C in the tissues from the cut fronds, for maximal daily inside/outside differences that ranged from +4 °C to −2 °C (air daily extremes: −4 °C and 50 °C; mean monthly extremes: 4 °C and 37 °C; Hamidi *et al.* in preparation). Thus, the inner palm was warmer than air in fall and early winter. Conversely, the temperature inside the palm, which had reached its lowest temperature during the preceding winter, could be lower than or the same when the air began to warm in springtime. Episodes of important cooling or warming opposite to the seasonal evolution were transmitted into the palm with the aforementioned lag. The current results explain why snapshot measures without seasonal series and precision about the conditions of probing led to apparently conflicting results. The laws of physics suggest a higher buffer effect and possibly longer lag with respect to external variation in deeper tissues, which were not studied. These new correlation data enable a reliable quantitative estimate of the impact of living in the palm as compared to living outside, exposed to air temperatures.

4.4.3.2 Infested Palms

Infestation can range from some tiny larvae to a great many larvae, which have created a huge cavity (>1 m^3) filled with moist crunched fermenting palm tissues. These cavities are heat generators with hotter temperatures than adjacent healthy tissues and by far more than in open air, particularly in winter (up to 30 °C; Esteban-Duran *et al.* 1998; Abe *et al.* 2010). Abe *et al.* (2010) established that in oxidized actively fermenting material the most frequent temperature was 33–35 °C (26 out of 31 measures with 13–28 °C outdoors). A few measures reported values of up to 40 °C. In chewed, non-oxidized tissues close to unaltered palm tissue the temperature was 28 °C.

There is consensus about a higher temperature in the healthy tissues of infested palms as compared to tissues of RPW-free palms (Martín and Cabello 2005; Salama, Zaki, and Abdel-Razek 2009; Abe *et al.* 2010; Mozib El-Faki and El-Shafie 2013; Abbas *et al.* in preparation). Higher temperatures of palms and other plants under stress are a general phenomenon and monitoring the temperature of the palm fronds has been evaluated for early detecting RPW infestation (see Chapters 2 and 10, this volume). The amplitude of increase reported by the authors varies from 1 to 5 °C, depending on the study and the season. It could not be correlated to specific factors, such as the degree of damage. However, the studies by Mozib El-Faki and El-Shafie (2013) in date palms and Martín and Cabello (2005) in *P. canariensis*, where 1–20 larvae were inserted into the palms, suggest that the thermal difference can occur from a limited number of larvae/damage. As an illustration, the temperature at a depth of about 20 cm in the healthy stem tissue of naturally infested date palms (unknown number of larvae) was from 2 to 4.5 °C on an average above the temperature of control healthy palms depending on the season, based on replicated periodic measures realized over 2 complete years (2012–2014) in Egypt (Abbas *et al.* in preparation). In artificially infested (5–20 young larvae) potted *P. canariensis* with stem diameter of 40–50 cm, Martín and Cabello (2005) showed that mean daily temperature was from 1.2 to 2.8 °C higher in stem (10 cm depth) than outdoor from May to November in southern Spain. In the cold period (November to April), the temperature in the palm tended to become similar to air temperature in the coldest months. The inner palm temperature regularly oscillated between 10 and 5 °C in agreement with measurements by Hamidi *et al.* (in preparation) on the much taller specimens.

4.4.3.3 Global Impact on RPW Development

In healthy palms or with little population of RPW larvae, the lag of seasonal temperature evolution and the thermal inertia of the moist palm tissues make possible development in fall and even early winter when air temperature would stop it. Conversely, in spring, in spite of air temperatures, which would enable development, the latter will be delayed for the time necessary for heating the inner palm. The local minima and duration of the cold period will consequently result in a more or less long stop of development, doubled with a period when egg-laying is not possible (Dembilio and Jacas 2011; Dembilio *et al.* 2012). The heat necessary for complete larval development will be accumulated in a shorter time than predicted based on the air temperature considering the actual warmer average temperature in a healthy palm.

Adults, eggs, and pupae, which are mainly peripheral on the palm, will react more directly to the evolution of the air temperature as the buffer effect of the tissues where they live is less. The situation within a palm tree should vary according to exposure to the sun. Most of the pupal and adult population should be marginally affected by winter in all coastal areas (including the Atlantic, as in France) because low temperatures that fall below the lethal lower thresholds rarely last for long (Table 4.2 and Table 4.3). In turn, in more inland areas, RPW is unlikely to survive winter at adult and pupal stages because of the more regular and intense occurrence of such lethal lower temperatures.

The seasonal temperature lags of the thermal variation are moderated by RPW infestation as it leads to a general increase of the temperature of the palm tissues. Moderate to high infestation will therefore accelerate development. In the cavities with crunched fermenting tissue, the temperature is obviously still higher, particularly in winter when the differential with air increases. This situation still further reduces the impact of low winter temperature, by favoring survival of RPW close by and making a continuous development of the larvae hatched in late summer and fall possible. Possibly, reproduction occurs locally in the palm tree. A trade-off with a higher mortality and reduced offspring is nevertheless likely because 33 °C and more are beyond optimum for RPW (Table 4.2 and Table 4.3). To date, no quantitative information is available to support the contribution of the various points on the population dynamics, although it is often proposed to explain the rapid explosion and establishment of RPW in areas with considerably cold winters. The simulation presented in Section 4.4.5 illustrates the likelihood of this assumption (Fig. 4.3A).

4.4.4 Thermal and Hygrometric Thresholds and Optima for the Adult (Table 4.2)

4.4.4.1 Mating and Reproduction

The range 14–15.5 °C is critical for reproductive activity of the adults under laboratory conditions (Dembilio *et al*. 2012). Below 15 °C, for 15 or 30 days, adults neither mated nor laid eggs. Eggs could not hatch below 14 °C. From these observations, Dembilio *et al*. (2012) determined whether and how long adults could lay eggs based on standard climatic data in the Mediterranean. Replicated exposure ($n = 506$) from two to 32 weeks at constant 10, 12.5, or 15 °C and 10 °C with 2 h at 20 °C confirmed the absence of reproduction activity below 15 °C. Warmed up to 27 °C, survivors were able to mate and laid fertile eggs but with the cost of a much lower offspring (50–95% reduction) after more than 1 month at 15 °C as compared to RPW being kept at 27 °C (Hamidi *et al.* in preparation).

4.4.4.2 Feeding and Survival in Extreme Conditions

In the same experiment, adults normally fed at 15 °C but not at 10 °C, and fed very little at intermediate temperatures (Hamidi *et al.* in preparation). Absence of feeding at 10 °C reduced life span (twice as short) as compared to 27 °C. In contrast, exposure to 15 °C strongly increased the lifespan, roughly by the time spent under this chilling temperature. (Hamidi *et al.* in preparation). As a borer of living tissues and a tropical organism, RPW is adapted to live in a particularly moist environment and adults actively seek for humidity in hot conditions (Aldryhim and Khalil 2003). Sensitivity to higher temperature is enhanced by the decrease in humidity (Monzer and Srour 2009).

4.4.4.3 Motion and Flight

Pheromone-based traps reveal the seasonal timing of flights, which varies with the place due to population level and seasonality of the emergence. Flights are much lower during the rainy months than during the warmer and drier period in monsoon India (Faleiro 2006). In the Mediterranean and Middle East, flights are often bimodal, and low or absent in mid-summer and plain winter (e.g. Vidyasagar *et al*. 2000; Boutaleb *et al*. 2013; Conti, Raciti, and Cerrella, 2013; Hashim, Abdullah, and Tawfik 2013; Roberti *et al*. 2013). When two peaks are observed, flight is more important in fall than in spring. For instance, trap captures in Marsala (Italy) have shown two peaks in April and in September–October (Lo Bue, personal observation). In Qassasin (Ismailia Governorate, Egypt), two peaks of flight were observed in March and from September to November in 2011–2012 by Abbas and Al-Nasser (2012). In Israel, there are two almost merging peaks (April–June and August–November) (Soroker *et al*. 2005). They can also merge into a broader, one as in Catania (Sicily) (Longo, Suma, and La Pergola 2011). A unique peak of flight is reported in some places (e.g. Greece; Kontodimas, personal observation). There are reports of trap captures when mean air temperature is below 18 °C (e.g. in Corsica: FREDON Corse, 2008; in Sicily: Longo, Suma, and La Pergola 2011) and even around 10 °C in Var (France) and Valencia (Spain) (Rochat, personal observation). The captures likely involved flight, although some RPW might have simply crawled to the traps. Such flights may be facilitated by warming of the adults in the cavities in the palms where active fermentation occurs (see Section 4.4.3) or simply due to local heating by the sun.

RPW has been reported to go to pheromone traps mostly between 0:00 and 6:00 a.m. (night) or mainly in early morning and before dusk in tropical India (data reviewed in Faleiro 2006). This suggests that RPW can fly at different times of the day or night depending on the local weather conditions, but the protocols of the assays cannot exclude nocturnal captures of walking individuals that came close by the traps by flight at another time. To determine optima for adult motion, Hamidi *et al.* (in preparation) carried out on a 24-hour basis automated recording of walk and flight by young adults simultaneously with the actual climate parameters over 2 years (*ca.*11,000 focus observations over 7.5 to 44 °C from $n = 250$ RPW from a laboratory colony). RPW was able to take off from 18.5 °C up to 42 °C under a broad range of light intensity and humidity. However, 90% of flights ($n = 126$) occurred in the morning between 24 and 34 °C and peaked under maximal illumination within the day and at the highest humidity (75% observations: 30–34 °C, > 60% RH). Similarly, walk was about twice as frequent above 33 °C and 80% RH as compared to the other conditions. RPW were observed walking on a broader range of thermal conditions at higher humidity > 60% than at dryer ones (Hamidi *et al.* in preparation). The experimental results agreed with the aforementioned literature reports on natural flights, where flying was scarce or non-existent in summer when mean daily temperatures exceeded 35 °C (overview of the literature reports) and air moisture was particularly low, but were more significant in the fall with decreasing temperatures.

4.4.5 Refined Development Modelling and Flight Predicting for Temperate Areas

The various thermal constants and thresholds reported (Table 4.2 and Table 4.3) enable modelling the egg-laying period and the yearly development under various plausible scenarios regarding the temperature undergone by RPW and therefore estimating the seasonal potential emergences and flights.

In an earlier attempt based on a simple ratio from MYT and with an approximated development threshold of 14 °C for all stages, Dembilio and Jacas (2011) determined that RPW could complete from 0.8 to 1.9 generations a year in the different regions of the Iberian peninsula: two successive cycles are possible when MYT > 19 °C and less than 1 when MYT < 15 °C. The period of egg-laying was estimated over the whole Mediterranean in Dembilio *et al.* (2012).

Using the development thresholds for every pre-immature stage, calculations showed that development at constant 25, 30, 35, or 38 °C would allow 3.9, 5.8, 7.6, or 8.7 successive generations with minimum and maximum duration for a cycle of 94 and 42 days, respectively, without consideration of mortality (Table 4.2). It is a question of theoretical values, which help compare the potential of RPW multiplication with respect to the temperature of development. These values and the heat created by infestation support the reports of several successive generations in a suitable palm (e.g. Ferry and Gomez 2012), although there is no formal evidence for it based on genetic markers that would ascertain the kinship of the individuals.

The actual natural situation is much more complex because the temperature varies seasonally creating different conditions in palms. In the absence of infestation, simulation using the same development parameters and the climate values of various Mediterranean cities shows that the duration of RPW development follows a dissymmetric or even bimodal pattern due to the cold season, which stops the development and kills a substantial proportion of the population for some time (Martín and Cabello 2005; Dembilio and Jacas 2011; Fig. 4.3A). In the extreme case, long stop of development due to wintry deficit of heat together with a high mortality, larvae develop according to two cohorts: the rapid- and the slow-developing ones, which respectively give adults the same year (in summer or fall) and the next year (spring and summer) of egg-laying (Fig. 4.3A for Perpignan and Palermo cities with the three lower temperatures of development). As an example, in Palermo with the estimated inner palm temperature, RPW complete development within 2–6 months the same year, and predominantly within 2–3 months or within 7–10 months the next year. The pattern of development times directly determines the potential emergences and therefore the number of living adults at any moment, which consequently shows similar dissymmetric or bimodal patterns (Fig. 4.3B: all cities inner palm temperature). As soon as the RPW are more protected in the palm and/or undergo a milder winter with less mortality and a shorter cessation of development, the durations of development are shorter and less variable. This results in an abundance of living adults that is less dissymmetric over the year with a simple lower number in winter and early spring as compared to summer and fall, and even tends toward a unique peak that is shifted to the summer (Fig. 4.3B: all cities, infested palm temperatures).

Estimates of adult life span and more particularly thermal conditions for flight, including the possibility of adults warmed in highly infested palm trees to fly when air temperature is below optimum, enable simulation of flight under scenarios of development in healthy palm, slightly and more severely infested palm trees according to the local climate (Fig. 4.3C). Bimodal flights appear only when the development is clearly impacted by a winter which splits development into two separated cohorts. When winter stringency is attenuated, as in warmer infested palms, the flight occurs as a longer peak centered in summer (Fig. 4.3C). The estival eclipses of flight that are often observed do not clearly appear in such simulations, suggesting that other factors than simple thermal optima regulate these flights. Such models should nevertheless help to fit more accurately the timing for pheromone-based trap installation and follow-up under the various climatic conditions of the Mediterranean and EU, especially in spring and fall.

4.5 Conclusion

4.5.1 Relation to the Host Palm in the Invasion Area

RPW is a tropical insect that has adapted to the entire Mediterranean and expended far beyond for the last 25 years due to the boom of trading and planting ornamental and date palm trees. Even though RPW only develops on palms, it propagates very efficiently in the largest palm species with the main economic value in the Mediterranean Basin: date palm and Canary Islands date palm. Both palm species are highly susceptible to RPW, and the latter particularly favors rapid increase of its populations. Most of the other palm species present in the landscapes, particularly with high patrimonial value—such as the endemic *P. theophrasti*, *J. chilensis*, the *Washingtonia* spp.—can be killed by the pest. The relative susceptibility of these palms cannot be established based on yet too scarce information but deserve attention by monitoring. Only *T. fortunei* and *C. humilis* are very rarely damaged by RPW. Experiments showed probable resistance in these species, which reduces egg-laying and does not allow efficient development. However, the mechanism has not been established yet. In the absence of dedicated experimental data to assess this differential susceptibility, the severe damage to *P. canariensis* seems to reflect a simple conjunction of its morphophysiological traits with its prevalence in the EU and the Mediterranean. The species offers the most important resource suitable to RPW development whose accessibility to egg-laying is naturally favored by the morphology of the frond bases, large and soft, and possibly the regular pruning for aesthetic reasons, which consists of flush cutting many living fronds ("pineapple cut") and the emission of large amounts of odors known to attract RPW. *P. archon* attacks could also open access to RPW females for oviposition. Major attention should be paid to this risk as PBM is expected to spread to the southern and southeastern shores of the Mediterranean where it is yet absent but may adapt to date palm.

Comparatively speaking, *T. fortunei* and *C. humilis* provide much more limited resources for the larval development and less accessible areas to the females. Damage to the date palm is historical and RPW has formerly coexisted with this species. Damage is favored by offshoot removal. Experimentation is necessary to evaluate hypotheses about the origin of the apparent tolerance or high susceptibility to RPW of certain palm species, hybrids, or possibly varieties in date palm. They require behavioral assays to determine at which step of the insect–plant relationship the insect can recognize and select the plant and/or overcome its defense. Biochemical and high throughput genomic approaches should help correlate RPW infestation capability to palm-relevant traits.

4.5.2 Development and Adaptation to Temperate Climate

The RPW have adapted to Mediterranean winter conditions, essentially due to their borer lifestyle. Common sense observations have been recently supported by a series of experimental data, which determined the thresholds for behavior and survival. Living deep in palm tissue protects the pre-immature stages from the coldest periods with an average yearly exposure to a higher temperature than in the air. The difference varies seasonally depending on the situation within the plant. It essentially consists of a buffer effect and of an accumulation of the thermal changes in the air over 10 days in *P. canariensis*. RPW in the palms can therefore develop longer in fall and early winter than would be expected from the external temperature. In turn, development is possible in palms later in spring than air values would allow. RPW life becomes impossible at all stages only below 4.5 °C. Between 4.5 °C and 10 °C, development, feeding, and reproduction are stopped and severely altered and the eggs and tiny larvae die. Significant numbers of last instar larvae, pupae, and adults can survive to one month under these values. Between 10 °C and 15 °C, most vital functions at any stages are stopped but not irreversibly compromised. Many individuals will survive and resume activity with warming. Values below 4.5 °C are only exceptionally reached in the inner tissues of large palms and are rare at the periphery of the palm as well. Experimentation evidenced that mild temperatures (*ca.*15 °C) set the adults in stand-by. In turn, values between 10 and 15 °C are typical in the Mediterranean, and appear marginally detrimental, which explains RPW acclimatization to the local climate.

Protection from wintry low temperature is obviously reinforced by the existence of a hotter microclimate within in the palm trees due to the plant's reaction to infestation. In the case of severe infestation, local warming likely favors survival and accelerates development. In the Mediterranean and neighboring areas with seasonal thermal variation, larvae develop according to two dynamics: with or without stop of development during late winter and spring depending on the time of egg-laying and of the intensity of chillness. This leads to adult emergences that follow in most places a dissymmetric seasonal pattern, with few emergences in spring and a peak in summer and fall. When the winter effect is important, the peak is lagged to fall while less or negligible cold will lead to a summer and broader peak. Experimentation showed RPW adults to optimally fly from 27 to 34 °C. At higher and lower temperatures flights become negligible, although in late fall and winter warming in infested palms or local heating by the sun exposition can enable some flight, which is supported by captures in pheromone-baited traps reported over the whole Mediterranean. Taken together, experimental and field data provide us with reliable information for better modelling of the dynamics of RPW population than using the general climatic models fitted to the thermal limits for palm growth.

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5

Rhynchophorus ferrugineus: Behavior, Ecology, and Communication

Ezio Peri[1], Didier Rochat[2], Gregor Belušič[3], Marko Ilić[3], Victoria Soroker[4], Shay Barkan[4], Salvatore Guarino[1], Paolo Lo Bue[1] and Stefano Colazza[1]

[1] Department of Agricultural and Forest Sciences, University of Palermo, Italy
[2] Sensory Ecology Department (UMR 1392), Institute of Ecology and Environmental Sciences of Paris, France
[3] Department of Biology, Biotechnical Faculty, University of Ljubljana, Slovenia
[4] Department of Entomology, Agricultural Research Organization, The Volcani Center, Rishon LeZion , Israel

5.1 Introduction

Originating in southern Asia and Melanesia, where it is a serious pest of a broad range of palms including coconut, date, and oil palms, in the last 30 years the red palm weevil (RPW) has spread quickly across the Middle East and Europe. During this rapid and aggressive invasion process, the RPW has adapted to the new abiotic environment and to new host plants, developing new interactions and showing competitiveness under the new conditions. Moving from one geographical region to another, the RPW has had to adapt not only to climatic conditions that are often different from those in its native distribution range—moving, for example, from its native humid areas to the warmer arid regions of Arabic countries—but also to very different ecological conditions, such as semi-deserts, scrublands, or urban areas. Indeed, weevils from native environments, where they feed on wild (e.g. sago) and cultivated (e.g. coconut and betel) palms, have colonized new agricultural areas where other palm species are cultivated for economic purposes, for example date palm orchards, and urban areas where palms are planted for ornamental purposes. Moreover, during its geographic spread, the RPW has infested several new host plant species association, sometimes modifying its behavior. For example, observing plants of *Phoenix canariensis* and *P. dactylifera* infested by these weevils, it is possible to discern different attack strategies. Indeed, RPW larval infestation preferably develop making tunnels and large cavities at the base of the date palm trees where attractive offshoots grow, while it is preferentially located in the crown tissues when attacks occur on Canary Island date palms (see Chapter 2, this volume). During their foraging behavior, weevils rely on a series of physical factors and chemical stimuli, which drive the phytophagous insects to locate and attack suitable host palms. Among the physical factors, visual signals such as color and size play an important role in mediating RPW behavior (Abuagla and Al-Deeb 2011). Among chemical stimuli, pheromones and palm kairomones are mainly used to trigger either mate or host location, or both in synergy.

Handbook of Major Palm Pests: Biology and Management, First Edition.
Edited by Victoria Soroker and Stefano Colazza.

Host-colonization strategies are known for other phytophagous coleopteran species, such as the bark beetles, which are characterized by the emission of a pheromone eliciting aggregation behavior of the population on a new host upon which they can feed, mate, and reproduce (Wood 1984; Raffa *et al.* 1993). This host-colonization process is divided into four phases: (1) dispersal: the new adults emerge and move away from the host tree; (2) selection: insects orient to and evaluate a potential host by spying host stimuli, prior to and/or after landing on the tree, select the host plant and start feeding; (3) concentration: female and/or male feeding insects release attractive pheromones and recruit conspecifics—this step ends when no more pheromone is released and/or anti-attractants are released; and (4) establishment: mating and oviposition occur in the new host—for species attacking living hosts, this step can be increased by the introduction of symbiotic fungi, which induce tree death and, as a consequence, facilitate some of the beetles' behaviors, such as mating, tunneling, and oviposition.

Data on RPW palm-colonization strategies are still limited and do not fit the bark beetle scheme (Wertheim *et al.* 2004). Although RPW shelter endosymbionts, their contribution to overcoming the host palm's defense is unlikely, contrary to their role in supplementing the natural diets shown in other Dryophthoridae weevils (Lefèvre *et al.* 2004). As an ancestral trait of the taxonomic group, palm weevils are totally linked, both as adults and as larvae, to living palm trees. Larvae especially need healthy tissues for optimal development. The species would therefore not benefit from massive destruction of its hosts. This point is supported by the absence of reports of high palm mortality due to palm weevils, including RPW, in natural habitats or even in cultivated lands. Our view is dramatically skewed by the very high mortality caused on *P. canariensis* by RPW in the invasion area, and to a much lesser extent to *P. dactylifera* and *Cocos nucifera*, all three cultivated species (see Chapter 4, this volume).

However, RPW aggregation pheromone is admitted to allow long-range orientation to palm trees and mediation of mating behavior. Moreover, many species of weevils have been shown to respond to volatiles from palms or their cut parts (Giblin-Davis *et al.* 1994; Gries *et al.* 1994). The attractiveness of plant volatiles not only mediates RPW host-location behavior, but should also allow the pest to discern the more susceptible plants. Indeed, bioassays under laboratory conditions show that RPW females prefer palm tissue volatiles from certain date palm cultivars, in which the species can better develop (Faleiro *et al.* 2014). These findings demonstrate that RPW use a complex chemical communication system to locate suitable host palms for feeding and reproduction.

In this chapter, we describe intraspecific and interspecific behaviors of RPW. In particular, we review studies on the stimuli and factors that mediate these behaviors, focusing on chemical stimuli and physical factors used by RPW during the phases of location and selection of the host palm, aggregation of the adults, and subsequent stages.

5.2 Main Behaviors Involved in Species Dynamics

5.2.1 Aggregation and Mating Behaviors

The behavior of adult palm weevils, *Rhynchophorus* spp., and of related Dryophthoridae weevils is characterized by their crucial ability to aggregate on host plants (Wertheim *et al.* 2004; Pherobase 2015). The function of aggregation behavior is broadly defined as "forming an aggregation that serves for protection, reproduction, feeding or a combination thereof" (Borden 1983). This process is divided into two steps: long-range location and short-range recognition. First, palm weevils actively fly over long distances following chemical cues, such as aggregation pheromone and host plant odor (see Section 5.2.2), to colonize a new host. Flight is often influenced by seasonal conditions, increasing with high temperature and adequate relative humidity (Weissling *et al.* 1994; Aldryhim and Khalil 2003). Once the adult weevil individuals are in close proximity, close-range recognition processes occur, such as pair formation through courtship and separation after copulation (Kamiya *et al.* 2015).

The precise function and evolutionary advantage of aggregating on the host plants by means of a male-produced aggregation pheromone have been discussed by Landolt and Phillips (1997), Wertheim *et al.* (2004), and Hallett, Crespi, and Borden (2004). From ecological and evolutionary perspectives, aggregation based on the response to aggregation pheromones, as in the RPW, would essentially contribute to co-locating mates and dispersed plant resources, such as palms, that are mostly clustered at a low density in natural habitats. This is particularly likely when one considers that the host plant odor synergizes with attraction to the aggregation pheromone, or the reverse, as the palm is preferentially pioneered when it is wounded, and only in a second step males will signal it by emitting aggregation pheromone. This hypothesis has been interestingly completed by Inghillesi *et al.*'s (2013, 2015) investigations into sexual behavior within groups of RPW.

To study the precopulatory and mating behavior of palm weevils, laboratory observations were carried out in which adults of both sexes were kept in couples or in groups. During mate-recognition behavior, some palm weevil species seem to respond to cuticle-bound courtship pheromones of conspecific females (Rochat 1991). *Rhynchophorus palmarum* (L.) males are also able to exhibit precopulatory behavior (i.e. a jerky swinging motion of the body) after antennating dead females but not dead male decoys or female decoys that have been washed with hexane, a solvent that removes several cuticular compounds (Rochat 1991). In the case of *Rhynchophorus cruentatus* (F.), males antennate the pronotum of live conspecifics and mount males and females with equal aplomb (Weissling, unpublished observation). *R. cruentatus* males are morphologically well adapted to mating in aggregations, as they possess a row of setae, commonly referred to as a "sex comb," on the tibiae of the forelegs (Vanderbilt, Giblin-Davis, and Weissling 1998).

Similar to the other palm weevils, RPW is characterized by a marked aggregation phenomenon (i.e. quite high densities inside the palm stems, especially in *P. canariensis*), which imposes continuous and frequent interactions among group members that determine the promiscuous behavior and gregarious system of this pest (Inghillesi *et al.* 2013). The ethology of this species has been generally investigated in laboratory observations, where adult RPW were kept in couples or in groups to study their mating behavior. The mating behavior sequence was first investigated by Kaakeh (1998), who observed and recorded three behavioral steps under laboratory conditions: (1) pre-mounting, characterized by the male's slow approach of a female, touching her last abdominal segment with his snout followed by the middle section of the female elytra with his snout and antennae; (2) mounting, with the male touching the thorax of the female and grasping her abdomen with his prothoracic legs; and (3) copulation, defined as the time period from beginning of abdominal flexing of the male until it dismounts from the female. The same study revealed a strong influence of the adult's age on mating behavior, in particular the length of copulation increased with increasing weevil age. Although a well-defined courtship behavior prior to mounting was not reported, Al-Ayedh and Rasool (2010) described RPW mating as "appeared as males' coarse attempts to mate with inconspicuous ritualized rostral rubbing, antennal tapping, or mate guarding." More recently, a study carried out by Inghillesi *et al.* (2013) observed that adult males and females of RPW kept in groups for 4–10 days strongly interact within the first hour after aggregation, determining a highly promiscuous interaction network in which each individual interacts with many other individuals. In this gregarious context, males interfere actively with rivals, showing high levels of activity, while females adopt a passive role. Indeed, this highly promiscuous mating system of RPW is characterized by male individuals' intense search for a partner and their rapid mating with several partners and, on the other hand, by rival males' forced interruptions of copulations. However, the social network is highly non-random and irregular: a few males almost completely monopolize reproduction, behaving as key players in the mating network (Inghillesi *et al.* 2015). This promiscuous mating system of RPW also occurred under laboratory conditions with the closely related allopatric species *Rhynchophorus vulneratus* (Panzer), where interspecific mating was observed. This finding suggests that these two species have similar or identical precopulatory behavior, in addition to their very close genetic proximity, in agreement with geographical speciation (Hallett *et al.* 1993; Rugman-Jones *et al.* 2013).

In RPW, mating can occur at any time of the day and even during the egg-laying process, and its duration is variable, taking from 1 to 5 min (Ince, Porcelli, and Al-Jboory 2011). After mating, females lay their eggs in palm tissues by adopting a special drilling behavior. Indeed, females first create a small wound on the palm tissue with their strong mandibles, then they move their mouthparts front and back to create deep holes in which they lay their eggs (Ince, Porcelli, and Al-Jboory 2011; see Chapter 4, this volume).

5.2.2 Flight and Dispersal Capability (Role of Age, Sex, and Mating Status)

Adult weevils disperse from one tree to another by flying, and like most insects that use scattered resources, RPW rely on very sensitive olfaction to locate mates and host trees (Hallett *et al*. 1993; Giblin-Davis *et al*. 1996a). Direct observations of flying RPW show that these insects are good fliers that can fly rather high, over 15 m at take-off, and can easily land on palm tree tops (Soroker and Barkan, personal observation). However, it is still not clear how far they actually do fly and how fast they disperse in the new territories. To evaluate the flight distance capability of RPW, one must first discriminate between flight potential and actual performance. Flight potential is estimated by pure physiological parameters, while actual performance also depends on environmental parameters, such as climatic conditions (mostly temperature and winds), and host and pheromone availability. Flight potential is usually assessed in the laboratory by a relatively simple tool: the flight mill (Box 5.1).

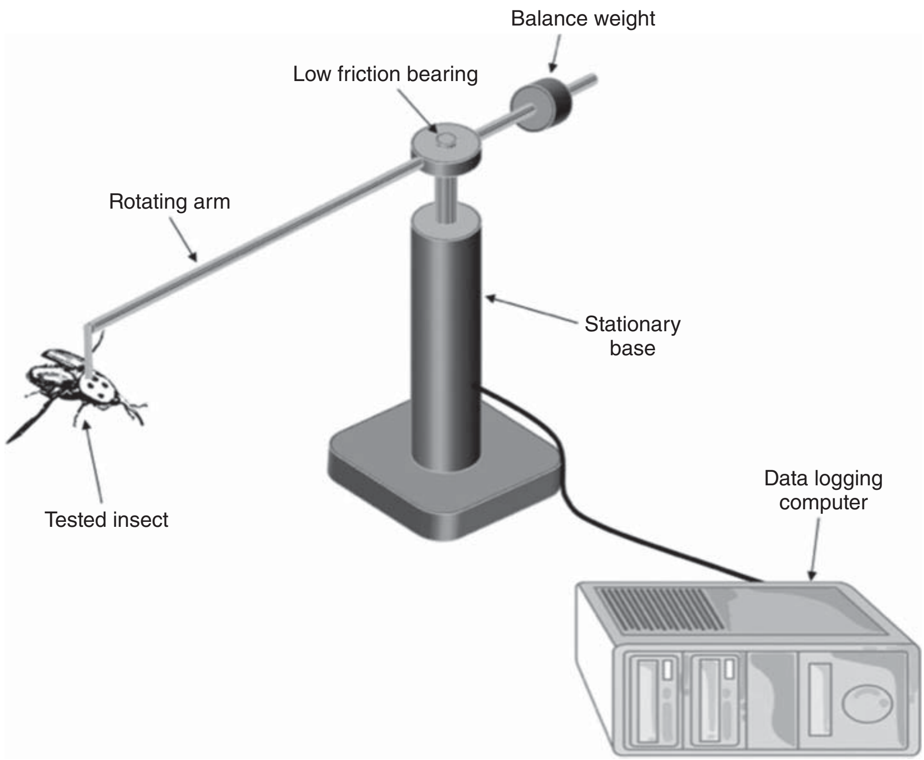
This device is essentially a miniature mill with horizontal rotation with an insect attached to it (Fig. 5.1).

During the insect's flight, the number of rotations and elapsed time are recorded and analyzed by a computer for flight characteristics such as speed, time, and distance. This method is commonly used to evaluate the flight dispersal potential of insects from different orders, including beetles, for example Scolytidae (*Ips sexdentatus*; De Geer Jactel and Gaillard 1991), Buprestidae (*Agrilus planipennis* Fairmaire; Taylor *et al.* 2010), and Coccinellidae (Maes *et al.* 2014). Recently, Avalos, Marti-Campoy, and Soto (2014) used flight mills to investigate

Box 5.1

Flight Mill

The flight mill is a simple device for studying flight capabilities and energetics. This device is in essence a miniature mill with horizontal rotation to which an insect is attached. During the insect's flight, the number of rotations and elapsed time are recorded and later used to calculate flight variables such as velocity, time, and distance. To date, field tracking insects' flight is still very challenging, while the flight mill device offers an easy alternative for estimating flight performance and dispersal potential. Although the calibration of flight mills to obtain complete estimates of the natural dispersal capacity of an insect remains a significant obstacle, flight mill experiments can yield important information when used in a comparative approach.



the flight performance of RPW under laboratory conditions (25 ± 2 °C). They found that 46% of the weevils were able to cover, in a single non-stop flight, a distance of 0.1 to > 5 km, with an average of 1.3 km and a maximum of 11.2 km. In our studies (Barkan, personal observation), more than 80% of the population flew 5–20 km, much longer distances than reported by Avalos, Marti-Campoy, and Soto (2014), while the distance covered in a single non-stop flight was highly variable among individuals and ranged between 0.1 and 50 km. This great difference between the two studies could be explained by the fact that our flight trials were conducted at a higher test temperature (30 ± 2 °C),

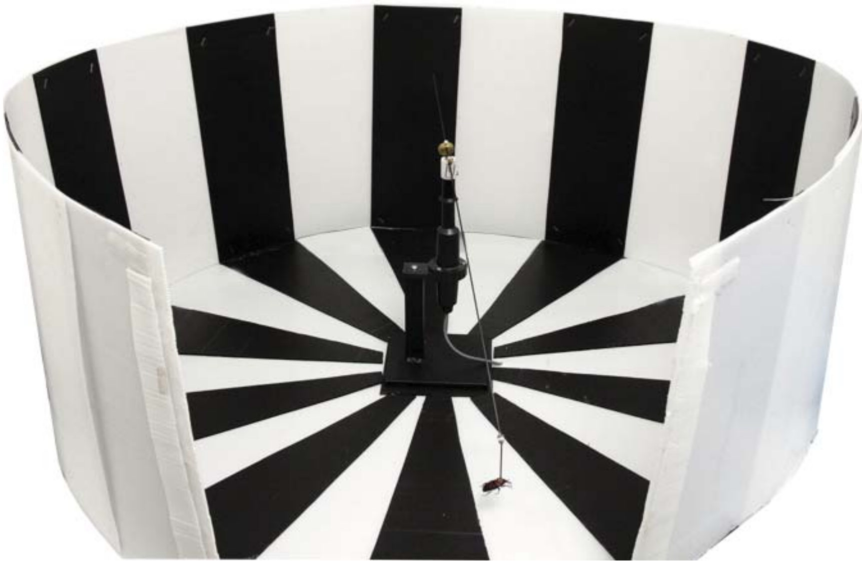


Figure 5.1 Flight mill device in the Volcani Center (Israel) with a tethered red palm weevil at the tip of the rotating arm. Black and white stripes are installed to provide visual stimuli for the flying weevil.

which is apparently closer to the insect's optimum flight temperature, which ranges from 30 to 40 °C (Hamidi *et al.*, in preparation), corresponding to their native biogeographical area. It is also worth indicating that in observations in cage experiments under natural conditions the weevils did not fly at temperatures below 18°C. By subjecting the beetles to repeated flight opportunities, we also showed that they could cover a distance of more than 300 km and perform up to 11 flights during their lifetime. Flight performance was not influenced by sex or body size in either study, whereas age did play a role. In fact, the percentage of flying weevils was lower among the newly emerged (1-week-old) individuals compared to the older ones (8–23 days old) (Avalos, Marti-Campoy, and Soto 2014). However, weevils maintained their flight abilities until over 3 months of age (Barkan, personal observation). The question remains: to what extent do these measurements reflect the natural flight performance? It is clear that the flight mill design has a great impact on performance. In the basic flight mill used by Avalos, Marti-Campoy, and Soto (2014), the flying weevils were tethered at a fixed height, and did not need to support their own body mass during flight. Even when this lift issue was solved with a more sophisticated flight mill (Barkan, personal observation), where beetles had to produce lift during flight, other flight parameters were still highly influenced by the flight mill's orbital flight path. Moreover, none of these mill experiments addressed navigation efforts or considered wind interference.

On the other hand, evaluating an insect's flight ability under natural conditions is very challenging and is also not free of flaws. An indirect estimation can be made by using pheromone traps when the location of the infected trees is known. Based on this method, in India and the Middle East, it was shown that RPW tend to fly short distances of ~100 m if there are suitable palms within this range (Vidyasagar *et al.* 2000; Faleiro *et al.* 2002; Oehlschlager 2005, 2012). In Israel, monitoring of weevil dispersal from infested urban areas using pheromone traps revealed their dispersion over 13–19 km in a period of 22 months (see Chapter 10, this volume). These values are much lower than their potential. This is not surprising as environmental cues are expected to play a crucial role in weevil dispersal.

One of the most accurate methods for field evaluation of actual insect dispersal is by mark-and-recapture, where insects are marked, released from a known location, and later recaptured and identified at another location. Using this method in date palm plantations showed that both male and female weevils can fly up to 7 km between release and recapture sites within 3–5 days (Abbas *et al.* 2006). The accuracy of these measurements is not clear as the authors indicated that captures in the traps not only fluctuated seasonally but were presumably affected by local conditions, such as degree of infestation and shelter availability. Moreover, the percentage of recaptured weevils was generally rather low (below 15%), and the total distance flown between the two sites was unknown since no direct tracking was obtained.

Another method for tracking insect dispersal is by using radio or GPS transmitters. Unlike the mark-and-recapture method, radio transmitters are able to produce online information regarding insects' flight speed and location. Micro radio telemetry has been used on several occasions for insect tracking, such as for three *Bombus* species (Hagen, Wikelski, and Kissling 2011). So far, the major limitations of this method are the transmitter's size and weight, which are still challenging for small insects, and its short battery life. In any case, no radio tracking data for RPW are yet available.

5.3 Chemical Cues

5.3.1 Pheromones

Similar to many species of insect and other animals known to aggregate for mating purposes (Landolt and Phillips 1997), palm weevils often aggregate in response to a male-produced aggregation pheromone (Walgenbach *et al.* 1983; Moura *et al.* 1989; Rochat *et al.* 1991a, b; Budenberg, Ndiege, and Karago 1993; Gries *et al.* 1994; Giblin-Davis *et al.* 1994). These compounds act in the processes of both mate location and aggregation of conspecifics (Bartelt 1999). Evolutionary biologists have investigated the advantages for males calling in conspecifics, which invites competition from other males (Thornhill and Alcock 1983), and the advantages of multiple mating for females, such as the acquisition of "good genes" and increased genetic diversity within clutches (Lewin 1988; Sakurai 1996; Yasui 1998; Wertheim *et al.* 2004).

Studies of the chemical volatiles produced by both sexes were carried out by airstream collection followed by gas chromatography–mass spectrometry (GC–MS) analysis revealed the presence of male-produced aggregation pheromones for many species in the subfamilies Rhynchophorinae and Dryophthorinae (Giblin-Davis *et al.* 1996b). In particular, male-produced aggregation pheromone has been demonstrated for *R. palmarum* (Moura *et al.* 1989; Rochat *et al.* 1991a), *R. cruentatus* (Weissling, Giblin-Davis, and Scheffrahn 1993), *Rhynchophorus phoenicis* (F.) (Gries *et al.* 1994), *Metamasius hemipterus* (Olivier) (Rochat *et al.* 1991b; Giblin-Davis *et al.* 1996b), *Cosmopolites sordidus* Germar (Budenberg, Ndiege, and Karago, 1993), and *Sitophilus* spp. (Walgenbach *et al.* 1983). In the case of *R. cruentatus*, sexual stimulation in weevil aggregations appears to be semiochemically mediated. Indeed, under laboratory conditions, males were significantly more stimulated to mate in the presence of the synthetic aggregation pheromone cruentol (5-methyl-4-octanol; Vanderbilt, Giblin-Davis, and Weissling 1998).

Evidence of the presence of a male-produced aggregation pheromone in *R. ferrugineus* and the sympatric species *R. vulneratus* was provided in a study by Hallett *et al.* (1993). In this study, air collection of volatiles produced from cohorts of 20 RPW male or female adults, followed by gas chromatography-electroantennography detection (GC-EAD) analysis (Box 5.2) revealed the presence of two male-specific compounds that elicited strong depolarization by male and female antennae.

These compounds were identified as 4-methyl-5-nonanol (major component), termed ferrugineol, and the related ketone 4-methyl-5-nonanone (minor component), or ferrugineone. The natural compounds proved to be optically pure isomers (4*S*,5*S*)-ferrugineol and (4*S*)-ferrugineone. The non-natural isomers were inactive, as

Box 5.2

Electroantennography

Electroantennography or **EAG** is a technique invented in 1957 by the German biologist Dietrich Schneider, who showed that by connecting the antenna of an insect between two electrodes it was possible to record a depolarization of the antennal potential in response to stimulation by volatile compounds. The amplitude of the response, which correlates to the frequency of generated nerve impulses, was found to increase with increasing concentrations of the chemical stimulus until a saturation level was reached (Roelofs 1984). The EAG method can be used for many purposes, such as screening biologically active compounds, purification of extracts, identification of active fractions, and selection of active synthetic compounds. Pheromone and other attractants generally produce strong EAG responses in the receiver. However, these responses are not always linked with a specific behavior. This technique can be coupled with the efficient separating power of gas chromatography (GC) to produce a versatile technique for identifying insect olfactory stimulants (Cork *et al*. 1991).

The picture shows a RPW antenna connected to two glass capillary electrodes filled with saline solution and a silver wire to feed the electrical antennal signal to appropriate electronic devices for EAG recordings.

reflected by EAG and behavior (Pérez *et al.* 1996). The initial behavioral evaluation showed that ferrugineol attracts RPW, while mitigated results did not support pheromone activity of ferrugineone (Hallett *et al.* 1993; Pérez *et al.* 1996). Larger-scale field trapping in Saudi Arabia showed that ferrugineone increases trap catches relative to ferrugineol alone, leading to the conclusion that it is an actual pheromone component (Abozuhairah, Vidyasagar, and Abraham 1996).

Thus ferrugineol and ferrugineone at a ratio of 10:1, as demonstrated in the field test using traps, are attractive to male and female adults, mainly catching "ready-to-mate" adults and already fecundated females (Gunawardena and Bandarage 1995; Kalleshwaraswamy, Jagadish, and Puttaswamy 2005; Poorjavad, Goldansaz, and Avand-Faghih 2009). Ferrugineol is the major aggregation pheromone for other weevils as well, such as *R. vulneratus* and *Rhynchophorus bilineatus* (Montrouzier), and for the neotropical *Metamasius hemipterus* (L.) and *Dynamis borassi* (F.) (Oehlschlager *et al.* 1995; Pérez *et al.* 1995).

The production of aggregation pheromones may serve to recruit widely distributed conspecifics to rare resources (i.e. stressed hosts). Therefore, it may be advantageous for males to call females as a way of reducing the amount of time spent searching for widely dispersed potential mates. This may also be an adaptation that enables *R. cruentatus* to cope with the seasonal emergence patterns characteristic of this species (Weissling *et al.* 1994), and to overwhelm the defenses of a potential palm host (Giblin-Davis *et al.* 1996b).

Aggregation pheromone for RPW has been widely used for monitoring and mass trapping of this pest (see Chapter 12, this volume).

5.3.2 Plant Volatile Chemicals

Locating a host plant is crucial for a phytophagous insect to fulfill its nutritional requirements and find suitable oviposition sites (Bruce, Wadhams, and Woodcock, 2005). The host-finding and acceptance or rejection of plants by herbivorous organisms depend on their behavioral responses to physical and chemical plant features (Finch and Collier 2000). In the case of phytophagous insects, the importance of the role of host plant odors in mediating location of food sources and egg-deposition sites has been widely described (Visser 1986; Finch and Collier 2000). The use of plant volatiles for host location and recognition by insects very much depends on their excellent ability to process olfactory signals, especially considering that in a natural environment they are bathed in many different volatile chemicals at different concentrations and in different combinations (Bruce and Pickett 2011). From this they need to pick out relevant host odor cues with ephemeral exposure and against high background noise (Schröder and Hilker 2008). Among weevils, plant odors have been proven to trigger the processes of host recognition and finding in many cases. For example, *Anthonomus grandis* Boheman, a narrowly oligophagous insect, detects its host plant at some distance, and utilizes information about a wide range of chemical structures in its olfactory-mediated behavior (Dickens 1990). In the case of the cabbage seed weevil *Ceutorhynchus assimilis* Payk, host plant extracts attract adults in the laboratory and in the field (Evans and Allen-Williams 1998).

Field observations have shown that palm weevils often use odor cues to orient to their host palms and related attractive plants. Attraction is essentially synergistic with the aggregation pheromone (Moura *et al.* 1989; Rochat *et al.* 1991a; Hernández *et al.* 1992; Hallet *et al.* 1993; Weissling, Giblin-Davis, and Scheffrahn 1993; Azmi *et al.* 2014).

Owing to the economic importance of palm weevils, the host plant volatiles have been mainly investigated to find attractants useful for plant protection, rather than to understand the mechanisms of the palm weevil interaction from an ecological perspective (Giblin-Davis *et al.* 1994; Gries *et al.* 1994; Rochat *et al.* 2000). Studies have focused on the molecules that enhance the pheromone attraction for monitoring and mass trapping (Guarino *et al.* 2011; Vacas *et al.* 2014). Consequently, the data about the chemical cues that may drive the weevils to the host plant are mainly obtained indirectly from applied studies and relate to chemicals that increase attraction to the aggregation pheromones.

Field studies and anecdotal observation show that cut palm tissues strongly improve attraction to adults (Rochat *et al.* 1991a) or to pheromone traps for *Rhynchophorus* species in the field (e.g. Hallett *et al.* 1993). Host volatiles produced from these tissues were found to be synergistic with the aggregation pheromones, for example in *R. palmarum* (Rochat *et al.* 2000). A study carried out by Giblin-Davis and Howard (1989) observed that in the case of *R. cruentatus*, adults prefer to infest plants that have been severely stressed by strong pruning over healthy plants. In an olfactometer, Rochat *et al.* (2000) showed that *R. palmarum* was attracted from over 1 m to the odor emanating from actively fermenting sap of oil palm but not to the same sap that had achieved alcoholic fermentation. This supported the role of fermentation volatile chemicals in attraction of the American palm weevil to recently cut palm tissues (Rochat *et al.* 1991a). Various studies on several *Rhynchophorus* species have investigated the odors emitted by several palm substrates and showed the abundant presence of many fermentation compounds, such as short-chain esters and alcohols (Jaffé *et al.* 1993; Giblin-Davis *et al.* 1994; Gries *et al.* 1994; Rochat *et al.* 2000; Vacas *et al.* 2014). Some of these compounds proved to be co-attractive or synergistic with the pheromones after screening by EAG followed by chemical analysis and behavioral bioassays in the laboratory and/or field. In particular, pheromone co-attractant skills were observed for the so-called palm esters (ethyl acetate, ethyl propionate, ethyl butyrate and ethyl isobutyrate) for several palm weevils, such as *R. phoenicis*, *R. cruentatus*, *R. palmarum*, and *R. ferrugineus* (Table 5.1 and references therein).

However, the behavioral impact of the various selected chemicals seems to be extremely complex, either enhancing or synergistic with the pheromone, or boosting the pheromone complemented with a natural plant substrate, depending on the species and on the dose (Table 5.1). For instance, a synergistic attraction to ethyl acetate and aggregation pheromone was demonstrated only in *R. cruentatus* and *M. hemipterus* where it could replace 0.5 kg of palm tissue but not 1.5 kg of the same palm tissue or of sugarcane (Giblin-Davis *et al*. 1994, 1996b). With the aforementioned exception, none of the "palm esters" or related molecules was as effective as palm or other fermenting plant tissue at enhancing pheromonal attraction (Jaffé *et al.* 1993; Giblin-Davis *et al.* 1994; Gries *et al.* 1994; Vacas, Primo, and Navarro-Llopis 2013; Vacas *et al.* 2014). Based on olfactometer and field assays, Jaffé *et al.* (1993) proposed that such fermentation volatiles were not sufficient to attract *R. palmarum* in the field. Weevils may use complex odor mixtures to locate and recognize the palms, with only precise relative proportions of the components being meaningful to the insect (Jaffé *et al.* 1993). To understand how these compounds are detected by the olfactory system, the sensory structures of the antennae of *R. palmarum* were studied and characterized morphologically by scanning and transmission electron microscopy (Said *et al.* 2003). In that study, tuning of the olfactory sensilla to volatile compounds present in the weevil environment was determined using single-sensillum recordings. The study showed a high sensitivity and specificity of most of the olfactory receptor neurons (ORNs),

Table 5.1 Field activity of synthetic compounds evaluated for enhancing attraction to the aggregation pheromone of various palm weevils and a related species.

Dryophthorine species

Rhynchophorus ferrugineus

Synthetic chemical/mixture (ratio) [a]	Dose [b]	A	B	P	S	X	R	Natural [c]
Ethyl acetate (EtAc)	100			–			–	Mo PC [11]
	210			–			–	D 1.2 [1]
	60-1100			–				[10]
	2200			≤				[10]
	?+Mo [d]					?		[5]
	?		+					DF [12]
Ethyl propionate (EtPro)	140			–			–	D 1.2 [1]
	?+Mo					?		[5]
Ethyl butyrate (EtBut)	90			–			–	D 1.2 [1]
Ethyl isobutyrate								
Ethyl (S)-(–)-lactate	10			–			–	D 1.2 [1]
Ethyl caproate								
Ethyl caprylate								
Isobutyl propionate								
Isopropyl acetate								
Butyl acetate								
Ethanol (EtOH)								

Rhynchophorus palmarum

Synthetic chemical/mixture (ratio) [a]	Dose	A	B	P	X	R	Natural
Ethyl acetate (EtAc)	1500				+	+	SC 0.6 [8]
	?		+			–	SC [6]
	?		–				SC [12]
Ethyl propionate (EtPro)							
Ethyl butyrate (EtBut)							
Ethyl isobutyrate							
Ethyl (S)-(–)-lactate							
Ethyl caproate							
Ethyl caprylate							
Isobutyl propionate							
Isopropyl acetate							
Butyl acetate							
Ethanol (EtOH)	1100				–	–	SC 0.6 [8]

Rhynchophorus cruentatus

Synthetic chemical/mixture (ratio) [a]	Dose	A	S	R	Natural
Ethyl acetate (EtAc)	110	–	+	–	P 0.5 [2]
	500, 1900	–	+	±	+R: P 0.5 [2]
					–R: P 1.5 [2]
	850			–	SC 1.5 [2]
Ethyl propionate (EtPro)					
Ethyl butyrate (EtBut)	20-450	–	+	–	P 0.5, SC 1,5 [2]
Ethyl isobutyrate	30-40	–	+	–	P 0.5, SC 1.5 [2]
	230	–	–	–	P 0.5 [2]
Ethyl (S)-(–)-lactate	?	–	±	±	+R: P 0.5, SC 1.5 [2]
					–R: P 1.5 [2]
Ethyl caproate	3	–	–	–	P 0.5 [2]
Ethyl caprylate	1	–	–	–	P 0.5 [2]
Isobutyl propionate					
Isopropyl acetate	70	–	–	–	P 0.5 [2]
Butyl acetate	20	–	–	–	P 0.5 [2]
Ethanol (EtOH)	30-560	–	±	–	P 0.5 [2]

Rhynchophorus phoenicis

Synthetic chemical/mixture (ratio) [a]	Dose	P	X	R	Natural
Ethyl acetate (EtAc)	30	–			[4]
Ethyl propionate (EtPro)	30	+	+	–	OP 1 [4]
Ethyl butyrate (EtBut)	?	–			[4]
Ethyl isobutyrate	?	–			[4]
Ethyl (S)-(–)-lactate					
Ethyl caproate					
Ethyl caprylate					
Isobutyl propionate	?	–			[4]
Isopropyl acetate					
Butyl acetate					
Ethanol (EtOH)					

Metamasius hemipterus

Synthetic chemical/mixture (ratio) [a]	Dose	A	B	P	S	R	Natural
Ethyl acetate (EtAc)	20						SC 0.25 [7]
	680						SC 0.25 [3]
	680						SC 0.1, 0.25 [3]
	880	+					[3]
Ethyl propionate (EtPro)	20						SC 0.25 [7]
	380	+					[3]
	680						
Ethyl butyrate (EtBut)	20						
	150	–					
Ethyl isobutyrate							
Ethyl (S)-(–)-lactate							
Ethyl caproate							
Ethyl caprylate							
Isobutyl propionate							
Isopropyl acetate							
Butyl acetate							
Ethanol (EtOH)	7						[3]

(Continued)

Table 5.1 (Continued)

Synthetic chemical/mixture (ratio) [a]	Dryophthorine species																															
	Rhynchophorus ferrugineus								*Rhynchophorus palmarum*							*Rhynchophorus cruentatus*					*Rhynchophorus phoenicis*					*Metamasius hemipterus*						
	Dose [b]	A	B	P	S	X	R	Natural [c]	Dose	A	B	P	X	R	Natural	Dose	A	S	R	Natural	Dose	P	X	R	Natural	Dose	A	B	P	S	R	Natural
									?		–				SC [12]	50			–	SC 1.5 [2]												
Acetic acid																										8						[3]
Lactic Acid																?	–	–	–	P 0.5 [2]												
Caprylic acid																?	–	–	–	P 0.5 [2]												
Acetoin (ACE)	10			–				[11]																								
EtAc + EtPro (1:1)	?+Mo					?		[5]													60	–			[4]							
EtAc + EtOH (1:1)	120			+			–	Mo PC [11]	1500				–	±	SC 0.6 [8]																	
	280			+			#	D 0.34 [1]	?		–			+	SC [12]																	
	470	–			+		±	D 1.2 [1]																								
(3:1)	100			–			–	Mo PC [11]																								
(1:3)	100			+			–	Mo PC [11]																								
EtAc + 2-phenylEtOH (1:1)	110			–			–	Mo PC [11]																								
EtAc + EtOH + ACE (45:45:10)									650			+		+	SC 0.6 [9]																	
EtAc + EtOH + 3-methylbutanol (1:1:1)	130			+			–	Mo PC [11]																								
EtAc + EtOH + 3 m.c. [6] (66:27:5:1:1)									?			?		–	SC [6]																	
EtAc + EtPro + EtBut (1:1:1)																										60	?+					SC 0.25 [7]
																										1400						[3]

EtAc + EtPro + EtBut + propyl butyrate (1:1:1:1)	110	–		[11]					
EtAc + EtPro + EtBut + ACE + propyl butyrate (2:2:2:0.5:2)	70	–		[11]					
+ 11 m.c. (44:50:tr) [8]									
Mix G = EtAc + EtOH + ACE	30	–	–	D 1.2 [1]	650	+		+	SC 0.6 [9]
+ 13 m.c. (39:44:4:tr) [8]					1400			+	SC 0.6 [8]
Mix H = EtAc + EtOH + ACE					1500		–	+	SC 0.6 [8]
+ 25 m.c. (42:47:4.3:tr) [8]					?			–	SC [12]

References [1] Avand-Faghih 2004; [2] Giblin-Davis 1994; [3] Giblin-Davis *et al*. 1996; [4] Gries *et al*. 1994; [5] Guarino *et al*. 2011; [6] Jaffé *et al*. 1993; [7] Perez *et al*. 1997; [8] Rochat *et al*. 2000; [9] Said *et al*. 2005; [10] Vacas *et al*. 2013; [11] Vacas *et al*. 2014; [12] Oehlschlager 2012. The table summarizes only major references based on using synthetic aggregation pheromone and satisfactory statistical treatments of the data.

a) **Synthetic chemicals** are listed according to their structural similarity, and the mixtures according to increasing complexity with mention of only the main components (see references for detail). Several original data are not shown, as they were redundant with the selected ones. Ratio are provided mostly as v:v values. m.c.: minor components. Tr: trace (<2% of the mixtures).

b) **Dose** (mg/day) mainly corresponds to rounded actual mean daily emission. Some values are initial loads. ? reports an undetermined amount. Values separated by – indicate a range, with a minimum of 3 intermediate doses, which triggered the same activity. The activities on one line were obtained with the given dose(s).

c) **Natural plant lure** used to emit natural kairomones for comparison to the synthetic chemicals: D = date palm; DF = date fruit; Mo = molasses; OP = oil palm; P = Sabal palmetto; SC = sugarcane. The amount (kg) in one trap is reported when available. Unless 'fruit' is specified, the palm substrate is not always specified with precision but mostly corresponds to stem or rachis tissue.

d) The synthetic chemicals were associated to molasses and the assay did not include a control without molasses.

Field activity of the chemicals is coded in the columns headed by A, B, P, S, X and R. It is classified based on the type of comparisons carried out (see below) with the corresponding lure amounts under the conditions reported in the references. Information relative to the pheromones is not reported.

A attractant: the synthetic chemicals (K) caught more insects per se than an empty trap.

B booster: K increased the captures by pheromone (Ph) + a natural plant lure (N) irrespective of the experimental design and other conclusions.

P pheromone enhancer: K increased the captures by Ph in a comparison of Ph to Ph + K.

R replacer of natural plant lure: Ph + N and Ph + K were compared and performed similarly, irrespective of the design of the assay and other conclusions.

S synergist: Ph, K and Ph + K were compared simultaneously and the mixture caught more than the sum of the captures by K and by Ph.

X extrapolated synergist: Ph + N and Ph + K performed similarly (R) but Ph and K were not evaluated at the same time. The synergy was extrapolated based on other data (separate trial by the same authors or literature) without unambiguous evidence.

± indicates positive and negative results in two or more trials by the same authors with similar doses or controversial data.

? The assay does not correspond to the above situations and/or description does not allow one to conclude.

†**R** Ph + K performed better than Ph + N.

≤**P** Captures by Ph + K were lower than by Ph (female RPW with 2.2 g of EtAc).

particularly to its aggregation pheromone (rhynchophorol) and related compounds, as well as to components of two plant volatile reference blends (Said *et al.* 2003). In particular, the authors found specialist ORNs responding with high sensitivity to certain components of plant volatiles, particularly acetoin (3-hydroxy-2-butanone) and ethyl acetate, two fermentation compounds that commonly abound in the odors emitted by injured palms. Certain ORNs responded to both rhynchophorol and acetoin, or to the pheromone but only after stimulation by acetoin. The authors proposed that the synergistic behavioral response to the mixture of pheromone plus host plant odor might involve not only brain processing but also specific coding of the odor mixture by the antenna (Said *et al.* 2005). Such complexity suggests an adaptive trait of the olfactory system to optimize aggregation on palms, a major trait in the ecology of palm weevils.

Investigation of the olfactory processes that mediate the attraction of RPW to a host palm has been mainly carried out by analogy to the data obtained on related Dryophthorine weevils. Today they are still only partially understood. In particular, if the composition of palm odors attractive to RPW or that enhances orientation to the aggregation pheromone is well described (Vacas *et al.* 2014), the fraction of such odors necessary for the orientation remains undetermined. A reason for this is certainly the extreme complexity and variability of these odors, consisting of more than 100 components (e.g. Rochat *et al.* 2000; Vacas *et al.* 2014).

The RPW antenna was shown to respond to "palm esters" in a dose-dependent manner in an EAG study (Guarino *et al.* 2011), but also to various other components of palm odors (Gunawardena *et al.* 1998; Avand-Faghih 2004; Vacas *et al.* 2014). Ethyl acetate has long been reported as a booster of RPW traps baited with aggregation pheromone combined with a source of natural fermentation volatiles from sugar beet molasses or palm stem tissues or fruit (El-Sebay 2003; Guarino *et al.* 2011).

Thus, adding ethyl acetate to pheromone-baited traps with a natural source of fermenting volatiles has become common practice. At the same time, comparisons of ethyl acetate and other fermentation molecules as a substitute for the natural odor from plant substrates showed that the synthetic chemicals were almost always less efficient than the natural plant baits (Avand-Faghih 2004; Table 5.1). With the aim of developing more cost-effective traps (better attraction with lower maintenance costs, particularly by dispensing with the renewal of natural plant bait and the water necessary for fermentation), the contribution of ethyl acetate to traps without natural fermentation odor has been recently reinvestigated. No significant enhancement of the pheromone attraction in pyramidal traps set in an urban environment in Spain was observed (Vacas, Primo, and Navarro-Llopis 2013; Vacas *et al.* 2014). Therefore, the earlier claimed synergistic effect of ethyl acetate with the aggregation pheromone under field conditions was an erroneous extrapolation of the booster effect (Avand-Faghih 2004; Vacas, Primo, and Navarro-Llopis 2013; Vacas *et al.* 2014). In turn, mixtures of ethanol and ethyl acetate (1:1 and 3:1) proved to significantly enhance the pheromone, albeit to a lesser extent than a naturally fermenting substrate (i.e. molasses plus pieces of palm tissue) (Shagagh *et al.* 2008; Vacas *et al.* 2014; Table 5.1). This result corroborated an earlier work in which the 1:1 mixture proved to be synergistic with the aggregation pheromone and to be as efficient as 400 g date palm tissue in an Iranian date palm grove (Avand-Faghih 2004; Table 5.1). In turn, 1.2 kg palm tissue was more efficient than the mixture.

Other chemicals that might be attractive to RPW were also investigated by Gunawardena *et al.* (1998) using a steam distillate of coconut bark (*C. nucifera* L.). The authors identified 4-hydroxy-3-methoxystyrene, and gamma-nonanoic lactone, which gave strong EAG responses and showed some attraction to the weevil in an olfactometer assay; however, no field activity has ever been reported. The main limitation to selecting components of palm odors by EAG is that it cannot predict the behavioral activity, obviously precluding a breakthrough in the selection of the entire set of components necessary to attract RPW, and likely recognized as a whole. In conclusion, the palm tissues, particularly of healthy plants, also emit many chemicals that are not related to fermentation, as shown by Vacas *et al.* (2014) with the Canary Island date palm. The possible role of these compounds should be investigated as they may contribute to a palm odor bouquet, possibly not made up of characteristic palm compounds but rather, as in many cases, of more ubiquitous compounds that provide an odorant signature for the palm weevils (Birkett *et al.* 2004; Bruce, Wadhams, and Woodcock 2005; Bruce and Pickett 2011).

5.4 Vision and Visual Cues

5.4.1 Visual System

The visual system of *R. ferrugineus* is subject to modifications during its life cycle. Indeed, the larval stage lacks any external visual organs. However, the larvae show negative phototaxis when exposed to bright light, which is consistent with their preferred habitat: the dark interior of the palm trunk. It has been demonstrated that the substrate for the detection of light in the larva resides within its central nervous system. In a preparation of isolated ventral nerve cord, the frequency of rhythmic bursts of action potentials in the motor neurons (the crawling pattern) increased during exposure to light. Hence, light-dependent modulation of neural activity is mediated by sparse, non-identified photosensitive cells and not by an image-forming organ, such as an eye or ocellus (Hustert and Mashaly 2013).

The visual system of adult insects usually consists of compound eyes and ocelli. Compound eyes are an assembly of many small eyes that are the functional units, termed ommatidia or facets. Each facet is equivalent to a pixel in a camera sensor. The ocelli are camera-type eyes with a small retina giving a poorly focused image. The visual system of adult RPW is composed of a pair of compound eyes, while the ocelli are absent. The eyes are small relative to body size, positioned at the base of the rostrum (Fig. 5.2A). On the ventral side, the left and right eyes merge, whereas dorsally, they are separated by an ~1 mm gap. The eyes are narrow and elongated, measuring ~0.7 mm in the antero-posterior axis and ~2 mm in the dorsoventral axis. Each eye is an assembly of *ca.*3000 ommatidia. The estimated visual field of the weevil is $\sim 340° \times 60°$, sampled at ~1.5° angular resolution, as defined by the interommatidial angle. In other insects of similar size, the interommatidial angle can be much smaller and the resulting spatial acuity much higher (Land 1997). In the weevil, the eyes cover a large field of view and sample the visual space with modest spatial resolution. Human visual acuity is approximately two orders of magnitude higher than the resolving power of RPW eyes.

The eyes are probably subjected to substantial sheer forces during locomotion, feeding, and burrowing, since the large rostrum acts as a lever. Thus, they are reinforced by a very thick (>100 μm) cornea, and the entire retina is embedded in a hard chitinous mass, which wraps all facets into a beehive-like structure (Fig. 5.2B). The thick cornea is

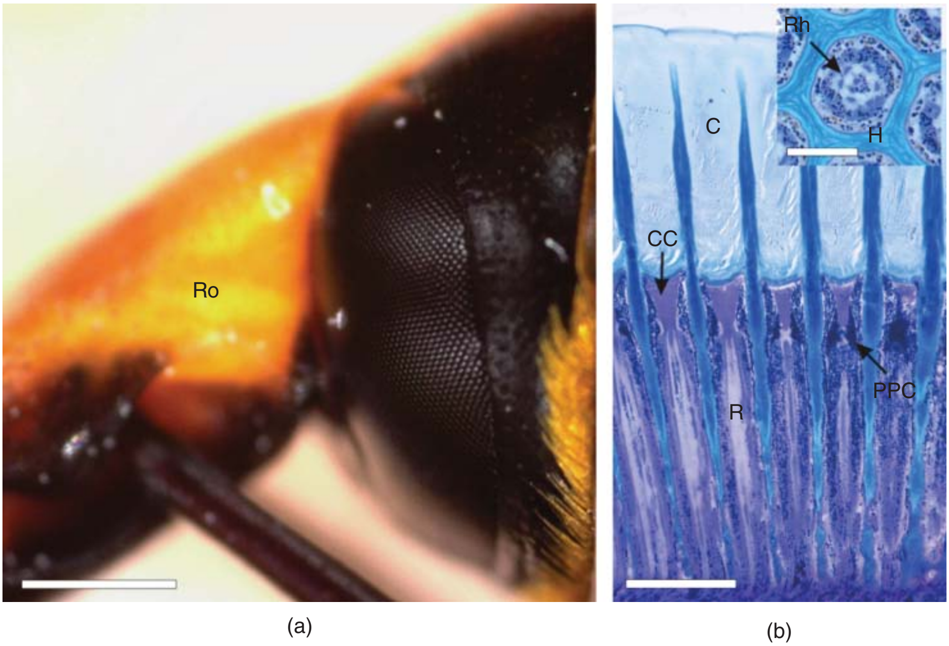


Figure 5.2 Visual system of *R. ferrugineus*. A. compound eye at the base of the rostrum (Ro). B., semi-thin sections of the retina; longitudinal section showing the cornea (C), crystalline cones (CC), primary pigment cells (PPC), photoreceptors (R). Inset, cross-section showing rhabdom (Rh) composed of six rhabdomeres at the periphery of the ommatidium and one rhabdomere at the center of the ommatidium, embedded in chitin (H). The macro photo was obtained with a USB microscope; the semi-thin sections were fixed with 3.5% glutaraldehyde and 4% paraformaldehyde, embedded in Spurr's resin, cut with a glass knife (1.5 μm) and stained with Azur II. Scale bars: A. 0.5 mm, B. main picture, 50 μm, inset, 20 μm. (*See color plate section for the color representation of this figure.*)

structured into elongated corneal lenses. These lenses, with a diameter of ~30 μm, focus light into the light-sensitive part of the facet, the rhabdom. The rhabdom (Fig. 5.2B, inset) is composed of the light-sensing rhabdomeres of the six photoreceptor cells at the peripheral part of the ommatidial cross-section and of a fused rhabdomere of the two photoreceptor cells in the central part of the ommatidium.

During single-cell recordings, we systematically observed that the electrical signals in the photoreceptors are very noisy. Responses to single photons were very large (up to ~4 mV) and resulted in rough receptor responses, even at intermediate light levels, while the whole dynamic working range (light-intensity span) of the photoreceptors was rather narrow. This indicates that the photoreceptor amplification rate is high, most likely due to the low optical sensitivity of the eye. We concluded that the eyes of the RPW are suited for operation in bright light and perform poorly in the dark.

5.4.2 Color Vision

Spectral sensitivity of the compound eye, measured by electroretinography (ERG) (Box 5.3), shows broadband sensitivity with two peaks: a large peak in the green part and a small peak in the UV part of the spectrum. Adaptation of the retina with UV light during the spectral scan selectively suppresses sensitivity in the UV part of the spectrum. Adaptation with green light suppresses sensitivity in both the green and

Box 5.3

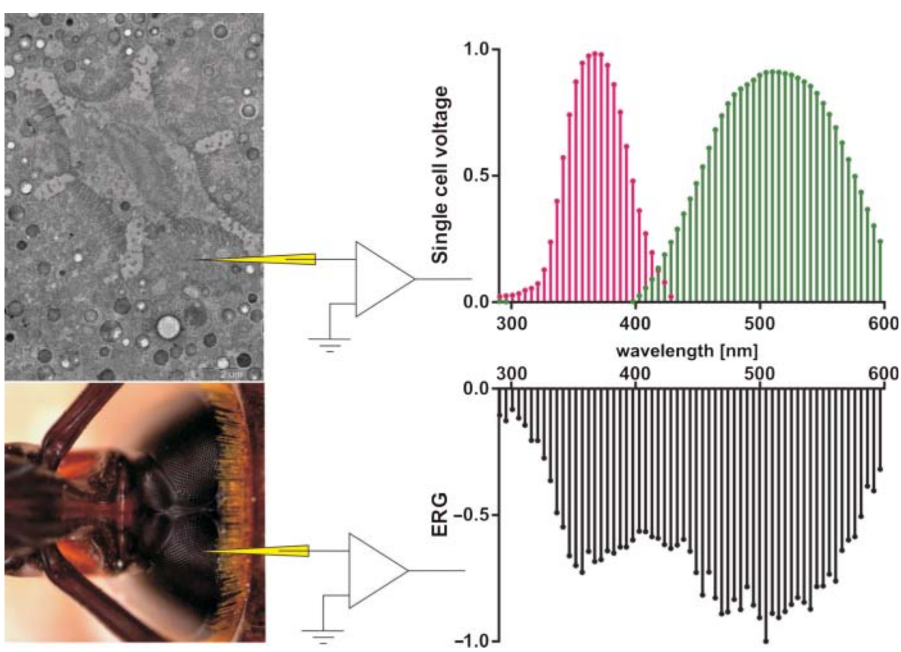
Electrophysiological testing of color vision

Light evokes tiny electrical events in the light-sensitive cells in the eye, the photoreceptor cells. These are changes in the electrical potential across the cell membrane, which trigger the secretion of neurotransmitters, so that the information about light is conveyed to the brain. Responses of the photoreceptors can be measured with microelectrodes. If a blunt electrode is inserted into the eye, mass recording of a large population of photoreceptors contributes to a compound electrical signal, the electroretinogram (ERG). Careful insertion of a sharp microelectrode through a microsurgically cut hole in the eye surface (cornea) allows for selective, single-unit recording of the receptor potential, created by the light response of a single photoreceptor cell.

Insect eyes are an assembly of different photoreceptor cell classes with sensitivities to different parts of the light spectrum. These classes can be identified by electrophysiological recording of spectral sensitivity during the presentation of a series of calibrated light flashes in a range of wavelengths, from UV to near infrared light (300–700 nm).

The ERG signal is non-specific and reflects the average response of many different photoreceptor cell classes. It can be used to roughly estimate the prevalence of different photoreceptor cells in the retina. Single-cell recording from the photoreceptors is performed with similar stimulus presentation as in the ERG. It is very specific and reveals the precise color sensitivity of individual cells. Large numbers of cells must be tested in order not to miss a photoreceptor class.

Microelectrode (spike) recording from the eye with a differential amplifier (triangle) of electrical potential of a single cell (upper row) or the entire retina (lower row)



(Continued)

Box 5.3 (Continued)

against the ground. Upper row, left; electron micrograph of a RPW ommatidium showing the rhabdom composed of six peripheral and two central photoreceptor cells with the light-sensitive part, the rhabdomere, composed of many tubular microvilli. Relative voltage from single cells (upper row, right) shows relative responses of a UV- (360 nm) and green- (520 nm) sensitive photoreceptor. Lower row, left: recording of ERG from the retina (shown ventrally). Lower row, right: ERG is a corneal-negative voltage signal, originating mostly from the green-sensitive and UV-sensitive cells, but no contribution from long-wavelength receptors (570 nm) can be distinguished.

UV parts (Fig. 5.3A). Hence, the RPW retina is equipped with at least two different classes of photoreceptors capable of conveying color vision, one with broadband sensitivity and one with narrowband UV sensitivity. Intracellular measurements from the photoreceptors with a sharp microelectrode (Fig. 5.3B) revealed that most (~60%) of the impaled cells had broad spectral sensitivity, very similar to the sensitivity of the eye measured with the ERG in the dark-adapted state. One-third of the impaled cells had narrow-band sensitivity to green light and no sensitivity in the UV. The rest of the cells had spectral sensitivity maxima in the UV (~5%) and in the yellow (~5%) part of the spectrum (Fig. 5.3B).

The photoreceptor arrangement in the ommatidium of *Rhynchophorus* is reminiscent of the so-called open rhabdom found in many other beetles (Meyer-Rochow and Gokan 1988; Mishra and Meyer-Rochow 2006; Meyer-Rochow and Mishra 2009). This is again very similar to the higher Diptera, such as the flies. In the flies, the six peripheral photoreceptors with broad spectral sensitivity form the achromatic (color-insensitive) channel, feeding the information into the motion-detection circuit directly beneath the retina, while the two central photoreceptors with different, but narrow-band, spectral sensitivities represent the substrate for color and polarization vision, feeding the information into deeper layers of the brain (Borst 2009). A similar photoreceptor arrangement, with the achromatic receptors at the periphery and color detectors in the center of the ommatidium, has been demonstrated in the red flour beetle *Tribolium* (Jackowska *et al.* 2007). The conspicuous morphological division of the rhabdom in the RPW (Fig. 5.2B, inset) suggests that its visual system can be functionally divided into two subsystems as well. Therefore, we assume that the photoreceptors of the RPW with broad sensitivity constitute the achromatic channel, which serves for detection of intensity contrasts and motion detection, while the narrow-band photoreceptors represent the substrate for trichromatic vision with UV, green, and yellow as the primary colors (Ilić *et al.* 2016).

All photoreceptors were sensitive to the direction of polarization of the light (polarization sensitivity ratio ~2).

5.4.3 Tuning of Color Vision to Visual Cues

The visually guided behavior of the RPW includes flight, terrestrial locomotion, and location and identification of hosts and conspecifics. Its color vision is probably tuned to these specific tasks.

As already noted, the weevil is a capable flier, navigating across long distances. In insects, stable flight requires horizon identification and stabilization, and this task is

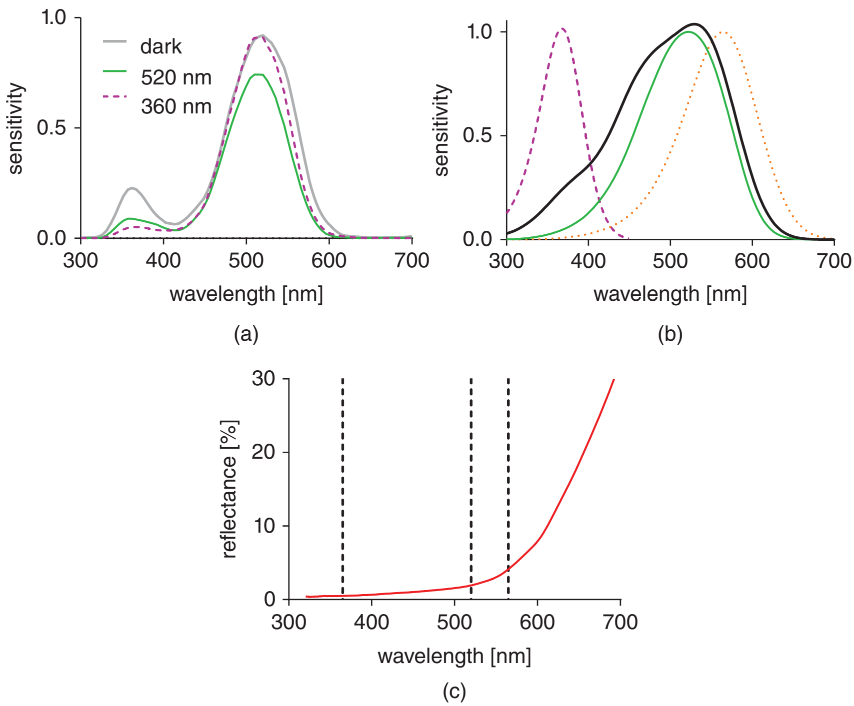


Figure 5.3 Spectral sensitivity of *R. ferrugineus* (A, B) and reflectance of its cuticle (C). A. Spectral sensitivity measured with electroretinography (ERG). Grey, black, and dashed curves correspond to sensitivity measured in the dark-adapted state, or with green (520 nm) and UV (360 nm) adapting light, respectively. Chromatic adaptation reveals selective suppression of sensitivity in the UV or non-selective suppression in the whole spectrum, corresponding to at least two classes of photoreceptors with peak sensitivity in the UV (360 nm) and a class with broadband sensitivity with peaks at 520 nm and 360 nm. B. Spectral sensitivity measured with sharp intracellular electrode. Photoreceptor classes are: thick curve, broadband-sensitive ($\lambda_{max} = 524$ nm; N = 30), dashed curve, UV-sensitive ($\lambda_{max} = 366$ nm; N = 3); thin curve, green-sensitive ($\lambda_{max} = 521$ nm; N = 19); dotted curve, yellow-sensitive ($\lambda_{max} = 564$ nm; N = 4). C. Reflectance of the red part of the weevil's cuticle, relative to the reflectance of an MgO standard, illuminated with a xenon arc lamp. Dotted bars, average sensitivities of the three classes of retinal photoreceptors with narrow-band sensitivity. Reflectance rises sharply above 550 nm. This can be optimally detected by two distinct classes of long-wavelength photoreceptors.

usually performed by the ocelli (Krapp 2009). These simple eyes, usually sensitive to UV light and longer wavelengths, are able to discriminate between the UV-rich sky and the reflectance from the ground, which lacks UV (Goodman 1981). In the RPW, the ocelli are absent and UV detection is performed by the retinal photoreceptors. Reflectance of the palm tree and weevil cuticle does not contain a strong UV component. Hence, we assume that the weevil's UV-sensitive photoreceptors are utilized primarily during locomotion.

The cuticle of adult weevils appears dark red with black spots. The red color is created by high cuticular reflectance at wavelengths > 550 nm. Such reflectance can be very well detected by a set of photoreceptors that are sensitive to the wavelengths within the sloping edge of the reflectance spectrum. RPW is equipped with green- and yellow-sensitive photoreceptors, which can optimally identify its red color. The cuticle does not reflect in the UV and this also creates a specific visual signal by keeping the UV photoreceptors non-excited. Thus, RPW color vision is tuned to the detection and recognition of conspecifics. The trichromatic set of photoreceptors is also suited to the identification of chlorophyll reflectance with a maximum in the green part of the spectrum, which creates the green color of foliage.

The red color of the weevil's cuticle should be rather easy to replicate since it contains no cryptic UV component, while the precise nuance between orange and red is subjected to large variations among individuals and populations. Interestingly, a study demonstrated greatest efficiency of black- and red-colored traps for the weevil (Abuagla and Al-Deeb 2011). Attraction to red and black color could be mediated by the major component of the weevil's visual system, the achromatic photoreceptors. Their sensitivity in the red part of the spectrum is very low (Fig. 5.3B), and they therefore detect red objects as very dark objects. A dark hole in the palm trunk for oviposition is probably a crucial visual cue for the weevil. Even though the red color of the trap could be specifically recognized as an intraspecific signal per se, the shape of the trap definitely did not mimic the shape of a weevil. Instead, a red trap could be perceived by the weevil as a dark spot, similar to the black trap. However, the color preference of an insect in a natural behavioral context cannot be directly inferred from the characteristics of its retina and the analysis of visual cues. Insect behavior is far more complex and depends on multiple sensory inputs. For example, naive *Papilio* butterflies prefer to visit blue patterns in the lab. In the presence of citrus scents, the preference in the females shifts to red color (Yoshida *et al*. 2015). Innate color preferences in insects can depend strongly on the exact behavioral context and can be altered at any level, from detection to multimodal interaction.

5.5 Conclusion

Understanding the ecology of an alien invasive pest such as *R. ferrugineus* is an important preliminary step in the development of reliable and sustainable tools for the management of its populations.

The RPW is characterized by the adult's ability to aggregate on palms. During the aggregation process, chemical and visual cues play a decisive role at intraspecific and interspecific levels, influencing long-range location and short-range recognition of the host and conspecifics. At present, the stimuli necessary for optimal aggregation on palm trees have been partially identified: the aggregation pheromone is described and available while the palm kairomone has been only partially decrypted. The visual capability of RPW based on scientific studies has only very recently been determined, while empirical field trials have provided information on orientation to semiochemicals, preferably in dark or red traps. These various pieces of information have already led to applications, mainly toward the development of pheromone/kairomone-baited traps, for monitoring and mass trapping of this pest. These environmentally friendly methods are particularly desirable in urban environments, where RPW has become one of the most disruptive pests in the cities of Mediterranean areas and people require pest and weed control without pesticides. However, to better exploit semiochemical-based traps, many aspects of the RPW ecology still need to be more deeply investigated, such as the dispersal processes of adults and the fine steps of host palm colonization, particularly the actual composition of the olfactory key emitted by injured palms which synergizes aggregation with the aggregation pheromone.

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6

Paysandisia archon: Taxonomy, Distribution, Biology, and Life Cycle

Nunzio Isidoro[1], Paola Riolo[1], Elisa Verdolini[1], Ezio Peri[2] and Laurence Beaudoin-Ollivier[3]

[1] Department of Agricultural, Food and Environmental Sciences, Marche Polytechnic University, Italy
[2] Department of Agricultural and Forest Sciences, University of Palermo, Italy
[3] Centre de coopération internationale en recherche agronomique pour le développement (CIRAD), Biological System Department, Research Unit Bioagresseurs, France

6.1 Introduction

The intensive worldwide trade of plants and goods, along with increasing tourist traffic, has resulted in the quite common accidental introduction of exotic insects throughout Europe (Pellizzari, Dalla Montà, and Vacante 2005). Moreover, owing to the Mediterranean climate, several alien subtropical species have recently become established. The palm borer moth (PBM) *Paysandisia archon* (Burmeister) has become invasive in many European countries, representing a serious threat to palms. One of the main reasons for this situation is the insect's confinement to the plant in almost all of its life stages, making observation and experimentation difficult, despite its large size. Moreover, information about the PBM, which was never a pest in its native range before settling in the Mediterranean Basin, is scarce, and many aspects of its biology, ecology, and ethology remain undetermined.

The present chapter reviews the current knowledge on the taxonomic position of the Castniidae family, and the current distribution, life cycle, and host range of the PBM. It also focuses on recent studies performed under European Mediterranean conditions.

6.2 Taxonomy of the Castniidae

The family Castniidae is considered to have originated in Gondwana as it is found in Australia (excluding Tasmania), Southeast Asia, and Central South America (Common 1990; Edwards *et al.* 1998). The taxonomic position of the Castniidae within the order Lepidoptera has changed over time. As previously speculated by Mosher (1916) and according to Miller (1986), the Castniidae has some similarities with the families Tortricidae and Cossidae. Edwards *et al.* (1998), based on adult characteristics provided by Minet (1991) and Kozlov, Kuznetzov, and Stekolnikov (1998), placed the Castniidae together with the families Sesiidae and Brachodidae. Moreover, molecular analysis

Handbook of Major Palm Pests: Biology and Management, First Edition.
Edited by Victoria Soroker and Stefano Colazza.

showed phylogenetic affinity with the Cossidae as well as the Sesiidae (Regier *et al*. 2009). Currently, Castniidae has been placed in the superfamily Cossoidea (van Nieukerken *et al*. 2011).

Traditionally, this family has included the subfamilies Tascininae and Castniinae (Edwards *et al*. 1998). The Tascininae is a small subfamily with a single genus *Tascina* Westwood, including four described species that occur in Southeast Asia and the Indo-Malayan region (Fukuda 2000). The Castniinae subfamily contains three tribes. The Castniini and Gazerini tribes are found in the Neotropics. The Synemoniini tribe occurs in the Australian region with 24 species described and placed in the genus *Synemon* Doubleday (Miller 1995; Edwards *et al*. 1998).

The arrangement in tribes was proposed by Westwood (1877) based on some species (Gazerini) that are involved in mimetic complexes with Nymphalidae butterflies; the remaining species were included in Castniini (Strand 1913; Lamas 1995; Miller 1995). However, other species in Castniini may also be involved in mimetic complexes, and the mimetic relationship with butterflies is also a feature in Tascininae and Synemoniini (Moraes and Duarte 2014).

The tribes Castniini and Gazerini make up the most diverse and abundant group of Castniidae. However, taxonomy based exclusively on wing color pattern has generated an exaggerated number of genera and species (Moraes and Duarte 2014). As a consequence, this group has been revisited several times, including quite recently. Miller (1995) listed 134 species of Neotropical Castniidae (Castniini and Gazerini). Lamas (1995) reduced this number to 81 species assigned to 32 genera. More recent revisions have listed 88 species assigned to 31 genera (Pierre and Pierre-Baltu, 2003; Espinoza and González 2005; Miller 2007, 2008; Vinciguerra 2011). Previous authors' hesitation to merge some genera is probably the result of the striking differences in wing pattern, contrasting with the similarities in other morphological traits (Moraes and Duarte 2014). The Neotropical species are currently included in only one tribe, Castniini, and the number of genera has been reduced from 31 to 16 (Moraes and Duarte 2014).

So far, *Paysandisia*, within the Castniini tribe, has been a monotypic genus, with the only species being *P. archon*. Moraes and Duarte (2014) observed that *Geyeria uruguayana* (Burmeister) has morphological attributes that are not related to the nominative genus, but to *Paysandisia*; therefore, based on the general morphological traits for males and females, they proposed a new combination: *Paysandisia uruguayana* (Burmeister) (*Geyeria*). The same authors believed that further morphological studies would show that the species included in genus *Paysandisia* are more closely related to other *Eupalamides* Hübner, and that the two genera could be synonymized (Moraes and Duarte 2014).

P. archon was originally described in 1880 from Argentina as *Castnia archon* by Burmeister, although there is confusion in some publications, where the year is given as 1878 or 1879 (Lepesme 1947; Sarto i Monteys 2002). About 30 years later, it was described as *Castnia josepha* by Oberthür (1914). Houlbert (1918) placed the species *archon* in the now invalid genus *Orthia* Herrich-Schäffer and the species *josepha* in the genus *Paysandisia*. Later, a full 50 years after it was described by Burmeister, Jorgensen (1930) published the first images of the species *C. archon* to the scientific community. Although, in the past, some authors, like Bourquin (1930, 1933) and Breyer (1931), noticed that *C. archon* and *C. josepha* were actually the same species, the taxonomy of the PBM continued to be debated. Indeed, Miller (1986) retained *archon* Burmeister (1880), in the monotypic genus *Paysandisia* Houlbert, 1918, and provided an accurate description of the genus. Later in the same year, Miller (1995) distinguished the Argentinian subspecies *archon archon* from the Uruguayan subspecies *archon josepha*, based only on their extremely sketchy knowledge of their distribution, while Lamas (1995), in his review of Neotropical Castniidae, considered *josepha* to be merely a synonym.

6.3 Distribution of *P. archon*

P. archon is a Neotropical species that is indigenous to South America: northeastern Argentina, Paraguay (Paraguayan Chaco), western Uruguay, and the southernmost state of Brazil, Rio Grande do Sul, all of which are located between the parallels 25° and 35°, just south of the Tropic of Capricorn. Here the moth inhabits extensive open areas where wild palms grow (Sarto i Monteys 2002). Its distribution is mainly scattered in local populations with low abundance levels (Montagud Alario 2004).

Although the moth is not a pest in its native areas, Houlbert (1918) gave a first indication that PBM larvae might cause damage to palm trees. Later, Bourquin (1933) reported severe damage to exotic palms in Paysandù (Uruguay). More recently, mainly in the province of Buenos Aires, where palms are not native, the PBM has become a pest of exotic palms introduced since 1998 for ornamental reasons (Sarto i Monteys and Aguilar 2005) (Fig. 6.1a).

The moth was probably accidentally introduced to Europe between 1992, when the first main import occurred, and 1998, with commodities, mostly *Butia yatay* (Martius) Beccari and *Trithrinax campestris* (Burmeister) Drude and Grisebach, imported from Argentina (Aguilar, Miller, and Sarto i Monteys 2001). The invaded area within Europe grew rapidly from the year 2000, after an initial delay for population establishment (EPPO 2008) (Fig. 6.1b). The presence of the moth was first reported in March 2001, in

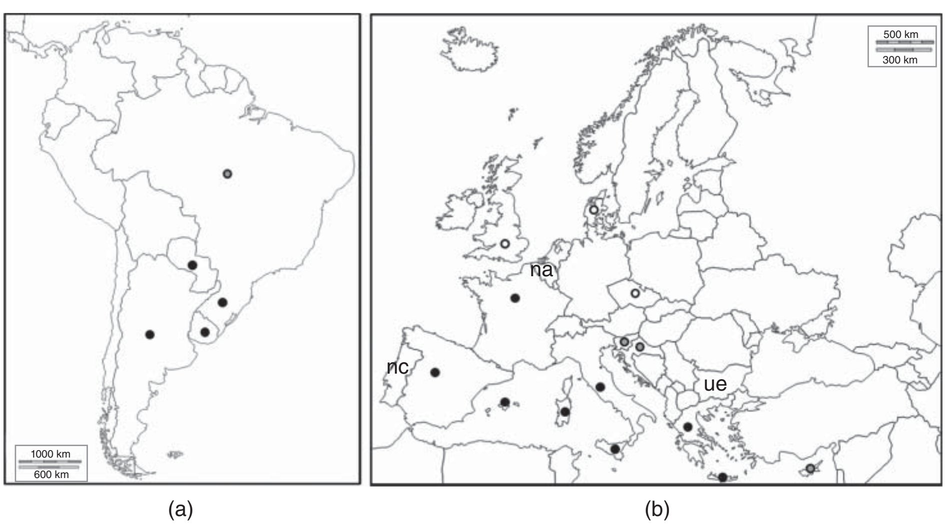

Figure 6.1 Global distribution of *P. archon*: (a) South America; (b) Europe. Black circles: pest presence; gray circles: pest presence in only a few areas; white circles: pest eradicated; na: pest present but not actionable; ue: pest under eradication; nc: pest presence reported but not confirmed.

Catalonia, in the province of Girona, Spain (Aguilar, Miller, and Sarto i Monteys 2001) and soon after, in July 2001, in the Department of Var near Hyères, France (Drescher and Dufay 2001).

Once established, the moth's spread followed the commercial routes of palms as well as natural local dispersal of adults. Since 2002, in Spain, the moth has been detected in several localities of the Valencian Community, the province of Castellón, Alicante, and Valencia, and in the Balearic Islands, Mallorca, and Menorca (EPPO RS 2003/157; 2004/049; Montagud Alario and Rodrigo Coll 2004). It is now present all along the Spanish Mediterranean coast from Girona to Alicante, and a few outbreaks have been reported from Madrid (EPPO RS 2010/058). In France, since 2002, it has also spread to the departments of Alpes-Maritimes, Aude, Bouches-du-Rhône, Gard, Gironde, Hérault, Pyrénées-Orientales, and Vaucluse (Drescher and Jaubert 2003; EPPO 2008; André and Tixier Malicorne 2013).

In November 2002, the moth was reported for the first time in Italy along the Salerno seafront (Campania) (Espinosa, Russo, and Di Muccio 2003). In the fall of 2003, in the province of Ascoli Piceno (Marche), damages were reported on palms due to "big white" larvae, and investigations revealed the presence of the moth in some nurseries in this province. The introduction was probably due to importation of infested trees from both Argentina and Spain (Riolo *et al*. 2004). The pest was then reported in other Italian regions: Puglia, Tuscany, and Sicily in 2004 (Colazza *et al.* 2005; Porcelli *et al.* 2005), Abruzzo in 2005 (CABI 2014), Liguria in 2008 (EPPO RS 2008/137; 2010/146), Emilia-Romagna (Bariselli and Vai 2009), Veneto and Friuli-Venezia Giulia in 2009 (EPPO RS 2009/109; 2010/054), Lazio and Lombardy in 2010 (EPPO RS 2010/098, 2010/207, 2011/150), Basilicata in 2011 (EPPO RS 2011/150), and Sardinia in 2012 (Ciampi 2012) (Fig. 6.2). At present, the moth is considered invasive in France, Italy, and Spain.

Over the years, the moth has been reported in other European countries due to infested palms imported from Italy and Spain (EPPO 2014). In the UK, after two single isolated records in 2002 in Northern Ireland and southern England (Patton and Perry 2002; EPPO RS 2003/121), two recordings were made in May and July 2007 in Kent and north London (Reid 2008). All affected palms were destroyed and the moth is now considered eradicated (EPPO RS 2009/142). The first record in Greece dates back to 2006 from two areas, Crete and Attica (Vassarmidaki, Thymakis, and Kontodimas 2006). In 2008, the moth was found for the first time in Slovenia (EPPO RS 2009/050), where it is now present in only one area, the community of Izola (EFSA PLH Panel 2014). In 2009, Bulgaria and Cyprus Island announced finding the moth (EU 2009a; Vassiliou *et al*. 2009). At present in those countries, PBM is considered under eradication in only a few areas (EFSA PLH Panel 2014). The same year, Denmark also reported its first finding of the moth indoors (Larsen 2009); today, it is considered eradicated (EFSA PLH Panel 2014). In 2010, in Switzerland, the moth's presence was first reported in a few occurrences and is now eradicated (EPPO RS 2010/145). In 2011, the Czech Republic announced the first record of the moth (EPPO RS 2011/137), now considered eradicated (EFSA PLH Panel 2014). The latest reports date back to 2011 in Portugal (Corley *et al*. 2012; EPPO 2014) and to 2012 in Croatia (Milek and Simala 2012). Finally, in Belgium, there were reports of adults in two locations in 2011 and 2012; there the moth is now considered transient but not actionable (EFSA PLH Panel 2014).

The accidental introduction and subsequent spread of PBM occurred by three pathways: (1) the commercial import of palms (Arecaceae) originating from areas where the

Figure 6.2 Detailed distribution of *P. archon* in Italy. Dates indicate the first PBM report in each region.

pest occurs, (2) the movement of palm trees from a contaminated area to one that is free of the pest, and (3) natural adult spread. The first pathway acts at the international level and is probably the main pathway by which the pest spreads over large distances, as it can often go undetected. The second one acts at the national level, as a consequence of not only commercial movement of plants but also of citizens' individual actions. The third pathway acts at the local level, depending on the flight abilities of the moth.

Today, the moth is listed as a quarantine pest in EPPO member countries (EPPO 2008), and the European Community, with Commission Decision of 10/02/2009 no 2009/7/EC, has established protective measures against the introduction into the Community of organisms harmful to plants or plant products and against their spread within the Community (EU 2009b). Thus, the risk of new introduction or spread of the insect within the EC by internal trade or natural spread is low. However, the southern part of the EPPO region (Mediterranean countries and Macaronesia) is most at risk.

6.4 Morphology of *P. archon* Stages

The *P. archon* egg is a typical fusiform Castniid egg, resembling a rice grain and bearing six to eight raised longitudinal ridges, which have associated aeropyles along their length, and the micropyle at one end of the long axis. When freshly laid, it is

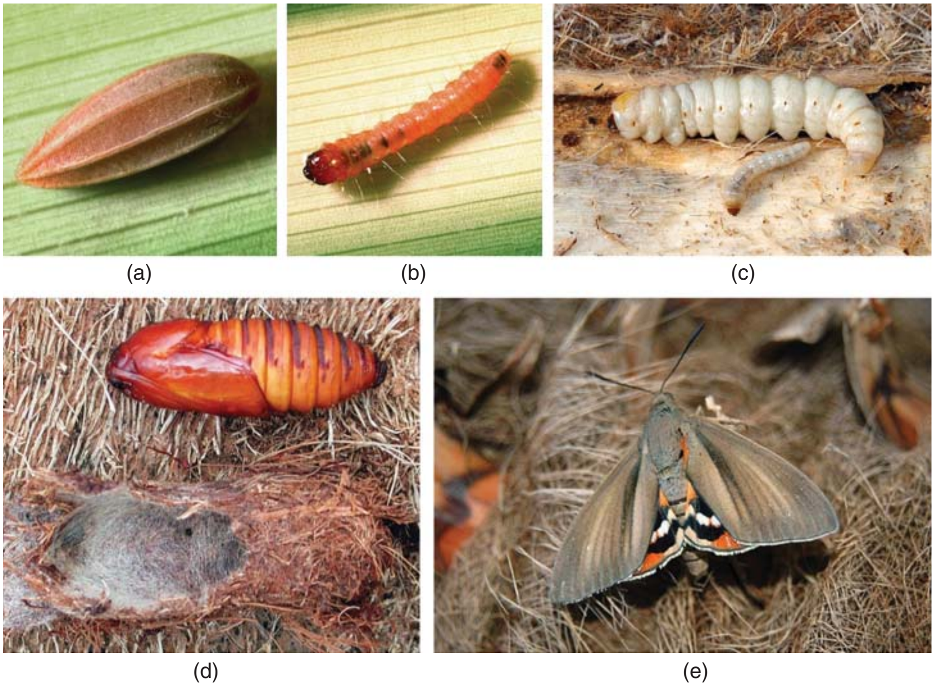

Figure 6.3 *P. archon* stages: (a) egg; (b) first instar larva; (c) larvae in various instars; (d) cocoon and pupa; (e) adult. (Source: Images by Paola Riolo)

creamy pink or light brown, becoming rosy brown as the days pass. Its length averages 4.69 ± 0.37 mm, with most measuring between 4.4 and 5.2 mm. Its width at the widest section averages 1.56 ± 0.11 mm, with most measuring between 1.50 and 1.60 mm (Sarto i Monteys *et al*. 2005) (Fig. 6.3a).

The larva emerges by gently splitting the egg chorion along one of the longitudinal ridges. Immediately after hatching, the larva is pink, except for the head capsule, which is light brown. Moreover, chaetotaxy differs in the number and length of the setae, which are much longer than in subsequent larval stages, and cuticular spinules are not present. Through the first instar, the rosy color fades to whitish and the long straight-lined setae becoming shorter. After the first molt, the larva becomes ivory white, chaetotaxy changes and the setae become much shorter, and cuticular spinules appear. These new traits are retained throughout the remaining larval stages. Earlier instars show a blackish dorsum as a consequence of the blackish longitudinal dorsal vessel clearly seen from outside the body. Later instars turn to a more intense ivory white and the dorsal vessel is less obvious. Light-brown cuticular spinules on the dorsum of the prothoracic segment form an "M" mark, which is more obvious in mid- and later instars. From the first to last instar, the larvae of *P. archon* increase dramatically in size. After emergence, the body length is 7.3 ± 2.2 mm, the width of the head capsule at the widest part being 1.00 ± 0.10 mm. When full-grown, before entering the prepupal stage, the larva may reach a body length of 9 cm, a width of 1.5 cm at mid-length, with the widest part of the head capsule being 7.84 ± 0.34 mm (Miller 1986; Sarto i Monteys and Aguilar 2005) (Fig 6.3b, c).

At first, the pupa is pale yellow, turning to reddish brown after the pupal cuticle darkens and hardens. The size of the pupa is about 5.5 cm (Sarto i Monteys and Aguilar, 2005). Most of the abdominal segments of the pupa are furnished dorsally with transversal rows of short spines pointing backwards. In particular, two rows of dorsal spines are present on segments II – VIII in males and on segments II – VII in females, and only one row in the last abdominal segments (Riolo, unpublished). The pupa is protected by a palm-fiber cocoon within the burrow. Under laboratory conditions, pupation may occur without this cocoon (Beaudoin-Ollivier, unpublished). The cocoons are fusiform with an average length of 5.8 cm, and are stout, with the inner walls smoothly coated by a layer of silk and secretions. The outer walls are loosely covered by fragments of palm fibers which make cocoons inconspicuous (Sarto i Monteys and Aguilar 2005) (Fig 6.3d).

The adult is a big diurnal moth, with a large wingspan of 6 – 11 cm. The forewings are greenish-brown, with a blackish-brown median band. The hindwings are orange with a wide transverse black band containing five or six white cells. The antennae are clubbed with a typical apical hook. Females are generally larger than males and bear a long telescopic ovipositor (Miller 1986; Sarto i Monteys and Aguilar 2005) (Fig 6.3e). For extensive descriptions and images of antennal and ovipositor morphology and fine structure, see Chapter 7, this volume.

6.5 Biology

6.5.1 Host Plants

P. archon seems to have a large range of genera within the monocotyledonous family of palms (Arecaceae) (Table 6.1).

In South America, Houlbert (1918) reported *Phoenix canariensis* Chabaud as a food plant for the moth in Paysandù (Uruguay). In the same area, Bourquin (1930, 1933) reported a list of host palm species, including *B. yatay*, *Chamaerops humilis* L., *Livistona chinensis* (Jacquin) Brown ex Martius, *P. canariensis*, and *T. campestris*. Lepesme (1947) reported *Latania* spp. in Argentina. In the state of Rio Grande do Sul (Brazil) (De Biezanko 1961) and in Uruguay (Ruffinelli 1967), *L. chinensis*, *P. canariensis*, and *Syagrus romanzoffiana* (Chamisso) Glassman were reported as host plants for *P. archon*. In the province of Buenos Aires, where palms are not native but have been introduced since 1998 for ornamental purposes, *B. yatay*, *Butia capitata* (Martius) Beccari, *P. canariensis*, and *T. campestris* were certainly affected (Sarto i Monteys and Aguilar 2005).

In Europe, the moth has a broad host range. In Spain (Catalonia, Valencian Community, and Balearic Islands), PBM infestation has been reported on *Brahea armata* Watson, *C. humilis*, a *Livistona* sp., *P. canariensis*, *Phoenix reclinata* Jacquin, *Phoenix roebelenii* O'Brien, a *Sabal* sp. (maybe *minor* (Jacquin) Persoon), *S. romanzoffiana*, *Trachycarpus fortunei* (Hooker) Wendland, *T. campestris*, *Washingtonia filifera* (Linden) Wendland, and *Washingtonia robusta* (Linden) Wendland (Sarto i Monteys and Aguilar, 2005).

In France, Drescher and Jaubert (2003) listed 21 PBM host palm species belonging to nine genera, some of which were not reported in Spain, such as *Brahea edulis* Wendland, *B. capitata*, *Phoenix dactylifera* L., *Phoenix sylvestris* (L.) Roxburgh, *Livistona australis* (Brown) Martius, *L. chinensis*, *Livistona decipiens* Beccari, *Livistona saribus* (Loureiro) Merrill ex Chevalier, *Sabal mexicana* Martius, *S. minor*, *Sabal palmetto* (Walter) Loddiges, and *Trachycarpus wagnerianus* Beccari. Moreover PBM infestation symptoms

Table 6.1 List and status of *P. archon* host plants.

Taxonomic position within Angiospermae, Monocotyledonae Clade: Commelinids Order: Arecales Family Arecaceae Subfamily, genus and species	Common name	Main features					Infestation: Conditions and amplitude
		Originating area	Originating climate and biotope	Economic value	Host and susceptibility status	Abundance	
Arecoideae							
Butia capitata (Martius) Beccari	Jelly p.	South America	Trop dry forest	Orn Cult	$H_{n;}$; H	r	Positive development under natural conditions in both native (6) and invasion (7) areas
Butia yatay (Martius) Beccari	Yatay p.	South America	Trop dry forest	Orn	H_n	r	Positive development under natural conditions in native area (3, 6)
Elaeis guineensis Jacquin	African oil p.	Africa panTrop	Trop moist forest	Cult	PH	0	Larval development under forced larval infestation (13)
Howea forsteriana Beccari	Kentia p., Thatch p.	Australia	Trop moist forest	Orn	H (Italy); H? (Portugal)	r	Positive development under natural conditions in invasion area (10, 14)
Jubea chilensis (Molina) Baillon	Chilean wine p.	Chile	Med forestland scrub	Orn	H	r	Report of symptoms in invasion area (8)
Syagrus romanzoffiana (Chamisso) Glassman	Queen p., giriba p.	South America	Trop dry forest	Orn	$H_{n;}$; H	r	Positive development under natural conditions both in native (4, 5) and invasion (6) area

Coryphoideae							
Brahea armata Watson	Mexican blue p., blue hesper p.	North and Central America	Desert and xeric shrubland	Orn	H_n	r	Positive development under natural conditions in invasion area (6, 7, 8)
Brahea edulis Wendland	Guadalupe p.	North and Central America	Desert and xeric shrubland	Orn	H	r	Positive development under natural conditions in invasion area (7)
Chamaerops humilis L.	European fan p.	Med basin	Med forest and scrub	Pat Orn	H_n; H+	+++	Positive development under natural conditions in native area (3) and very high mortality in invasion area (6, 7, 9, 12); larval development in semi field under natural egg-laying (12)
Latania spp.	Latan p.	Islands of Indian Ocean	Trop moist forest	Orn Pat	H_n	r	Positive development under natural conditions in native area (15)
Livistona australis (Brown) Martius	Cabbage-tree p.	Australia	Med forest and scrub	Orn Trad	H	r	Positive development under natural conditions in invasion area (6, 7)
Livistona chinensis (Jacquin) Brown ex Martius	Chinese fan p., fountain p.	Far East Asia	Med forest and scrub	Orn Trad	$H_{n;}$; H	r	Positive development under natural conditions in both native (3, 4, 5) and invasion (6, 7) areas
Livistona decipiens Beccari	Ribbon fan p.	Australia	Trop dry forest	Orn	H	r	Positive development under natural conditions in invasion area (6, 7)
Livistona saribus (Loureiro) Merril ex Chevalier	Taraw p.	Far East Asia	Trop moist forest	Orn	H	0	Positive development under natural conditions in invasion area (6, 7)
Phoenix canariensis Chabaud,	Canary p.	Canary Islands	Med forestland scrub	Pat Orn	H_n; H-	+++	Positive development under natural conditions in native area (1, 2, 3, 4, 5, 6) and very high mortality in invasion area (6, 7, 9, 12); larval development in semi field under natural egg-laying (12)

(*Continued*)

Table 6.1 (Continued)

Taxonomic position within Angiospermae, Monocotyledonae Clade: Commelinids Order: Arecales Family Arecaceae	Common name	Main features					Infestation: Conditions and amplitude
Subfamily, genus and species		Originating area	Originating climate and biotope	Economic value	Host and susceptibility status	Abundance	
Phoenix dactylifera L.	Date p.	Asia Middle East	Med forestland scrub	Cult	H	+++	Positive development under natural conditions in invasion area (7)
Phoenix reclinata Jacquin	Wild date p., Senegal date p.	Africa	Trop dry forest	Orn Trad	H	r	Positive development under natural conditions in invasion area (6)
Phoenix roebelenii O'Brien	Pygmy date p.	Far East Asia	Med forestland scrub	Orn	H	r	Positive development under natural conditions in invasion area (6)
Phoenix sylvestris (L.) Roxburgh	Silver date p. Sugar date p.	Asia	Med forestland scrub	Orn Trad	H	r	Positive development under natural conditions in invasion area (7)
Phoenix theophrasti Greuter	Cretan date p.	Med basin Greece Turkey	Med forestland scrub	Pat	H	r	Positive development under natural conditions in invasion area (11)
Sabal mexicana Martius	Mexican palmetto, Texas palmetto	North America	Med forestland scrub	Orn	H	r	Positive development under natural conditions in invasion area (7)
Sabal minor (Jaquin) Persoon	Dwarf palmetto, Bush palmetto	North America	Med forestland scrub	Orn	H	r	Positive development under natural conditions in invasion area (6)

Sabal palmetto (Walter) Loddiges	Cabbage p., palmetto p., cabbage palmetto	North America	Med forestland scrub	Orn	H	r	Positive development under natural conditions in invasion area (7)
Trachycarpus fortunei (Hooker) Wendland	Chusan p., windmill p., Chinese windmill p.	Asia China	Temperate mixed forest	Orn	H+	++	Very high mortality under natural conditions in invasion area (6, 7, 9, 12); larval development in semi field under natural egg-laying (12)
Trachycarpus wagnerianus Beccari	Dwarf windmill p.	Asia	Temperate mixed forest	Orn	H	r	Positive development under natural conditions in invasion area (7)
Tritinax campestris (Burmeister) Drude and Grisebach	Caranday p.	South America	Trop dry forest	Orn	$H_{n;}$; H	r	Positive development under natural conditions in both native (2, 3, 6) and invasion (6, 7) areas
Washingtonia filifera (Linden) Wendland	Desert fan p.	North America	Med forestland scrub	Orn	H+	++	Very high mortality under natural conditions in invasion area (6, 7, 9, 12)
Washingtonia robusta (Linden) Wendland	Mexican fan p.	North America	Desert and xeric shrubland	Orn	H+	++	Very high mortality under natural conditions in invasion area (6, 7, 9, 12); larval development in semi field under natural egg-laying (12)

Common names: p., palm.
Climate and Biotope: Med, Mediterranean; Trop, Tropical.
Economic/patrimonial value: Cult, cultivated for fruits; Orn, ornamental; Pat, patrimonial for biodiversity as locally native in one of the EU territories; Trad, traditional use (beverage, sugar…).
Host and susceptibility status: H_n, host in neotropics; H+, host in invading area with high susceptibility (high economic impact); H-, host in invading area with low susceptibility compared to abundance; H, host in invading area with insufficient data to establish degree of susceptibility; H?, host in invading area with unconfirmed record; PH, potential host (development possible under laboratory conditions).
Abundance in Mediterranean area and EU: +++, highly abundant and widely distributed; ++, locally abundant as avenue or park trees but much less than +++; r, rare and scattered in parks and gardens as compared to ++; 0, absent or extremely rare, essentially in greenhouses.
Infestation: Conditions and amplitude: The number refers to the reference in the reference list below.
References: 1. Houlbert 1918; 2. Bourquin 1930; 3. Bourquin 1933; 4. De Biezanko 1961; 5. Ruffinelli 1967; 6. Sarto i Monteys and Aguilar 2005; 7. Dresher & Jaubert 2003; 8. INRA 2014; 9. Riolo *et al.* 2004; 10. EPPO 2014; 11. Psirofonia & Niamouris 2013; 12. Riolo, personal observation; 13. Beaudoin-Ollivier *et al.* 2014; 14. Suma, personal observation; 15. Lepesme 1947.

have been observed on palm leaves of the genus *Jubaea* Kunth (INRA 2014), which is also listed in the legislation addressing PBM (EU 2009b).

In the Marche region of Italy, high plant mortality of up to 90% in ornamental palm nurseries has been recorded for *C. humilis*, *P. canariensis*, *T. fortunei*, and *Washingtonia* spp. Wendland (Riolo *et al*. 2004). No other PBM host palm species were subsequently recorded in other Italian regions or in other European countries, except for three single reports. Indeed, in Sicily in 2014, an attack was observed on a *Howea forsteriana* Beccari plant that was cultivated in a nursery where several *C. humilis* plants were seriously damaged (Suma, personal observation). Signs of a possible infestation on two *H. forsteriana* trees were also reported in Portugal, but this record remains unconfirmed (EPPO 2014). Moreover, in 2012, the first infestation by the moth on Cretan palm trees *Phoenix theophrasti* Greuter, an endemic species in Greece, was reported (Psirofonia and Niamouris 2013).

Although *P. archon* has not been reported to be a significant pest in South America, with the exception of reports from Buenos Aires (Sarto i Monteys and Aguilar 2005), and rarely kills date palms (*P. dactylifera*) or Canary palms (*P. canariensis*), it has been the cause of serious damage and plant mortalities in France, Italy, and Spain. Moreover, the native Mediterranean fan palm, *C. humilis*, which is endemic in natural Euro-Atlantic landscapes, is very susceptible to PBM attack (Riolo *et al*. 2004). Finally, a preliminary laboratory study established *Elaeis guineensis* Jacquin as a possible host for PBM (Beaudoin-Ollivier *et al*. 2014). Recent research under the Palm Protect project has aimed to determine the host palm tree range under European environmental conditions.

In France, observation of oviposition choice in field condition shows that mated females are capable of distinguishing palm species, preferring *P. canariensis* for oviposition when available. The mated ovipositing female moth did not avoid it, although less preferred than other palm species. Little damage has been reported on *W. robusta*, suggesting an antibiosis mechanism of resistance against this pest as observed also for RPW (Dembilio, Jacas, and Llácer 2009). Moreover, ovipositing females do not avoid palms with previously laid eggs (Frérot, personal communication and Beaudoin-Ollivier, unpublished). A significant choice for *W. filifera* that had been damaged the year before was observed compared to healthy palms of the same species (Beaudoin-Ollivier, unpublished). Oviposition observations in a wind tunnel showed that the orientation behavior of mated females is characteristic of a chemically mediated attraction and follows a chemo-anemotactic process (Frérot, personal communication).

Extensive periodic surveys were carried out in open fields in the Marche region: the highest degree of susceptibility to PBM was determined in *C. humilis*, followed in descending order by *T. fortunei*, *Washingtonia* spp., and *P. canariensis*. The highest level of infestation was observed on a 3.5 m tall *T. fortunei* palm tree, which harbored 20 specimens of PBM (larvae and pupae). Further surveys in a plantation of 3- to 10-year-old *T. fortunei* showed that 80% of the palms were infested. Infestation in nurseries on potted 2- to 3-year-old *C. humilis* was up to 95%. A semi field choice assay between palm species showed *W. robusta* and *T. fortunei* to be the most infested, followed in descending order by *C. humilis* and *P. canariensis*. The mean number of eggs and larvae in infested palms was higher in *P. canariensis*, although not significantly so (Riolo, personal observation). A similar choice assay carried out in the south of France revealed a preference for young *P. canariensis* seedlings for oviposition with a maximum of nine eggs per seedling. Then, *W. filifera* and *C. humilis* were chosen for oviposition, before *T. fortunei* and *E. guineensis* (Beaudoin-Ollivier, unpublished).

To locate a host plant, PBM can exploit volatile organic compounds emitted from the plants. The biological activity of some of these was evaluated by electrophysiological bioassays (EAG) (see Chapter 7, this volume). This investigation demonstrated that female and male moths, with higher sensitivity for the former, respond to linalool, one of the major compounds of palm volatiles, and to esters such as ethyl acetate, ethyl propionate, ethyl butyrate, ethyl isobutyrate, and ethyl lactate, produced by damaged and fermenting palm-tissue volatiles. Among the compounds tested, ethyl isobutyrate elicited the strongest antenna responses (Ruschioni *et al.* 2015).

6.5.2 Life Cycle

There is little information about *P. archon* from its native area due to the lack of economic importance. There is virtually no detailed information on its biology in Europe. Houlbert (1918) was the first to provide data on the biology and host plants of PBM. Later, Bourquin (1930, 1933, 1944) briefly described the moth stages and provided some biological data.

In Europe, adult moths are active during the hottest part of sunny days, from mid-May to September – October, with a peak in June – July. In contrast, adults are inactive under cloudy or rainy weather conditions (Riolo *et al.* 2004; Sarto i Monteys and Aguilar 2005; Liégeois, Tixier, and Beaudoin-Ollivier 2014). In Buenos Aires province, the occurrence of adults is reported from early November to early May; this is quite similar to the occurrence in the Northern hemisphere (Sarto i Monteys and Aguilar 2005).

The adult life span in the wild is unknown, although it is most likely to fall short of that found in captivity, where females live an average of 14.1 days and males 23.8 days, although there is information about the physiological status of the insects. Moreover, it was noticed that the adult life span could be significantly extended by refrigeration (Sarto i Monteys and Aguilar 2005). Observation in the Marche region, Italy, showed an adult life span ranging from a minimum of 3 days to a maximum of 20 days, with an average of 10.3 days (Riolo, Isidoro, and Nardi 2005), while mated caged males survived an average of 33 days (Riolo, personal observation). In France, under natural conditions, the mean life span of virgin encaged males was 21.0 ± 3.6 days (mean $\pm$ SD), whereas mated males survived 12.0 ± 2.0 days. Mated females lived 11.4 ± 2.3 days and virgin females 8.7 ± 3.4 days under natural conditions (Hamidi, personal observation). Despite their well-developed proboscis, adults have never been seen feeding in the wild or in captivity (Miller, 1986).

The times of the day at which adults emerge are quite numerous. Emergence may occur at night or in the morning, between 1000 and 1300 h (Sarto i Monteys and Aguilar 2005). Drescher and Jaubert (2003) reported emergences occurring early in the morning, before 0800 h, in the laboratory. The adults start to fly 1 – 2 h after emerging; they are strong flyers during the day and have a peak of flying activity between 1100 h and 1700 h in insect-proof tents (Drescher and Jaubert 2003). Dispersal capabilities of the adults have never been documented by tracking tagged individuals. Preliminary experiments to determine flight capability and conditions using a wind mill indicated a mean flight time of around 1 min, with maximum mean flight times of 2.76 and 4 min (♂ and ♀), maximum flight distances of 195 and 310 m (♂ and ♀), and a maximum speed of 6 – 7 km/h for virgin specimens of both sexes (Beaudoin-Ollivier, unpublished). Radio telemetry has been used to trace the movement of PBM under natural conditions. Results revealed high mobility for the females, which are responsible for the spread of the species (>500 m), whereas the males were successfully tracked in a restricted area estimated at 4 ha (Liégeois, Tixier, and Beaudoin-Ollivier 2014).

Recent studies indicate that 73% of the adults are sexually mature 3 h after emergence (Delle Vedove *et al*. 2012). In outdoor experiments, mating peaks between 1400 h and 1500 h, and 87% of the females are fertilized and start laying eggs 1.25 (±1.14) days after mating (Delle Vedove *et al*. 2012). Riolo *et al*. (2014) reported that in semi field conditions mating occurred mainly in the morning from 0930 to 1130 h; mated moths were 1–2 days old. Under laboratory conditions, mating occurred in the afternoon, as soon as the cage with males and females was in the sun (Beaudoin-Ollivier, unpublished).

Females are generally monandrous, but nevertheless remain attractive after mating (Delle Vedove *et al*. 2012). PBM males are expected to mate more than once (Delle Vedove *et al*. 2012), as in most Lepidoptera (Rutowski 1982). For extensive data on PBM courtship and mating behavior, refer to Chapter 7, this volume.

Females lay eggs singly, sometimes in small clusters but not glued, within the plant fibers, close to or in the crown of the palm, at the base of the leaf, on the stem, or in the terminal bud. The average number of eggs laid in the wild is not known but could be around 140 on the basis of observations of female dissections by Sarto i Monteys and Aguilar (2005). Eggs are found from late May to mid-October. As for embryonic development, hatching occurs after 12 to 21 days, depending on the temperature (Drescher and Jaubert 2003; Sarto i Monteys and Aguilar 2005). Because the larvae do not eat the chorion after hatching, hatched eggs can be found at any time within the palm fiber webs where they are laid (Sarto i Monteys and Aguilar, 2005).

The larvae start looking for food immediately after hatching and bore into the host plants. The larvae are endophagous for most of their lives and are highly lucifugal, with only the first instar being partly or fully exophagous. They feed by tunneling long galleries in the succulent plant material of stems, leaves, and fruit and complete their preimaginal development in the plants. For an extensive description and images of symptoms, refer to Chapter 9, this volume.

The final larval instar seems to be the ninth, although in captivity pupation has also been observed after the seventh or eighth instar (Sarto i Monteys and Aguilar 2005). The larval stage is the longest and most complex developmental stage; it is the only one that overwinters. During the winter, nearly all larval instars can be found within the palms in the wild, including prepupal larvae (Riolo, Isidoro, and Nardi 2005; Sarto i Monteys and Aguilar 2005). Although the overwintering larval populations live protected, cold winters might increase their mortality. A measure of larval survivorship capacity indicated that development for the immature stages is optimum when the temperature is fluctuating during the cold period (Beaudoin-Ollivier, unpublished).

The larval stage, including the prepupal period, lasts from 10.5 months in larvae having a 1-year cycle to 18.5 months in larvae having an almost 2-year cycle. One-year-cycle larvae are fully grown at the end of the winter, building their cocoons from mid-March to mid-April and becoming adults in early summer. Under laboratory conditions, the prepupal stage might be observed 6–8 months after hatching (Beaudoin-Ollivier, unpublished). Otherwise, 1-year-cycle larvae reach their last instar in late spring and become adults in late summer. Larvae that overwinter twice build their cocoons at the end of the second winter and, in this case, adults emerge in May–June of the second year. The prepupal stage, characterized by full-grown larvae making their cocoons, is made up of two periods. The first includes the time spent by the larva making the cocoon; the second one starts after the cocoon has been built and includes time spent by the larva inside the cocoon before conversion into a pupa. Its duration is very variable, from a few days to several weeks if lethargy occurs (Sarto i Monteys and Aguilar 2005).

The cocoons are always located near or on the surface of the trunk or leaf axillae, well camouflaged, at one end of the larval gallery. Cocoons with living pupae can be found from mid-March to mid-September, whereas empty cocoons can be found anytime as they remain on the palm after adult emergence. Sarto i Monteys and Aguilar (2005) reported that 43–66 days are necessary for pupae to complete their metamorphosis to adults, depending on when they formed; from 25 to 46 days have been reported in France (Beaudoin-Ollivier, unpublished). PBM pupae react to low temperatures by slowing down or halting their transformation into adults.

Overall, the PBM life cycle in Spain from egg to adult lasts from 12.8 months in specimens having a 1-year cycle to 22.1 months in specimens having a 2-year cycle (Sarto i Monteys and Aguilar 2005). In Europe, all stages of the pest (eggs, larvae, pupae, and adults) can be observed during the summer (Riolo *et al*. 2004).

6.6 Conclusion

P. archon has been able to successfully invade the Euro-Mediterranean area despite earlier actions and regulations. A review of available data, as a starting point, along with relevant new investigations, is therefore necessary to fill in the knowledge gaps in assessing host selectivity and its underlying mechanisms, dispersal capabilities of the pest, and the duration of its life cycle under Euro-Mediterranean conditions. The data will support decisions for risk assessment, improvement of monitoring, and control means for use by EU Plant Protection authorities and NPPOs, as well as regulation.

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7

Paysandisia archon: Behavior, Ecology, and Communication

Brigitte Frérot[1], Rachid Hamidi[1], Nunzio Isidoro[2], Paola Riolo[2], Sara Ruschioni[2], Ezio Peri[3], Roberto Romani[4], Gregor Belušič[5] and Primož Pirih[6]

[1] *Institute of Ecology and Environmental Sciences of Paris, Sensory Ecology Department (UMR 1392), Institut national de la recherche agronomique, INRA Versailles, France*
[2] *Department of Agricultural, Food and Environmental Sciences, Marche Polytechnic University, Italy*
[3] *Department of Agricultural and Forest Sciences, University of Palermo, Italy*
[4] *Department of Agricultural, Food and Environmental Sciences, University of Perugia, Italy*
[5] *Department of Biology, Biotechnical Faculty, University of Ljubljana, Slovenia*
[6] *Graduate University for Advanced Sciences, Sokendai, Kanagawa, Japan*

7.1 Introduction

The order Lepidoptera is separated into two groups: Rhopalocera (butterflies), which includes most of the day-flying Lepidoptera, and Heterocera (moths) containing most of the night-flying Lepidoptera. The period of flying activity is for most of the Lepidoptera correlated with wing pattern: diurnally active adult Lepidoptera usually bear colored and shiny wings that are used primarily for display or mimicry, while nocturnally active usually bear gray or brownish wings for camouflage, since visual communication is less suitable during night-time. Visual cues are known to be very important for day-flying Lepidoptera and several behavioral studies have reported that these cues drive mating behaviors (Hill 1991; Jiggins *et al*. 2001; Hernandez-Roldan *et al*. 2014). In moths, visual cues are considered minor stimulation and most of the environmental perceptions rely on odors.

P. archon belongs to the Heterocera (moth group) but it is a day-flying lepidopteran. Other day-flying Lepidoptera moths include the Zygaenidae and some Tortricidae that exhibit brightly colored wings, as perceived by human vision, but they also produce a sex pheromone (Zagatti and Renou 1984; Witzgall and Frérot 1989).

A few studies have reported on the cues used to find host plants in day-flying Lepidoptera as well as night-flying moths, although more is known for the latter group, where chemical cues are reported to steer host-plant localization. In all Lepidoptera, physical cues are also known to act during host-plant selection and during probing behavior exhibited by gravid females (Catalayud *et al*. 2008).

With *P. archon*, we are dealing with an original insect, newly introduced, and developing into an urban biotope that is different from that in the native area. This chapter covers intraspecific behaviors and interactions with host plants, with a focus on chemical and visual cues.

Handbook of Major Palm Pests: Biology and Management, First Edition.
Edited by Victoria Soroker and Stefano Colazza.

7.2 *P. archon* Reproductive Behavior

In moths, reproductive behavior follows a specific scheme with few exceptions. The adult female releases a sex pheromone produced by an epidermic gland located at the abdominal extremity between the 8th and 9th segments. Pheromone release is associated with a particular behavior characterized by abdomen extension and referred to as "calling behavior." The pheromone is perceived at long range by the antennae of mature males that fly up to the air stream carrying the pheromone molecules. During calling behavior, the female distends the abdomen and exposes the gland part which is usually invaginated under the 7th segment. The reproductive behavior follows a diel periodicity and is related to the maturity of the insects. The courtship behavior can be very simple (Frérot *et al*. 2006) or very sophisticated, with a chemical dialogue between the male and females (Baker and Cardé 1979). Little is known about sexual behavior in Castniidae moths. Studies on the reproductive behavior of *P. archon* were predominantly performed to identify a sex pheromone, which could be used to monitor populations.

7.2.1 Diel Periodicity of Mating

The female calling and mating behaviors are periodic events controlled by the diel periodicity. Delle-Vedove *et al*. (2014) demonstrated that mating occurs under cage conditions during the daytime, for most pairs from 10:00 to 17:00 h. Observations *in natura* have corroborated these observations, with a mating period from 12:00 h to 15:00 h (Hamidi, personal observation).

The female can mate from the day of adult molting. Female polyandry is infrequent and was reported for only 6% of the studied pairs. After dissection of the *bursa copulatrix* of females collected *in natura*, 100% of the mated females bore only one spermatophore (Hamidi, personal observation).

7.2.2 Courtship Behavior

Detailed qualitative and quantitative descriptions of *P. archon* male and female reproductive behavior have been reported in two recent studies showing that the courtship is a sequence of stereotyped behavioral steps (Delle-Vedove *et al*. 2014; Riolo *et al*. 2014). A likely perching mate-locating behavior is performed by males; females trigger the courtship sequence by approaching perching males, which then pursue the females (Delle-Vedove *et al*. 2014; Riolo *et al*. 2014). Female courtship solicitation has also been observed in Pieridae (Rutowski 1980; Daniels 2007) and Nymphalidae (Bergman *et al*. 2007) species. This male activation mechanism suggested the lack of a long-range female sex pheromone, which was then confirmed by histological and electrophysiological investigations of the ovipositor (see Section 7.2.3).

A different type of mate-localization behavior was observed by Sarto i Monteys *et al*. (2012), in which the perching or patrolling male first locates and approaches the female. In some butterflies, one individual can perform both types of behavior or can alternate between the two, depending on ecological factors (Scott 1974; Dennis and Shreeve 1988). However, no data were reported by Sarto i Monteys *et al*. (2012) on the "perching index"—the proportion of copulations initiated by a sitting male relative to a flying male (Scott 1974).

The courtship sequence of *P. archon* is composed of five main steps: female flight approaching the male (the female approaches the perching male by flight); pair flight

Table 7.1 Behaviors observed in *P. archon* males and females during courtship (from Riolo *et al.* 2014).

Behavior	Description
Main courtship sequence	
Female flight **(FF)**	The ♀ approaches the perching ♂ by flight
Pair flight **(PF)**	The ♂ chases the ♀ and both fly together
Alighting close/approaching **(A)**	The ♂ and ♀ alight facing upwards, or approach each other by walking (<10 cm from each other)
Copulation attempt **(CA)**	The ♂ curls its abdomen and shows the claspers, trying to grasp the ♀ copulatory orifice
Clasping **(Cl)**	The ♂ clasps the ♀ genitalia
Copulation **(Cp)**	The ♂ and ♀ stay motionless in copula, facing upwards
Other ♂/♀ behaviors	
Contact **(C)**	The ♂ or ♀ approaches the opposite sex and touches its wings with the antennae or forelegs
Head dipping **(HD)**	The ♂ dips its head under the ♀ abdomen or wings
Immobility **(I)**	The ♂ or ♀ stay motionless
Walking **(W)**	The ♂ or ♀ walk
Flying **(F)**	The ♂ or ♀ fly
Alighting distant **(AD)**	The ♂ or ♀ alight facing upwards (>50 cm from each other)
Antenna cleaning **(AC)**	The ♂ or ♀ brush their antennae once or repeatedly
Ovipositor extrusion **(OE)**	The ♀ extrudes the ovipositor once or repeatedly

(the male chases the female and both fly together); alighting close (male and female alight facing upwards, or approach each other by walking, < 10 cm from each other); copulation attempt (the male curls its abdomen and shows the claspers); and clasping (the male clasps the female genitalia). All of these steps are necessary for copulation to occur (Table 7.1; Fig. 7.1) (Riolo *et al.* 2014).

Multiple repetitions of courtship steps are engaged by both males and females. The average courtship duration was 60.99 ± 18.97 min (mean ± SE), and the longest copulation lasted 94.58 min. On average, adults mated from 0 ± 2 days of age (Riolo *et al.* 2014). Despite the stereotypy of the behavioral sequence, *P. archon* courtship is variable and complex, especially in terms of the number of components and event transitions, which also involve other optional male and female behaviors (Riolo *et al.* 2014).

Mating in *P. archon* depends basically on the success of the pair flight, which appears to be a crucial behavioral step. Sarto i Monteys *et al.* (2012) reported that the *P. archon* male wing appears to distribute a scent over the female antenna during the pair flight. Putative short-range male pheromones have been identified from the proximal halves of male forewings and hindwings. These compounds are released in a passive process associated with the flight phase of the courtship, inducing the female to alight (Sarto i Monteys *et al.* 2012).

However, during *P. archon* pair flight, the colored hindwings might serve to stimulate mate recognition, as it has been reported for several butterfly species belonging to the families Nymphalidae, Papilionidae, and Pieridae (Vane-Wright and Boppré 1993; Robertson and Monteiro 2005; Kemp 2007).

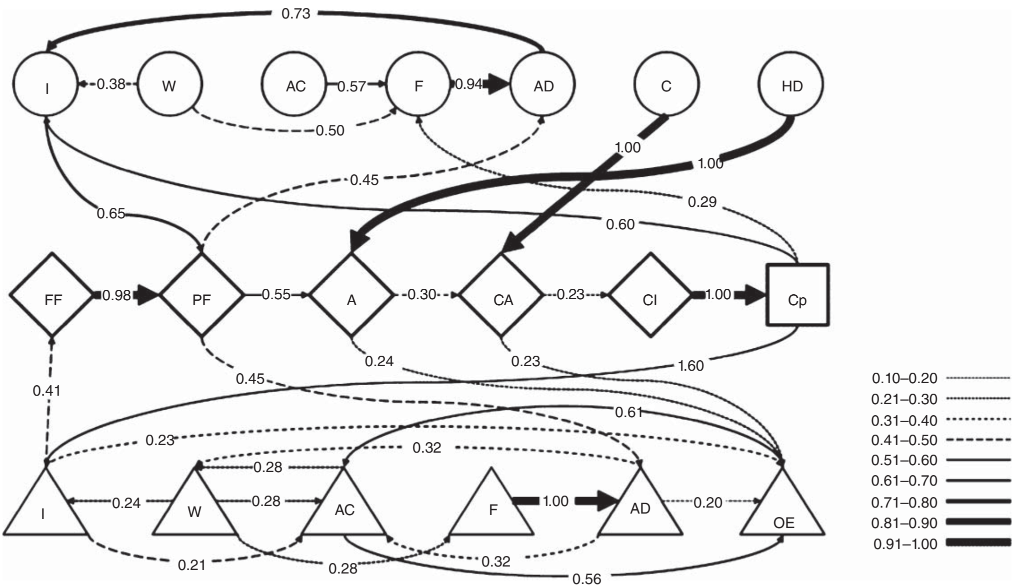


Figure 7.1 Flowchart of behavioral transition probabilities representing successful courtship sequences for *P. archon*. Diamonds (and the square, representing the final step) represent the main courtship sequence; circles represent other male behaviors, and triangles represent other female behaviors. Numbers and corresponding thicknesses of arrows (see legend) are conditional probabilities of a particular transition occurring between two behavioral acts. Transitions of < 0.20 are not included, to enhance the clarity of the figure. Descriptions and abbreviations of behaviors are listed in Table 7.1 (from Riolo *et al*. 2014).

Alighting at close range after the pair flight appears to represent acceptance of the *P. archon* male by the female, which has been reported as one of the functions of close-range pheromones for both moths and butterflies (Brower, Brower, and Cranston 1965; Grant and Brady 1975).

The other behaviors recorded during the courtship were: contact (the male/female approaches the opposite sex and touches its wings with the antennae or forelegs), head dipping (the male dips its head under the female abdomen or wings), immobility, walking, flying, alighting distant (the male or female alight facing upwards, >50 cm from each other), antenna cleaning (the male or female brush their antennae once or repeatedly), and ovipositor extrusion (the female extrudes the ovipositor once or repeatedly) (Riolo *et al.* 2014). In particular, a higher antennal cleaning frequency was observed for females. Antennal grooming enhances the sensitivity of the peripheral olfactory system (Böröczky *et al.* 2013) and may also enhance the female perception of volatiles both for mate and plant-host recognition (Renwick and Chew 1994).

Ovipositor extrusions were observed in *P. archon* females, but this behavior seems not to be related to calling behavior; instead, it might be involved in the female physiological state (i.e. egg load) or in thermoregulatory activity (Riolo *et al.* 2014). Indeed, no morphological evidence of the presence of a pheromone gland has been found on the ovipositor of *P. archon* (see Section 7.2.3).

In *P. archon* males, a particular "scratching behavior" was observed that could be related to the emission of short-range pheromone compounds from male mid-legs (Hamidi, personal observation; Frérot *et al.* 2013). However, male scratching was also observed when males were alone in cages, suggesting that the role of male scent is not restricted to courtship, and may be involved in searching and locating conspecific males (Delle-Vedove *et al.* 2014).

To investigate the role of antennal olfaction and visual stimuli in mate recognition, Riolo *et al.* (2014) carried out bioassays with antennectomized adults and dummies. When normal females were tested with antennectomized males, successful courtship was observed, but without copulation. However, when normal males were tested with antennectomized females, the entire courtship sequence was performed, and copulation did occur. Moreover, the males repeatedly approached (by walking) the dummy females, touched the dummy wings with the forelegs, and one copulation attempt was observed. Females were observed flying toward the male dummy and alighting close several times and touching the male dummies with the forelegs. These observations suggest that antennal olfactory stimuli have more important roles in the *P. archon* male than female during courtship, and that visual stimuli are involved in mate communication. Olfactory and visual cues might operate synergistically and help the female in her decision to accept or reject a specific male, as has been reported for different Pieridae species (Rutowski 1978; Silberglied and Taylor 1978). However, the presence of a single correct stimulus in males can be sufficient to lead females to copulation (Riolo *et al.* 2014).

7.2.3 Chemical Cues

P. archon has a telescopic ovipositor, which consists of the last three abdominal segments: the 8th uromere forms the ovipositor base, and the 9th and 10th uromeres are fused together, forming the true ovipositor. The 9th and 10th uromeres are connected to the base by an intersegmental membrane that is about as long as the two uromeres together. In the resting position, the ovipositor lies completely retracted beneath the abdomen. SEM images of the outer surface of the intersegmental membrane show parallel series of longitudinal grooves, and a smooth surface that is devoid of any apertures or projections (Fig. 7.2). Histological investigations revealed that the epidermal cells of the intersegmental membrane do not have the typical features of glandular cells, as have been observed for many pheromone glands (Fig. 7.2) (Riolo *et al*. 2014).

These histological observations were further supported by electrophysiological analysis. A total of 24 compounds were identified from solvent extractions of virgin female ovipositors: 5 aromatic compounds, 4 alcohols, 4 aliphatic aldehydes, 4 terpenes, 4 hydrocarbons, 2 acids, and 1 ketone. None of the identified compounds elicited any significant gas chromatography-electroantennography detection (GC-EAD) responses on male antennae (Riolo *et al*. 2014).

The Castniidae males possess diverse and often spectacular androconia (Le Cerf 1936), which in *P. archon* are located on the extremity of the mid-legs (Frérot *et al*. 2013). The androconia release huge quantities of the pheromone-like compound E2,Z13-16:OH (Frérot *et al*. 2013). This compound was first identified by Sarto i Monteys *et al*. (2012) but from wing extracts, probably because of passive adsorption on the wing cuticle. This compound was previously identified in other Sesioidea, confirming the classification of *P. archon* and, by extension, the Castniid family in the Sesioidea, in this systematic group. Recently, Quero *et al*. (2016) confirmed the presence of large quantities of E2,Z13-16:OH in extracts from midlegs. They also reported that males P. archon produce a variety of other pheromone like components. Analysis of the wing extracts showed the presence of two isomers of farnesal and three different acetates were identified from the male genitalia extract, although the biological activity of all these compounds is still unknown.

7.3 Host-Finding and Chemical Cues

P. archon developed as a specialist insect on its original host plants, the palms. The real biotope from which it comes is not well defined. The species was described from Paysandú in Uruguay. The conditions in this region differ significantly from those in regions populated by the moth in Europe. The latter landscape, including new fauna and flora and associated odors, is completely different from that encountered in the native biotope. In Europe, *P. archon* is an urban and commercial nurseries lepidopteran.

7.3.1 Behavior

All gravid females observed under controlled conditions or in the wild are attracted by palms and land on the upper part of the crown, never on the leaves (Fig. 7.3). There, they exhibit probing behavior that includes antennation and probing with the ovipositor. Observations using palms covered with a dark sheet to eliminate visual cues confirmed that mated females are attracted by palm chemical cues (Hamidi and Frérot, 2016).

7.3.2 Antenna Morphology

The role of host-plant volatiles involved in host-plant location by *P. archon* has been reported (Ruschioni *et al*. 2015). The role of olfaction in *P. archon* is crucial, and is mediated mainly by antennal olfactory sensilla. Sarto i Monteys *et al*. (2012) and Ruschioni *et al*. (2015) investigated the structure of the antennae of *P. archon*, which are characterized by a basal scape, a short pedicel, and an elongated flagellum, typically swollen in its distal part and ending in the apiculus (Fig. 7.4). The absence of sexual dimorphism combined with the above-mentioned features make the antennae of *P. archon* much more similar to those of butterflies than moths (Myers 1968; Odendaal 1985; Carlsson

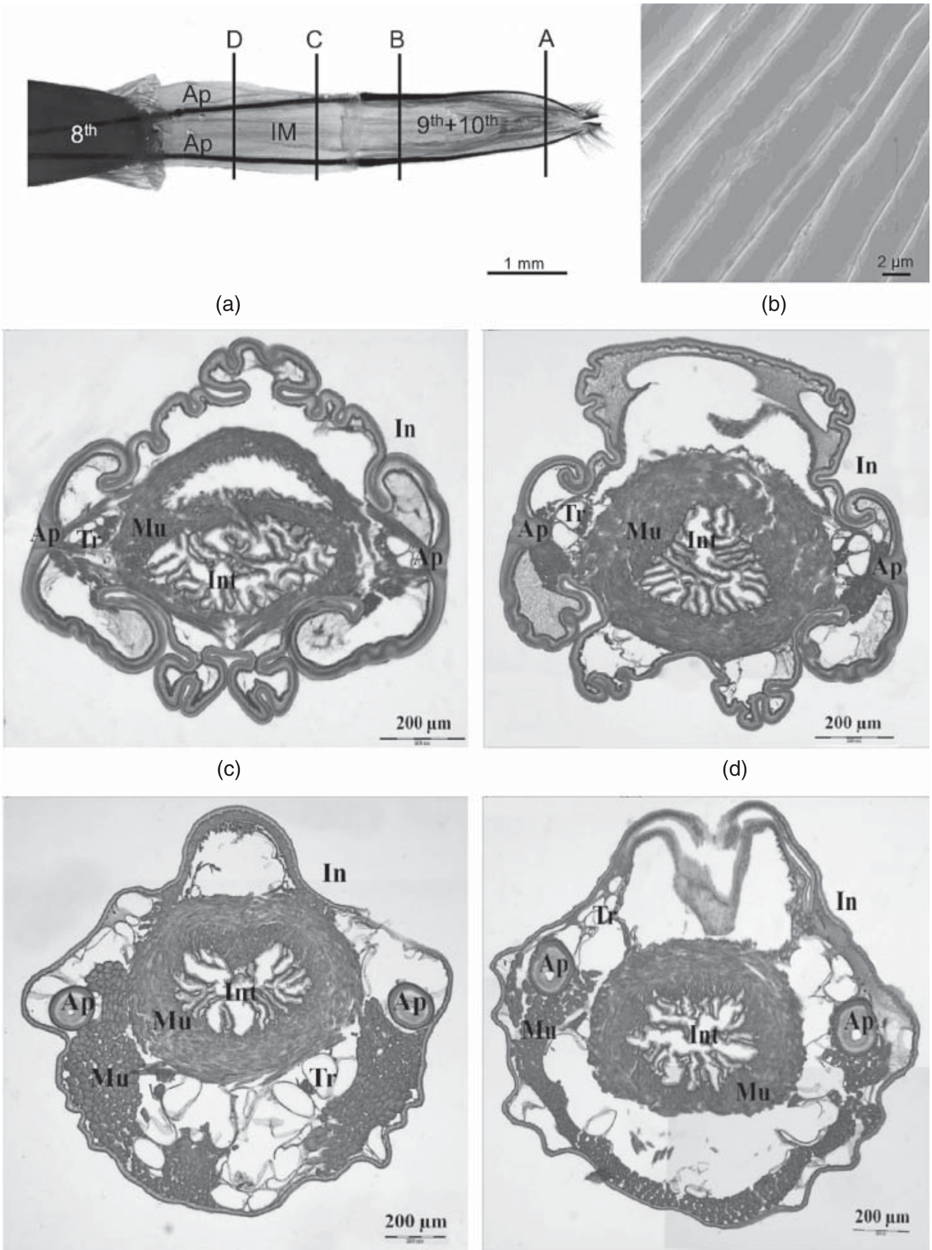
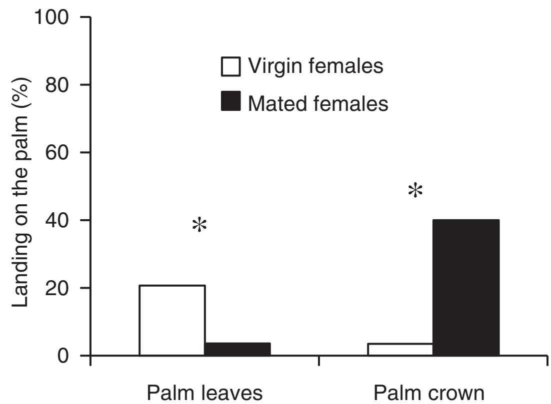


Figure 7.2 *P. archon* ovipositor. (a) Light microscopic dorsal view showing 8th uromere, intersegmental membrane (IM), 9th and 10th uromeres, and apodemes (Ap). (b) SEM detail of intersegmental membrane outer surface. (c, d) Cross-section of 9th and 10th uromeres at positions A and B (Fig. 7.2a). (e, f) Cross-section of intersegmental membrane at positions C and D (Fig. 7.2a). In, integument; Pr, proctodeum; Mu, muscle; Tr, trachea. Scale bar: 1 mm (a), 2 µm (b), 200 µm (c–f) (from Riolo *et al*. 2014).

Figure 7.3 Percentage of virgin and mated female landings observed on either palm leaves or crown under wind-tunnel conditions ($n = 29$ and $n = 61$, respectively) (Hamidi and Frérot, 2016).



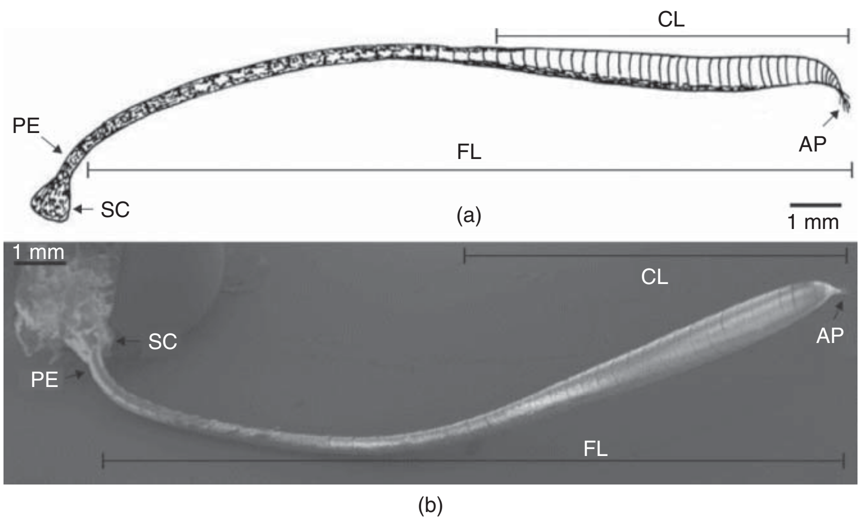


Figure 7.4 Schematic drawing (a) and SEM overall view (b) of an antenna of a *P. archon* male. SC, scape; PE, pedicel; FL, flagellum; CL, club; AP, apiculus. Scale bars: 1 mm (from Ruschioni *et al*. 2015).

et al. 2013). While most of the antennal surface is covered with enlarged and distally dentate scales, sensilla are located over about 20% of the total antennal surface, termed the "sensillar area." The sensillum types occurring in this area are:

- sensilla trichoidea, characterized by an elongated cuticular shaft that decreases in diameter toward the apex. These sensilla show numerous dorsally located pores and are inserted into the antennal wall through an inflexible socket (Fig. 7.5a, b). Transmission electron microscopy (TEM) revealed a thick-walled sensory cuticle with two or three unbranched sensory neurons (Fig. 7.5c, d). These are the most abundant type of sensilla, occurring in relatively higher numbers in *P. archon* males;
- sensilla basiconica, showing an evenly perforated sensory cuticle organized in a long, thin shaft (Fig. 7.5e, f). In this case, the 2–3 sensory neurons develop into several

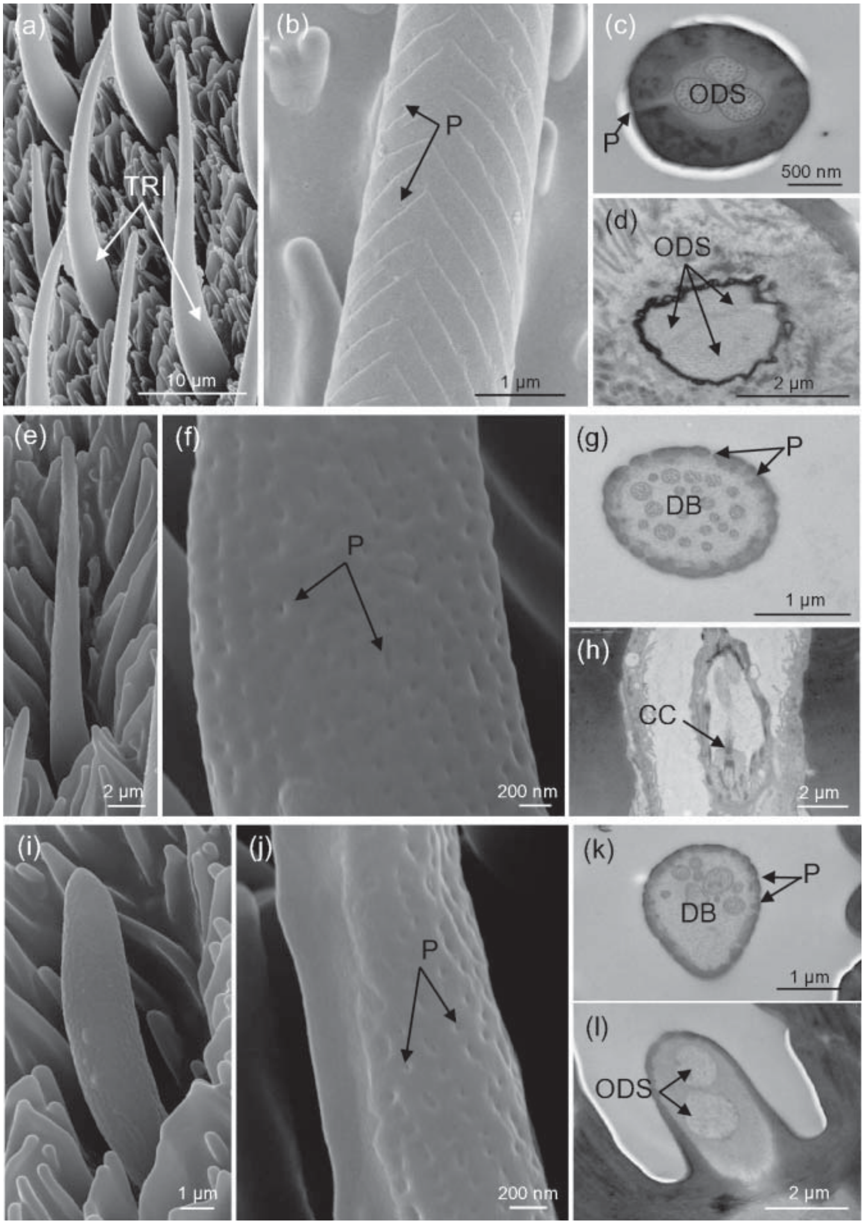


Figure 7.5 Representative SEM (a, b, e, f, i, j) and TEM (c, d, g, h, k, l) images of the most abundant sensillae on the antennae of *P. archon*. (a–d) Sensilla trichoidea, showing low-magnification details (a), herringbone grooves and pores (P) (b), and cross-sections of the shaft with thick-walled cuticle pierced by pores (P) and outer dendritic segments (ODS) with three sensory neurons (c), and of the base with three sensory neurons enclosed in a common dendritic sheath (ODS) (d). (e–h) Sensilla basiconica, showing low-magnification details (e), the numerous pores (P) (f), cross-section of the shaft with the thin-walled cuticle with pores (P), and dendritic branches (DB) (g), and an oblique section of the base at the level of the ciliary constriction (CC) (h). (i–l) Sensilla auricilica, showing low-magnification details (i), the numerous pores (P) (j), cross-section of the shaft with the thin-walled cuticle with pores (P), and dendritic branches (DB) (k), and an oblique section of the base, with two sensory neurons enclosed in a common dendritic sheath (ODS) (l). Scale bars: 10 µm (a); 2 µm (d, e, h, l); 1 µm (b, g, i, k); 500 nm (c); 200 nm (f, j) (Ruschioni *et al*. 2015).

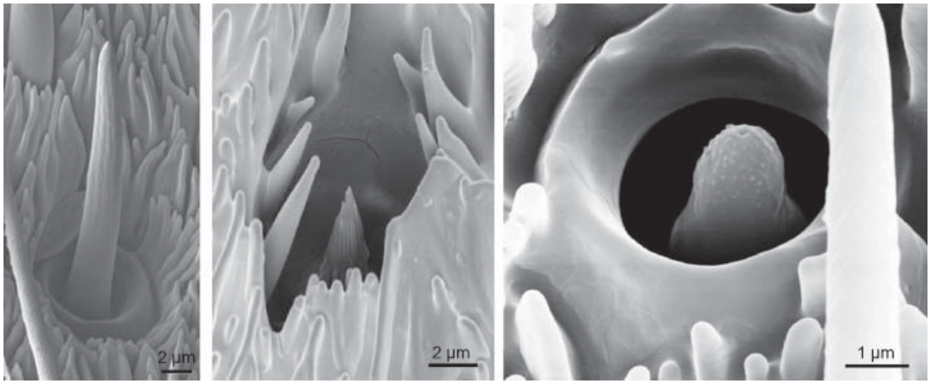


Figure 7.6 Representative SEM images of the less numerous sensilla types. (a) Sensilla chaetica. (b) Sensilla coeloconica. (c) Sensilla ampullacea (Ruschioni *et al*. 2015).

dendritic branches inside the shaft lumen (Fig. 7.5g, h). These sensilla are more abundant in females than males;

- sensilla auricilica have a laterally flattened cuticular shaft and the sensory cuticle is also perforated by numerous minute pores over its surface (Fig. 7.5i, j). Two sensory neurons innervate this sensillum, producing dendritic branches (Fig. 7.5k, l). Sensilla auricilica are present in both sexes, but more in female than in males;
- sensilla chaetica are very long and present in both sexes in relatively low numbers. The sensory cuticle is not perforated except for the presence of an apical pore (Fig. 7.6a). There are five sensory neurons associated with this sensillum, four of which enter the peg while the fifth ends at the articulated socket in a tubular body;
- sensilla coeloconica, present in low numbers in both sexes with no differences. They appear as grooved pegs hidden inside a cuticular cavity (Fig. 7.6b). The peg is perforated by numerous pores, and each sensillum has three sensory neurons;
- sensilla ampullacea, present in limited numbers in both sexes, with an aporous peg almost completely embedded inside the antennal cuticular wall (Fig. 7.6c).
- The antennae of the palm borer moth (PBM) are equipped with at least three different types of olfactory sensilla (i.e. sensilla trichoidea, sensilla basiconica, and sensilla auricilica). Using electrophysiological recordings, it has been shown that *P. archon* antennae respond positively to host-plant volatiles, but single sensillum recordings are required to determine the precise role of the different sensilla. Although *P. archon* belongs to a moth family, their antennae show obvious homologies with those of day-flying butterflies (e.g. no sexual dimorphism, clubbed structure, reduced sensillar area where the different sensilla are concentrated). This is of great importance in terms of the evolution of different communication and selection strategies between the two main Lepidoptera groups (i.e. butterflies (diurnal, based on visual cues) and moths (nocturnal, based on pheromone production/detection)). Identifying and understanding the mechanisms involved in the perception of host-derived stimuli would be of great benefit in the implementation of monitoring and management techniques for *P. archon*.

7.3.3 Chemical Cues

Locating a host plant is a crucial step in *P. archon*. In this host-location process, *P. archon* can combine semiochemical cues and physical information, such as plant color, shape, and texture. Electrophysiological studies on moths have suggested a role for plant volatiles in host-plant recognition (Ruschioni *et al.* 2015). Indeed, plant volatiles are often complex mixtures of chemicals, some of which are detected by the highly sensitive olfactory system of phytophagous insects to locate suitable host plants. As a consequence, to characterize the biologically active compounds in these mixtures, techniques such as high-resolution GC coupled with EAG are required (see Chapter 5, this volume). EAG bioassays carried out to determine the role of *P. archon* antennae in perceiving plant volatiles showed that they respond to ester and terpene compounds previously identified as volatiles of damaged and/or fermenting palm tissues. In particular, *P. archon* antennae showed responses to linalool, ethyl acetate, ethyl propionate, ethyl butyrate, ethyl isobutyrate, and ethyl lactate (Ruschioni *et al.* 2015). Linalool is a terpene alcohol found in many flowers and spice plants and one of the major compounds of palm volatiles (Knudsen, Tollsten, and Bergström 1993; Caissard *et al.* 2004). Esters, also produced by damaged and fermenting palm-tissue (Vacas *et al.* 2014), can attract other insect pests of palms, such as some palm weevil species (see Chapter 5, this volume). *P. archon* males and females both responded to these potential host-plant volatiles, but females showed higher sensitivity. In both cases, *P. archon* antennae showed dose-dependent EAG responses, with the highest ethyl isobutyrate dose of 1000 μg tested for both sexes (Ruschioni *et al.* 2015). These findings, combined with morphological and ultrastructural studies on the *P. archon* olfactory system (Sarto i Monteys *et al.* 2012; Ruschioni *et al.* 2015), suggest that these potential host-plant volatile compounds can mediate the host-location behavior of *P. archon*. However, information about the chemical cues exploited by *P. archon* during the host-location process is still lacking; moreover, the chemicals tested in the laboratory are non-specific compounds that are mainly produced by fermenting tissues of infested palms. Therefore, further studies are needed to determine the roles of volatiles from infested and/or healthy palms in the field. The appropriate combination of physical traits (e.g. color, shape, and size of the host plant), and chemical sensory inputs involved in recognition of a plant as a host by *P. archon* to locate suitable oviposition sites, also need to be identified.

7.3.4 Conclusion

Results from the various analyses leave no doubt that gravid females localize and choose the host palm on the basis of olfactory cues through olfactory sensilla, especially sensilla basiconica. Plant volatile organic compounds elicit EAG responses and moths behave in wind-tunnel trials and in the field with a characteristic attraction flight. Day-flying butterflies also rely on olfactory cues to navigate toward their host plants, but other sensory modalities are involved in the final decision process.

7.4 Visual Cues: Their Roles in Mate and Host Location

The main visual organ of insects, the compound eye, is an assembly of several hundred to several thousand ommatidia. In each ommatidium, the dioptric apparatus, composed of the corneal facet lens and the crystalline cone, directs light to the underlying rhabdom, which contains microvillar parts of photoreceptor cells with the light-sensitive rhodopsin molecules. In a single ommatidium, there are 6 – 12 photoreceptors that may belong to different classes of spectral sensitivity. Insect photoreceptors are often sensitive to light polarization, due to the orientation of the rhodopsin molecules in the microvilli (Wehner and Labhart 2006; Land and Nilsson 2012).

In the apposition eye, the ommatidia are optically isolated by the longitudinal sheaths of pigments. In the superposition eye, the dioptric apparatuses are separated from the photoreceptive parts by a clear zone. Each dioptric apparatus then serves adjacent ommatidia. Conversely, up to a few hundred adjacent dioptric apparatuses focus the light coming from a particular direction to a single rhabdom unit, increasing the light-catching of the photoreceptors (Stavenga 2006; Belušič, Pirih, and Stavenga 2013).

The apposition eye is suitable for diurnal activity, but it may also be used by some crepuscular and nocturnal insects (bees: Greiner, Ribi, and Warrant 2004; butterflies: Frederiksen 2008). The superposition design, on the other hand, is used by some diurnally active insects, for example the hummingbird hawk-moth *Macroglossum stellatarum* (Warrant, Bartsch, and Günther 1999), the Ascalaphus owlfly *Libelloides macaronius* (Belušič, Pirih, and Stavenga 2013), and notably the skipper butterflies of the family Hesperiidae (Horridge, Giddings, and Stange, 1972). Because the most studied families of moths (Bombycidae, Sphingidae, Noctuidae, Arctiidae) have superposition eyes and all common butterfly families (Nymphalidae, Pieridae, Papilionidae, Lycaenidae) have apposition eyes (Nilson, Land, and Howard 1988), an unfortunate false implication leads to an untested credo that, among Lepidoptera, only butterflies have apposition eyes.

The honeybee's eye, with photoreceptors that are sensitive to ultraviolet (UV), blue and green wavelengths, is the classical model for insect eyes, but there are many variations on this scheme. A single photoreceptor may express more than a single opsin gene. A compound eye might be composed of several types of ommatidia with different photoreceptor-class allocations. The distribution of ommatidial types may be different in the dorsal and ventral parts of the eye. Butterflies with up to 10 photoreceptor classes with sexual dimorphism have been reported (Arikawa 2003; Wakakuwa, Stavenga, and Arikawa 2007; Ogawa 2013).

Apart from the compound eyes, most flying insects possess an ocellar system. This system is commonly composed of three external ocelli—simple (camera) eyes with lenses (e.g., in flies, bees, and locusts). The spectral sensitivity of the ocelli is usually dichromatic, with UV and green photoreceptors. The ocellar lenses are under-focused, so the ocelli have low spatial resolution. The ocellar system is used to estimate the head's orientation relative to the horizon (pitch and roll angles) for the purpose of flight stabilization, exploiting the property of the visual world below the horizon, which reflects a very small amount of UV and thus creates a large contrast with the UV-enriched sky hemisphere, whereas the contrast in the green part of the spectrum is much smaller (Mizunami 1994; Taylor and Krapp 2007; Krapp 2009).

In Lepidoptera, external ocelli have been found in Noctuidae (Dow and Eaton 1976) and Sphingidae (Dickens and Eaton 1973), for example. Lense-less, internal ocelli have also been described (e.g. in the nocturnal moth *Manduca sexta*). Internal ocelli serve for circadian clocking rather than for flight stabilization (Eaton 1971).

7.4.1 Optical Design of *P. archon*'s Retina

The compound eye of the *P. archon* female measures about 3 mm laterally by 5 mm sagittally and contains around 10,000 facets (Fig. 7.7). The dimensions of the male eye, which has about 7000 facets, are about a fifth smaller. The diameter of the facet lenses in both sexes is approximately 25 μm. Each compound eye covers an almost hemispherical visual field; the two visual fields overlap frontally, with a dorso-frontal acute zone, and there is a posterior dead angle. The interommatidial angles vary between 1.2° and 1.5° and are possibly somewhat smaller (1.0°) in the acute zone.

Macrophotography of the *P. archon* compound eye reveals a pseudopupil pattern (Fig. 7.7a), which is a telltale sign of the apposition eye design and is otherwise encountered in bees, locusts, and some butterfly families (Stavenga 1979). The rhabdoms start immediately below the crystalline cone and the retina lacks any clear zone (Fig. 7.7b). The compound eye structure of *P. archon* is typical for an apposition eye.

Although the name PBM may suggest otherwise, *P. archon* actually has eyes that are very similar in design to those of the common diurnal butterfly families. Even though this may be a surprise from a phylogenetic standpoint (Regier *et al*. 2013; Kawahara and Breinholt 2014), it fits well with the exclusive diurnal activity of *Paysandisia.*

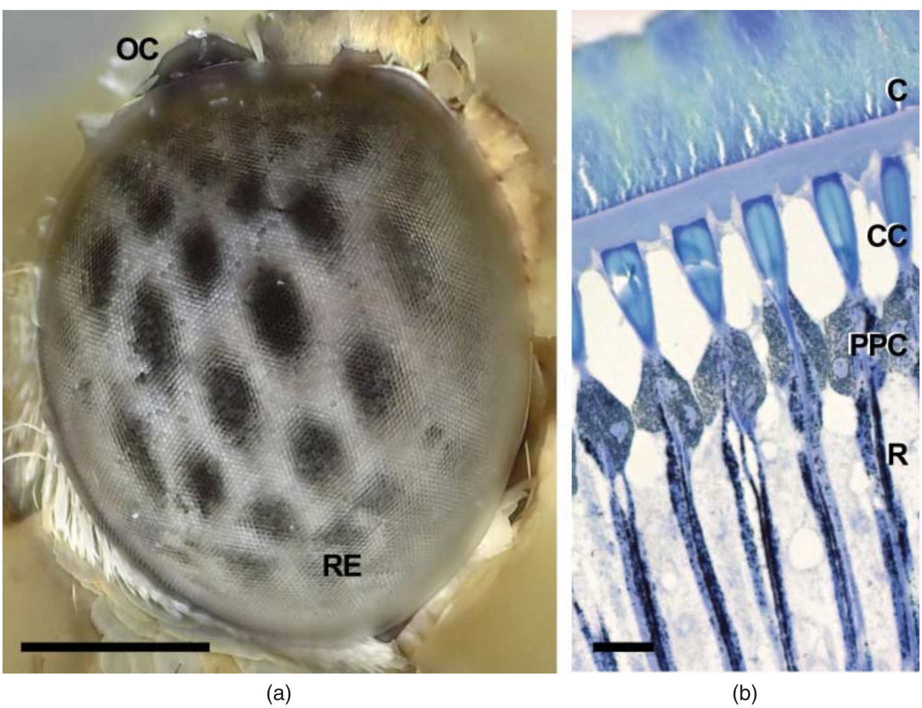


Figure 7.7 Visual system of *P. archon*. (a) The compound eye (RE, retina) and ocellus (OC) of a female moth, immobilized with beeswax (yellow mass). The compound eye has multiple pronounced pseudopupils (dark spots). (b) Semi-thin cross-section of the distal part of the retina, with (distal to proximal): cornea (C), crystalline cones (CC), primary pigment cells (PPC) and photoreceptor cells (R) showing dark stripes of perirhabdomal pigment granules. The rhabdoms of the photoreceptor cells (adjacent to the perirhabdomal pigments) connect to the tip of the CC. Scale bar: 1 μm (a), 20 μm (b). (*See color plate section for the color representation of this figure.*)

7.4.2 Spectral Sensitivity of the Ocelli

P. archon has two ocelli with lenses that are approximately 0.5 mm in diameter. The spectral sensitivity of the ocelli, measured by electroretinography (ERG), exhibits two peaks in the UV and green parts of the spectrum (Fig. 7.8a).

A similar system with two ocelli and UV–green dichromatic sensitivity has been described for the noctuid moth *Trichoplusia ni* (Dow and Eaton 1976; Eaton 1976). We

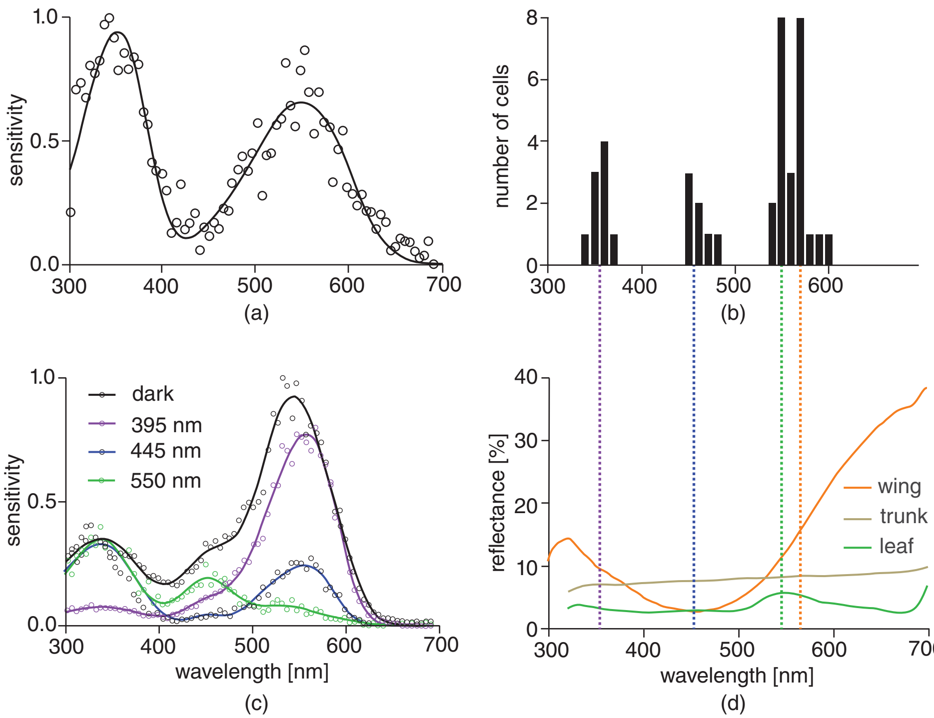


Figure 7.8 Spectral sensitivity of *P. archon* ocelli (a) and compound eyes (b, c) and representative spectra of the relevant environmental cues. (a) Spectral sensitivity of ocellus, measured by ERG. Data are fitted with double nomogram function with peak sensitivities at 350 and 550 nm. (b) Distribution of spectral sensitivity peaks of impaled photoreceptors, grouped in 10 nm bins. The 40 cells comprise three clearly distinguishable classes (UV peaking at 355 nm, blue peaking at 454 nm, long wavelength, LW). The peaks of the LW photoreceptors are widely dispersed across a 50 nm interval (550–600 nm) with bimodal distribution, forming two distinct classes (green-sensitive peaking at 550 nm, orange-sensitive peaking at 570 nm). (c) Spectral sensitivity of a compound eye obtained with ERG. Data are smoothed by adjacent averaging. Black curve shows sensitivity of dark-adapted retina. Pink, blue, and green curves correspond to retina adapted with UV, blue, and green light at 395, 445, and 550 nm, respectively. Chromatic adaptation reveals selective suppression of sensitivity in the three parts of the spectrum, corresponding to at least three classes of photoreceptors with peak sensitivities at 350, 450, and 550 nm. (d) Reflectance spectra of relevant visual cues. Dotted bars show average sensitivities of four classes of retinal photoreceptors. Orange curve shows the reflectance spectrum of orange scales on the inner wings. Reflectance rises monotonically above 500 nm with the steepest slope between 550 and 600 nm, coinciding with the peaks of the two LW photoreceptor classes. In addition, there is a smaller reflectance peak in the UV. The green curve shows reflectance of the host-plant leaves (*Washingtonia filifera*). The leaves have a reflectance peak in the green part (550 nm) and in the near infrared part of the spectrum (>700 nm). The gray curve shows that the reflectance spectrum of the trunk, which appears silvery-brown to us, has a flat reflectance spectrum that rises slightly toward the LW part. (*See color plate section for the color representation of this figure.*)

note that, although the most common form of the ocellar system has three external ocelli, a system with two external ocelli provides enough information for the estimation of flight angles. We therefore assume that the ocelli in *P. archon* are used for flight control. This may be important for the design of behavioral experiments.

7.4.3 Spectral and Polarization Sensitivity of the Retina

Spectral sensitivity of the compound eye, measured extracellularly via ERG, shows broadband sensitivity. Chromatic adaptation of the retina with monochromatic light at different wavelengths selectively suppresses the sensitivity in the UV, blue, and green parts of the spectrum, respectively (Fig. 7.8c). The extracellular measurements suggest that the retina of *P. archon* is equipped with at least three different classes of photoreceptors.

Intracellular measurements of photoreceptor spectral sensitivities with a sharp microelectrode revealed that their maxima could be grouped into four classes with peaks at about 360, 460, 550, and 570 nm, respectively (Fig. 7.8b). All photoreceptor classes were sensitive to the direction of polarization of the light. The ratio of sensitivity to linearly polarized light in the preferred and non-preferred direction was about 1:2 in all spectral classes.

In *P. archon*, the basic trichromatic scheme (UV – blue – green) seems to be expanded by an additional long-wavelength-sensitive photoreceptor class. The 20 nm difference in the peaks of the two long-wavelength photoreceptor classes may seem small, but it is well above the measurement and template-fitting error. Cases of closely peaking receptor classes have been reported from several species of butterfly, for example *Pieris rapae* (Wakakuwa, Stavenga, and Arikawa 2007) and *Colias erate* (Pirih, Arikawa, and Stavenga 2010; Ogawa *et al*. 2013). The sensitivity difference of the two long-wavelength classes could be due to the presence of two opsin genes or to optical screening mechanisms.

7.4.4 Tuning of Vision to Visual Cues

The most important visual cues are located on conspecifics and host plants. The body of *P. archon* is mostly covered by brown scales, which mimic the brown color of the palm trunk and allow the animal to camouflage itself on the host plant. The inner wings have black, white, and orange scales. The wing colors are diffuse and not polarized. The reflectance of black and white scales is spectrally flat. The reflectance of the orange scales rises steadily above the minimum at 460 nm and has a smaller peak in the UV region (Fig. 7.8d). The orange spots probably play an important signaling role during courtship behavior, which consists of pronounced, rhythmical displays of the inner wing upon landing.

We may, with some caution, think of *P. archon*'s three color channels as analogous to the situation in humans, plus an additional UV channel. The peaks of human S, M, and L rod receptors are 420, 534, and 564 nm, respectively (note that the peak difference of the latter two is only 30 nm). The wavelength-discrimination ability of humans in the green – red part of the spectrum, which is predominantly based on the M and L receptor classes, increases steadily from 530 nm toward 600 nm (Zhaoping, Geisler, and May 2011).

In *P. archon*, the two long-wavelength photoreceptor classes peak at 550 and 570 nm, respectively. In this part of the spectrum, the reflectance of the orange scales rises sharply. Using the analogy with human vision, we may assume that these two photoreceptor classes are well tuned for detecting the hue of the orange wing patch. The excitation of blue-sensitive photoreceptors by the orange patch would be low, while the UV photoreceptor class might be able to detect the smaller UV reflectance peak, which is nevertheless brighter than the trunk background (Fig. 7.8d). The compound eye of *P. archon* thus seems well equipped for detection of the orange patch and for determination of the orange hue.

The palm trees do not bear any specific color that can be immediately distinguishable from the surrounding vegetation. The spectral signature of leaves is mostly due to chlorophyll, with the scattering peak in the green part of the spectrum coinciding with the 550 nm photoreceptor class. The high reflectance in the near-infrared part of the spectrum is beyond the detection range of *P. archon* vision (Fig. 7.8d).

The color of palm trunks is either brown or silver. Brown trunks have a monotonically rising reflectance from the short toward the long-wavelength part of the spectrum, while a silver trunk has a flat reflectance spectrum, potentially creating a motif reflecting in the UV range.

In Fig. 7.9, we give a simple simulation of the visual acuity and polarization sensitivity of *P. archon*'s compound eye. An urban scene with several palm trees extends

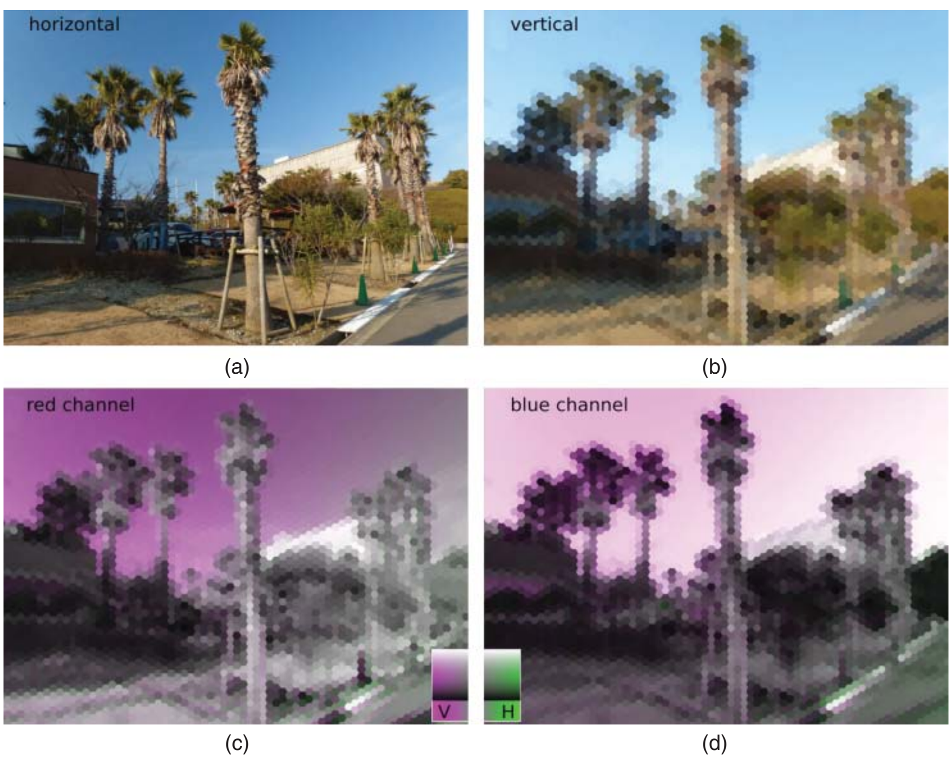


Figure 7.9 Simulation of an urban visual scene containing palm trees using the visual acuity of *P. archon*. The scene extends about 90° × 60°. (a) RGB picture taken with the polarizer set horizontally to minimize sky irradiance. (b) RGB picture taken with the polarizer set vertically and down-sampled to match the optical acuity of *P. archon*. (c) Polarization and intensity contrast in the red channel. (d) Polarization and intensity contrast in the blue channel. Non-polarized pixels are shown in gray; magenta and green tints indicate vertical and horizontal polarizations, respectively. Down-sampled facets span approximately 1.5°. (*See color plate section for the color representation of this figure.*)

about 90° × 60° (Fig. 7.9a). The nearest palm tree is about 10 m away. The scene has been down-sampled to simulate *P. archon*'s visual acuity (Fig. 7.9b). When one looks at the picture from afar, it becomes clear that, despite the down-sampling, there is more than enough visual information to recognize palm trees with rather high certainty. In Fig. 7.9c and d, the potential polarization clues are shown. Non-polarized pixels are gray, whereas blue and magenta tints indicate polarization in the vertical and horizontal direction, respectively. While the leaves and trunks are approximately as bright as the sky background in the red channel, they stand out as being non-polarized (Fig. 7.9c). In the blue channel, the trees form a dark contrast against the sky (Fig. 7.9d). We note that the tree–sky contrast would be even stronger in the UV channel (Belušič, Pirih, and Stavenga 2013). The dry leaves form a bright stripe in the long-wavelength channel. Under direct sun illumination, the cuticular wax present on the leaves of some palm trees may additionally create spectrally neutral (white) specular reflections, which are highly polarized at grazing incidence angles (not shown). The polarization angle of specular reflections is similar to that of the sky background in that direction.

It is possible that *P. archon* uses a combination of visual clues (e.g. the trunk silhouette, the characteristic pattern of the foliage, the polarization, and the spectral signatures) to detect the palm trees. The use of true color vision (Kelber, Vorobyev, and Osorio 2003) has been shown for foraging behavior in the butterfly *Papilio xuthus* (Kinoshita, Shimada, and Arikawa 1999), which uses four out of eight photoreceptor types for this behavior (Koshitaka *et al.* 2008). However, the same tetrachromatic system is not necessarily used for all behavioral tasks: importantly, motion vision in insects is normally color-insensitive and based on the output from the main green–blue photoreceptor class (Kelber, Vorobyev, and Osorio 2003). In the case of *P. archon*, the neural system for detecting mates might, for instance, be based only on the blue, green, and yellow channels, while the neural system for detecting palm trees could be based on the UV and yellow channels.

7.4.5 Hints for Designing Visual Traps and Laboratory Experiments

If one wishes to design visual targets resembling *P. archon* wing coloration and shape, it is—for now—best to assume that all color channels are potentially used for color discrimination. If orange color is to be exploited for the construction of visual traps and lures, it should mimic well the reflectance of the orange scales. We have constructed lures by using a set of four monochromatic LED lights. In the greenhouse, the animals did not react to the presentation of the flashing orange lights, whereas they could be attracted to dead specimens glued to a wooden pole and, to some extent, to dummies printed on paper. The most straightforward explanation for the failure of the LED lure is that the wing coloration works as a proximity-recognition signal by virtue of both its color and its pattern, and not as a distance signal, based only on color. Many nocturnal insects are attracted to bright, UV-rich light. Unfortunately, *P. archon* has not been observed to fly at night, and using black light as a lure during the day does not seem feasible, even under overcast conditions.

The well-developed ocellar system in *P. archon* suggests that behavioral experiments in the laboratory should be performed in sufficiently bright ambient light, with attention to the upper visual hemisphere being rich in UV light. Given the animal's size and preference for high temperature, we recommend that behavioral experiments be performed in warm and spacious environments. We also suggest that the experiments be performed at normal relative humidity (50–70%) to avoid desiccation shock in the animals.

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8

Natural Enemies of *Rhynchophorus ferrugineus* and *Paysandisia archon*

Lola Ortega-García[1], Elisabeth Tabone[2], Laurence Beaudoin-Ollivier[3], Dana Ment[4], Maurane Buradino[2], Josep A. Jaques[5,], Inmaculada Garrido-Jurado[1], Oscar Dembilio[5] and Enrique Quesada Moraga[1]*

[1] Unidad Entomologia Agricola, Dpto. Ciencias y Recursos Agricolas y Forestales, Campus de Rabanales C4 2 planta, Spain
[2] INRA PACA Center, National Institut of Agriculture, UEFM, Entomology and Mediterranean Forest Unit, France
[3] Centre de coopération internationale en recherche agronomique pour le développement (CIRAD), Biological System Department, Research Unit Bioagresseurs, France
[4] Department of Entomology, Agricultural Research Organization, The Volcani Center, Rishon LeZion, Israel
[5] Universitat Jaume I, Department of Agricultural and Environmental Sciences, Campus del Riu Sec, Spain

8.1 Introduction

The red palm weevil (RPW) *Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Curculionidae) and the palm borer moth (PBM) *Paysandisia archon* (Burmeister) (Lepidoptera: Castniidae) are considered the two most serious pests for many species of commercial and ornamental palms in the Mediterranean Basin. Both species were accidentally introduced into Europe from southern Asia (RPW) and Argentina (PBM), and their rapid spread is causing important economic damage (Sarto i Monteys and Aguilar 2005; Faleiro 2006; Chapter 3, this volume).

The larvae of both species represent the most dangerous stage, as they feed on the soft fibers of the palm trunk and terminal bud tissues. The damage usually only becomes visible a long time after infestation, resulting, in most cases, in the palm's death. The concealed larval development inside the palm and the consequently late detection make the fight against these pests a difficult issue (Murphy and Briscoe 1999; Faleiro 2006; Chapter 12, this volume). Control strategies against RPW and PBM have largely relied on the use of chemical treatments. However, the current European Union directive 2009/128/EC on the sustainable use of pesticides has greatly diminished the number of admissible chemical products. Together with society's growing awareness of environmental protection and the ornamental character of palm trees, resulting in their placement in public gardens, the use of chemical insecticides is limited. Other alternatives, such as biological control, are required for successful integrated pest management.

Biological control is defined as the reduction of pest populations using other organisms, sometimes the pests' own natural enemies (van Lenteren 2012). Natural enemies

*J.A. Jaques was formerly J.A. Jacas

Handbook of Major Palm Pests: Biology and Management, First Edition.
Edited by Victoria Soroker and Stefano Colazza.

of insects as biological control agents include predators, parasitoids, and pathogens, and there are mainly three strategies for their use (van Lenteren 2012):

- Conservation of natural enemies that are already present in the area into which the pest has spread.
- Intentional introduction of natural enemies to control an insect pest that was accidentally introduced into a new geographical area that lacks its associated natural enemies for classical biological control.
- Augmentation of natural enemies, which involves their supplemental release. This method can be carried out in two different ways: (i) release of a large number of individuals (inundative release), aimed at a one-time reduction in the pest population, or (ii) small releases of natural enemies over a period of time (inoculative release) to establish a population in the selected area.

Herein we summarize the natural enemies of both RPW and PBM in their natural and introduced habitats.

8.2 Natural Enemies

There are only a few references to the use of parasitoids and predators in the control of RPW and PBM, and they do not play an important part in controlling either pest, perhaps because of the latter's hidden habits during their life cycles (Reginald 1973).

The restrictions on the introduction of alien biological control agents are of great importance since they can have negative effects on native species and ecosystems, causing major economic losses in agriculture and damaging the environment. Another possibility is the use of predators and parasitoids that are already present in these palm pests' new areas of distribution, as well as those that act on other closely related species (Faleiro 2006).

8.2.1 Parasitoids

Parasitoids are those arthropods whose immature stage develops on or inside the insect host, causing its death, while adults are free-living. The activity of these parasitoids is limited to one or a few closely related host species, because they must be adapted to the host's life cycle.

S. erratica Smith (Hymenoptera: Scoliidae) has been described as a natural parasite of RPW larvae on several occasions, although it is not specific to the Curculionidae (Wattanapongsiri 1966; Peter 1989). Females of *S. erratica* lay eggs on the paralyzed host larvae, and construct a cell around them. The wasp larvae feed ectoparasitically on the host (Murphy and Briscoe 1999). Iyer (1940) observed *S. fuscicauda* Bottcher (Diptera: Sarcophagidae) to be a natural enemy of RPW. Individuals of this family differ from most flies in that they are ovoviviparous: the eggs remain inside the female's body until the embryo is fully developed. Larvae are then deposited on the larvae and adults of their host. Another important family within the Diptera that is involved in biological control of palm weevils is the Tachinidae, such as the *Billaea* (formerly *Paratheresia*) species. Most of those tachinids are parasitoids of Coleoptera and Lepidoptera. The larvae develop inside the host, causing its death (Clausen 1940), and most are very specific to their host. Two *Billaea* species (*B. menezesi* and *B. rhynchophorae*) have been used successfully in biological control programs of a related species, parasitizing *Rhynchophorus palmarum* (L.) larvae (Murphy and Briscoe 1999). *Paratheresia menezesi* (Townsend) is a gregarious parasitoid of *R. palmarum* and has been recorded from oil plantations in Bahia, Brazil (Moura, Mariau, and Delabie 1993). Studies by those authors in the early 1990s indicated that approximately 50% of the *R. palmarum* population was parasitized. In plantations of piassava palm and African oil palm in Brazil, 40% were parasitized by *Billaea rhynchophorae* (Blanchard) (Guimaraes, Townsend, and van Emden 1977; Moura, Mariau, and Delabie 1993).

Similarly, not much is known about parasitoids and predators of PBM. Although parasitoids have been reported in Neotropical castniids, and field observations have indicated that PBM eggs are parasitized by hymenopterous parasitoids (Sarto i Monteys and Aguilar 2005), no natural parasitoids have been described for PBM in any publication to date. The related castniid *Cyparissius daedalus* (Cramer), a pest of African oil palm in Latin America, lays eggs of similar size and shape to PBM on the crown of the palms (Genty, Desmier de Chenon, and Morin 1978; Korytkowski and Ruiz 1980; Huguenot and Vera 1981). *Ooencyrtus* sp. (Hymenoptera: Encyrtidae) was reported as natural egg parasitoid of *C. daedalus* and potential for biological control was suggested by Aldana and Calvache (2002) and Aldana, Calvache, and Higuera (2004), with mass release of the parasitoid in a Colombian oil palm plantation leading to an up to 22% increase in parasitism on *C. daedalus* eggs after 18 months. With the aim of reducing larval damage to hosts, the egg parasitoids, such as *Trichogramma*, are especially interesting because they attack the egg stage of the pest before most of the damage occurs.

Tests have been carried out to evaluate the possible use of *Trichogramma* to control PBM populations. Nine *Trichogramma* strains were preliminarily selected according to their likeness in preferred ecosystem and their possible storage at cold temperature. Strain selection was first made in the laboratory in two stages: in a Plexiglas tube then in a mesocosm. For the mesocosm, eggs were placed in different stem spots to evaluate *Trichogramma*'s dispersion ability. At each step, strains giving the best results were selected. For reasons of confidentiality, the strain names were not mentioned, and codes were used instead. Four ratios were tested (1, 5, 10, and 15 *Trichogramma* females for 1 PBM egg) for 48 h, and the proportion of abortion due to the action of *Trichogramma* was determined (Fig. 8.1). Natural mortality rate (41%) was compared to that observed after "screening" (59%), and the latter was significantly higher than the average abortion rate of control eggs.

The number of embryos observed in each egg was not the same from one strain and ratio to the next, and no emergence of *Trichogramma* has so far been observed. However, *Trichogramma* showed a positive effect on egg mortality. The three most effective parasitoids were then tested in a confined mesocosm on a small palm, to take into account their ability to spread. These experiments were carried out under controlled conditions: $25 \pm 1\,°C$, $75 \pm 10\%$ relative humidity, and a 16 L:8D photoperiod. The parasitism rates were not significantly different among the three strains, but the abortion rates of the eggs deposited on the palms were significantly different from those of control eggs. Efficacy rates did not depend on egg position. Comparing the overall efficiency rate (abortion + parasitism) among the different egg positions around the feather grass showed no significant difference. Therefore, *Trichogramma*'s capacity for dispersion allows them to explore the host eggs all around the stipe. Pre-tests were performed in the field to determine the effectiveness of those parasitoids under natural conditions on PBM eggs. Prior to wide-scale application and commercialization of exotic parasitoids, it is vital that

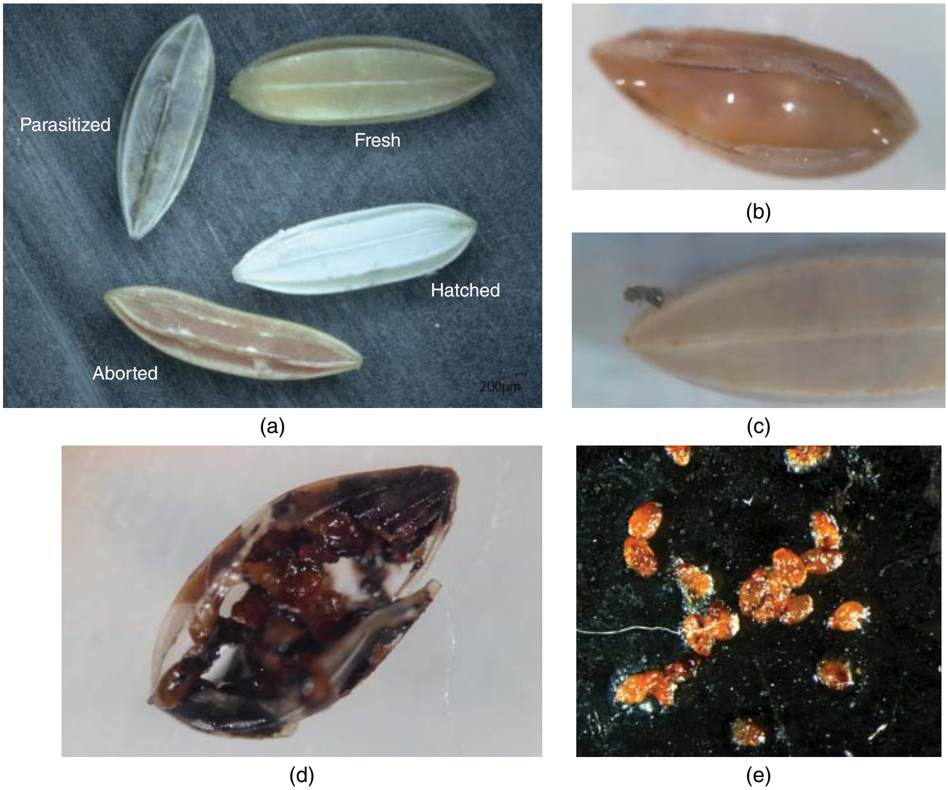

Figure 8.1 (a) Different states of PBM eggs. Unhatched eggs were dissected to see if they were infested or aborted. Dissection of these eggs revealed a grayish-yellow liquid substance (8× magnification). (b) Dissected PBM egg: the liquid indicates that the egg was aborted (neither embryo pest nor parasitoid is observed). Rarely, a dead young larva was found inside (11× magnification). (c) Female *Trichogramma* laying eggs in a PBM egg (23× magnification). (d, e) Egg of parasitized PBM, after dissection (16× magnification). The content reveals several *Trichogramma* pre-nymphs (recognizable by their red eyes).

non-target side effects be considered. Fresh PBM eggs ($n = 350$) exposed in the field from June to September 2014 in the Department of Hérault (France) did not show any signs of parasitism and neonate larvae emerged from any of the exposed eggs (Beaudoin-Ollivier, personal communication). Therefore, even if the laboratory experiments had shown PBM eggs as a possible target for *Trichogramma* sp., the impact of parasitoids under field conditions remains to be ascertained and needs to be further explored. Even if no emergence of *Trichogramma* in parasitized eggs was noted, these preliminary results are promising because more eggs were dead with *Trichogramma* than with the control, suggesting the development of *Trichogramma* to control PBM.

Mites of *Hypoaspis* (Acari: Laelapidae) and *Ameroseius* (Acari: Ameroseiidae) species have also been associated with RPW (Reginald 1973; Peter 1989). Mites from the family Uropodidae (Acari: Mesostigmata) have frequently been observed in large numbers in association with RPW in Israel and Italy (Fig. 8.2). These are not considered to play a role as biological control agents. However, as they populate each individual in huge numbers, they are expected to significantly compromise RPW flight abilities and thus dispersion.

Figure 8.2 Mites from the family Uropodidae (Acari: Mesostigmata) in association with RPW adults. (Photo by Victoria Soroker)

8.2.2 Predators

Insect predators are preferred over others predators such as mammals, birds, amphibians, reptiles, and fish, because they feed on a smaller range of prey species.

The earwig *Chelisoches morio* (F.) (Dermaptera: Chelisochidae) has been described as a common predator of RPW eggs and larvae in crowns of coconut plants in India (Abraham, Kurian, and Nayer 1973). *Euborellia annulipes* (Lucas) (Dermaptera: Anisolabididae) was also found in RPW-infested palms in Sicily and showed a high predation rate of RPW eggs in the laboratory (Massa and Lo Verde 2008; Mazza *et al.* 2014).

To date, no research data have been reported on PBM-predatory insects, although ants could be considered natural predators of eggs, as occurs with other castniid species (Esquivel 1981, 1983). In addition, natural control of the PBM is believed to be performed by some species of the Ichneumonidae family in Argentina (Sarto i Monteys and Aguilar 2005).

Some bird species have been reported as potential predators of both RPW and PBM, such as the common blackbird (*Turdus merula* L.), the common kestrel (*Falco tinnunculus* L.), and the common magpie (*Pica pica* L.). The latter occasionally feed on RPW adults, and populations of PBM are likely to be controlled by magpies and other ravens in Argentina (Sarto i Monteys and Aguilar 2005; Lo Verde *et al.* 2008). Predation of PBM larvae by magpies was observed during the spring when the larvae and prepupae are located near or on the surface of the trunk or leaf axillae at the end of the larval gallery (Beaudoin-Ollivier, personal communication).

Some mammals, such as the black rat *Rattus rattus* (L.) and the wood mouse *Apodemus sylvaticus* (L.) that use palms for shelter, have been described as predators of RPW adults and pupae, but their role in controlling the pests is very limited (Mazza *et al.* 2014). Again, it is difficult to quantify the real impact of predators on the RPW life cycle under natural conditions, but their practical use seems to be limited.

8.2.3 Entomopathogens

Insects can be infected by several disease-causing microorganisms, such as viruses, bacteria, nematodes, and fungi. These may reduce the insects' rates of feeding and growth, reduce or prevent their reproduction, or kill them.

8.2.3.1 Viruses

Viruses are obligate pathogens that can only reproduce within a host insect. Gopinadhan, Mohandas, and Nair (1990) reported the first case of a viral disease on RPW in India, causing deformed adults and reducing their lifespan. Those cytoplasmic polyhedrosis viruses were able to infect all stages of the insect under both field and laboratory conditions (Gopinadhan, Mohandas, and Nair 1990; El-Minshawy, Hendi, and Gadelhak 2005). Viruses have been little used as biological control agents against RPW, but they have been combined with nematodes to improve control of this pest (Salama and Abd-Elgawad 2002).

Entomopathogenic agents of viral origin, including a baculovirus, were found in around 20% of the population of leaf-eating Lepidoptera of the oil palm and coconut (Desmier de Chenon *et al*. 1988). Densovirus, a small virus of the Parvoviridae family that infects insects and crustaceans, has been tested under laboratory conditions using fresh PBM eggs, but no significant mortality was recorded (Beaudoin-Ollivier, personal communication).

8.2.3.2 Bacteria

Several bacteria of RPW have been tested for control of this pest (i.e. *P. aeruginosa* and different species of *Bacillus* and *Serratia*) (Dangar and Banerjee 1993; Banerjee and Dangar 1995; Alfazariy 2004; Salama *et al*. 2004). Among them, the genus *Bacillus* showed the highest RPW control efficacy under laboratory conditions. *Bacillus sphaericus* Neide, *B. megaterium* de Bary, and *B. laterosporus* Laubach produced a larval mortality of between 40 and 60%, with *B. sphaericus* being the most virulent, possibly due to its production of insecticidal crystal proteins (Salama *et al*. 2004). However, the strain was slightly to moderately toxic, as revealed by the LC50 value of *B. thuringiensis* (>2 mg/ml), and some of the surviving larvae showed midgut damage and a decrease in feed (Manachini *et al*. 2009). Further experiments showed that ingested spores of *B. thuringiensis* could invade the hemolymph in the vegetative form, affecting the immune system (Manachini *et al*. 2011).

8.2.3.3 Nematodes

Entomopathogenic nematodes (EPN) are obligatory parasites that are principally used in augmentative control (Grewal, Ehlers, and Shapiro-Ilan 2005). Nematode fauna has been associated with RPW, but their possible use as biocontrol agents remains unexplored (Kanzaki *et al*. 2008; Oreste *et al*. 2013). However, some nematodes from other hosts are commercially available for RPW control.

Although EPN have been described as belonging to 23 different families, the Steinernematidae and Heterorhabditidae contain the most interesting species in terms of becoming biocontrol agents, since they carry the specific pathogenic bacteria *Xenorhabdus* and *Photorhabdus*, respectively (Grewal, Ehlers, and Shapiro-Ilan 2005; Koppenhöfer 2007). These nematodes can actively find, penetrate, and infect the insect, releasing their symbiotic pathogenic bacteria into its hemocoel (Lacey and Georgis 2012).

Natural infections of RPW by the genera *Heterorhabditis* and *Steinernema* have been occasionally recorded (Atakan *et al*. 2009; Saleh *et al*. 2011). Several tests have been conducted in both the laboratory and the field to evaluate the efficacy of EPN in RPW control (Abbas, Saleh, and Akil 2001; Abbas *et al*. 2001; Saleh and Alheji 2003; Elawad *et al*. 2007; Llácer, Martínez, and Jacas 2009; Dembilio *et al*. 2010a; Nardi *et al*. 2011; Santhi *et al*. 2015).

In laboratory assays, most nematodes are pathogenic to RPW eggs, larvae, pupae, and adults; however, in field treatments, only a few species are effective (Shahina *et al*. 2009). The EPN species *Steinernema feltiae* Filipjev and *Heterorhabditis bacteriophora* Poinar have shown high infectivity for all developmental stages of RPW in laboratory assays. Recently, these nematodes were applied in semi-field and field tests to Canary palm trees inhabited by RPW. Interestingly, the nematodes were observed actively moving in the tree's inner tissues, infecting larvae and adults. Treatments of hundreds of trees showed recovery after nematode application (Glazer, personal communication). However, in general, inconsistent results were obtained when the EPN were applied in field experiments due to high temperatures, high UV radiation, and low relative humidity that affect nematode survival (Abbas, Saleh, and Akil 2001; Saleh *et al*. 2011). Use of chitosan in the formulation protected these biocontrol agents by increasing and stabilizing their efficacy (Dembilio *et al*. 2010a). *S. carpocapsae* was applied in a chitosan formulation for preventive and curative assays; it showed an efficiency of 98 and 80%, respectively, and in combination with chemical insecticides, it was highly effective against RPW in the field (Llácer, Martínez, and Jacas 2009; Dembilio *et al*. 2010a).

EPN have been shown to be compatible with a large number of chemical and biological products, as well as safe for non-target vertebrates and for the environment (Lacey and Georgis 2012). Moreover, their mass production in liquid media has significantly reduced production costs (Ehlers 2001). However, further studies into the lack of reproduction of some EPN inside RPW have to be addressed before their commercial exploitation as biocontrol agents (Mazza *et al*. 2014). In addition, the cryptic habitat of the RPW makes it difficult to discern the success of the treatments (Atwa and Hegazi 2014).

Both EPN genera have proven effective against the PBM (Nardi *et al*. 2009; Ricci *et al*. 2009). In Italy, the efficiency of *S. carpocapsae* against PBM in preventive and curative treatments was tested, and it impeded new infestations of PBM and significantly decreased the pest population (Nardi *et al*. 2009). On the other hand, PBM infection by nematodes was reported under *insectarium* conditions and the nematode was identified as *Rhabditis* (*Choriorhabditis*) *longicaudatus* (Bastian) (Sarto i Monteys and Aguilar 2005). Compared to *H. bacteriophora* and *S. feltiae*, *S. carpocapsae* has been revealed to be effective on PBM larvae and to cause rapid adult mortality. Experimental results showed the efficiency of nematodes, particularly *S. carpocapsae*, using curative sprays in the fall, with 83 and 87% efficacy relative to controls at doses of 1 million and 10 million/l, respectively (André, Chapin, and Villa 2011).

8.2.3.4 Fungi

The entomopathogenic fungi are natural enemies of arthropods and play an important role in their control (Goettel, Eilenberg, and Glare 2005). Several species of entomopathogenic fungi, in particular the asexual stage—entomopathogenic mitosporic ascomycetes (EMA)—have been found naturally infecting RPW and PBM specimens. The use of EMA as biological control agents against both insects has the following advantages: (1) they act through the cuticle, not by ingestion, facilitating the biocontrol action; (2) they share an ecological niche with the insect since they are naturally present in the soil of palm plantations, the phylloplane, and inside palms as endophytes; (3) they secrete compounds with insecticidal activity; (4) they are easy to mass-produce for the development of commercial insecticides (Fröhlich, Hyde, and Petrini 2000; Vey, Hoagland, and Butt 2001; Srivastava *et al*. 2009; Dembilio *et al*. 2010b; Quesada-Moraga, López-Díaz, and Landa 2014).

Several indigenous strains of EMA have shown excellent results against RPW eggs, larvae, and adults (Ghazavi and Avand-Faghih 2002; El-Sufty *et al*. 2009; Dembilio *et al*. 2010b;). *Beauveria bassiana* (Balsamo) Vuillemin (Ascomycota: Hypocreales) is one of the most common species isolated from RPW (Güerri-Agulló *et al.*, 2011). It has been found infecting specimens of *R. ferrugineus* throughout the Mediterranean Basin and the Middle East (Ghazavi and Avand-Faghih 2002; Shaiju-Simon and Gokulapalan 2003; El-Sufty *et al*. 2009; Dembilio *et al*. 2010b; Besse *et al*. 2011; Lo Verde *et al*. 2012; Francardi *et al*. 2013; Soroker *et al.* 2014). In addition, *Metarhizium anisopliae* (Metchnikoff) Sorokin (Ascomycota: Hypocreales) has been found infecting adults in the same regions, while *M. pinghaense* Q. T. Chen and H. L. Guo (Ascomycota: Hypocreales) has been found infecting them in Vietnam (Ghazavi and Avand-Faghih 2002; Francardi *et al*. 2013; Cito *et al*. 2014).

Recent studies have found specimens of *P. archon* naturally infected by *B. bassiana*, *B. pseudobassiana* S. A. Rehner and Humber and *Lecanicillium attenuatum* Zare and W. Gams (unpublished data). This was the first report of EMA isolated from PBM, even though there is a patent (FR2909838-A1) for the use of a commercial EMA for biological control of this insect (Besse-Millet, Bonhomme, and Panchaud 2008).

Regarding RPW, only two species naturally infect them in the Mediterranean Basin: *B. bassiana* and *M. anisopliae*. Molecular identification using elongation factor 1α (EF1α) and inter-simple sequence repeats (ISSR) revealed the persistence of isolates that were well adapted to Mediterranean environmental conditions and to this host (unpublished data). In recent years, RPW populations have become established in new areas of Israel, such as HaCarmel, Naharia, and HaBsor. HaCarmel and Naharia are northern coastal regions of Israel characterized by a Mediterranean climate, with hot and dry summers and cool rainy winters with high rainfall. In those areas, during the rainy season when RPW infestation was severe, adult and larvae sampled from infested trees were frequently found to be naturally infected with entomopathogenic fungi, mainly of the genus *Beauveria* but also *Metarhizium* spp. (Fig. 8.3). When RPW populations in those areas were reduced, the pathogens were rarely observed (Y. Nakache, personal communication). Moreover, adult RPW collected in infested Canary palms or in pheromone traps and brought to the laboratory were often observed dying naturally from one of these fungi, and occasionally infection was vertically transmitted from infected hosts to healthy individuals (G. Gindin and V. Soroker, personal communication). Virulence and ecology assays (effect of temperature, moisture, and UV-B radiation) were performed with isolates found throughout the Mediterranean Basin, to select the better-adapted strains for mycoinsectice development.

Several studies have been conducted in both the laboratory and the field with EMA; successful results were obtained against all developmental stages of RPW, along with sub-lethal effects on reproduction and their offspring (Gindin *et al*. 2006; Dembilio *et al*. 2010b). Pathogenicity to RPW was variable, but all *B. bassiana* isolates tested from the collection at the Agricultural Research Organisation (ARO) – Volcani Center in Israel were considerably less virulent than *M. anisopliae* isolates. The virulence of *M. anisopliae* to adult RPW differed significantly with application methodology: dusting caused approximately 85% mortality within a 2-week period while spraying caused 100% mortality within 5 weeks. Dusting of spores had a tremendous effect on fertility and reduced oviposition period from more than a month in the control group to a

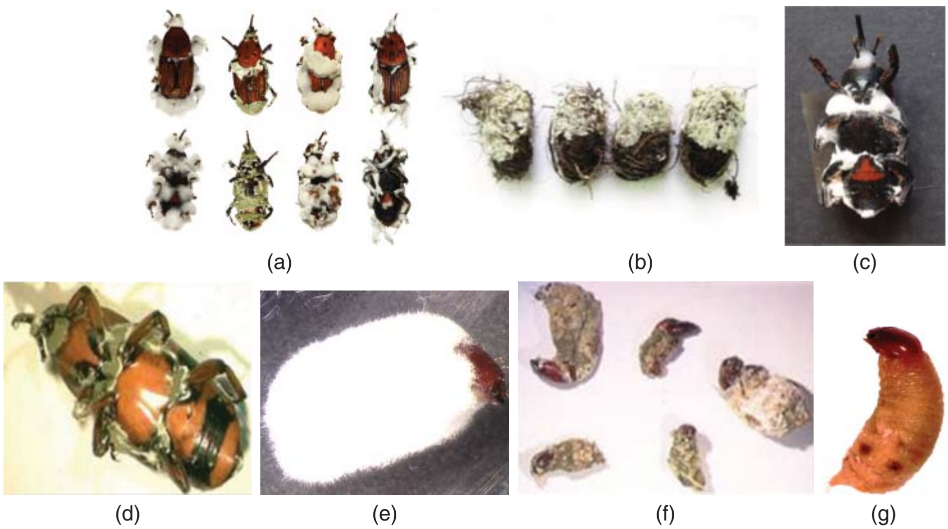

Figure 8.3 (A) Natural epizootics of *Beauveria* and *Metarhizium* spp. in RPW population in Israel. Adults infected with *Metarhizium* spp. ventral and dorsal views. (B) Cocoons infected with *Beauveria* spp. (C, D) Adults and (E, F) larvae infected with *Beauveria* and *Metarhizium* spp., respectively. (G) Dark spots indicate the entry points of fungal invasion. (Photos by Alex Protasov and Shlomit Levsky)

period of 7–11 days. However, horizontal transmission from females to eggs could not be verified (Gindin *et al.* 2006).

Regarding *P. archon*, *B. bassiana* 47 (Ostrinil®) has been successful as a preventive treatment under semi-field conditions. Besse, Crabos, and Panchaud (2013) and Besse *et al.* (2012) reported on two entomopathogenic fungi—both *B. bassiana* strains. Ostrinil® application resulted in mortality of larvae and was effective on pupae (inside the cocoon), delayed development of the surviving larvae, or caused abnormal emergence of sterile imagos in the lab and under field conditions. In contrast, strain Bb111B005 was only effective on larvae and adults. Ostrinil® has been recommended (Ministerial Order of June 5, 2009) (Decoin 2010).

Auto-dissemination devices have been tested to enable horizontal transmission between individuals (El-Sufty *et al.* 2011; Francardi *et al.* 2013). However, this issue needs to be improved by adapting myco-formulations to the chemical composition of the RPW adult and larval cuticles (Mazza *et al.* 2011). Since *R. ferrugineus* adults are mobile, they can vector the fungus to less accessible areas and spread it to cryptic individuals and/or life stages, which are otherwise hard to eradicate. The efficacy of direct application of *Metarhizium* spp. spores against RPW in infested areas, as either a dry formulation or emulsion, is being examined in Spain and will be examined in Israel and other Mediterranean countries in the future.

EMA have also been shown to be endophytes of a great number of plants, including palms (Fröhlich, Hyde, and Petrini 2000; Posada and Vega 2005; Meyling and Eilenberg 2006; Quesada-Moraga *et al.* 2006). Palm seeds dressed with a *B. bassiana* isolate were endophytically colonized in the roots and leaves. This, together with the recent demonstration of vertical transmission of EMA inside plants, opens up a wide range of new possibilities for the control of both pests via endophytic plant colonization

(Quesada-Moraga, López-Díaz, and Landa 2014). However, to date, only Arab and El-Deeb (2012) have addressed this topic: they fed RPW larvae an artificial diet supplemented with date-palm tissues with endophytic fungi and achieved 80% mortality in 14 days.

Finally, EMA can produce high-molecular-weight proteins or low-molecular-weight secondary metabolites that can also be applied against RPW and PBM adults and larvae. In preliminary results, the ingestion of crude extract produced by an *M. brunneum* strain containing destruxin A and A_2 (Lozano-Tovar *et al.* 2015) produced more than 90% mortality of L2 and L5 instar larvae of RPW. In addition, neurotoxin-like effects were observed in adults (unpublished data).

Trunk injection of chemical insecticides is the control method of choice against RPW (Speranza 2008). Fungal extracts might be injected into the palm trunk instead, reducing the insecticide's harmful effects on the environment and human health. Preliminary experiments in which crude extracts were injected into the trunk showed significant differences with the control in reducing live *R. ferrugineus* inside the plants. However, the dose still needs to be adjusted, since imidacloprid continues to show the best results in controlling this pest (unpublished data).

8.3 Perspectives on Biological Control of *R. ferrugineus* and *P. archon*

The EU Directive on the sustainable use of pesticides (Directive 2009/128/EC) has forced member states to implement integrated pest management in their territory, and promotes the use and development of methods that avoid environmental pollution and problems derived from the side effects of their use. Thus biological tools have received a considerable amount of attention as alternatives to chemical insecticides. Biological control can be defined as the use of living organisms or their products to control pests, in order to reduce the damage caused by insect pests to tolerable levels. First, the beneficial macro- or microorganisms need to be identified by studying the natural enemies of the pests in their environments or by selecting potential candidates to control them. This strategy has been followed for *R. ferrugineus* and *P. archon* control, as described in this chapter.

Regarding microorganisms, the entomopathogenic fungi probably offer the most successful control method. They share an ecological niche with RPW and PBM and have shown high effectiveness against both pests. Their contact mode of action, autodissemination potential (allowing reinfection of larvae within the stem), endophytic behavior (of some strains), and production of insecticidal compounds make entomopathogenic fungi especially relevant for the control of concealed insects. The cryptic habits of RPW and PBM make it difficult to detect the early stages of infestation. In this context, the application of new tools, such as trunk injections with bioinsecticides, could provide a real control alternative. Entomopathogenic fungi and their secreted insecticidal compounds can be produced in large amounts in the laboratory and are easily applied in the field.

In conclusion, the use of natural enemies to control RPW and PBM is an important pest management tool and a key component of integrated pest management programs in palm crops. In particular, entomopathogenic fungi are currently being evaluated under field conditions throughout the Mediterranean Basin using different inundation strategies, and they are showing highly promising results.

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9

Visual Identification and Characterization of *Rhynchophorus ferrugineus* and *Paysandisia archon* Infestation

Dimitris Kontodimas[1], Victoria Soroker[2], Costas Pontikakos[3], Pompeo Suma[4], Laurence Beaudoin-Ollivier[5], Filitsa Karamaouna[3] and Paola Riolo[6]

[1] *Department of Entomology & Agricultural Zoology, Benaki Phytopathological Institute, Athens, Greece*
[2] *Department of Entomology, Agricultural Research Organization, The Volcani Center, Rishon LeZion, Israel*
[3] *Department of Pesticides' Control and Phytopharmacy, Benaki Phytopathological Institute, Athens, Greece*
[4] *Department of Agriculture, Food and Environment, Applied Entomology Section, University of Catania, Italy*
[5] *Centre de coopération internationale en recherche agronomique pour le développement (CIRAD), Biological System Department, Research Unit Bioagresseurs, France*
[6] *Department of Agricultural, Food and Environmental Sciences, Marche Polytechnic University, Italy*

9.1 Introduction

As mentioned in Chapter 3, this volume, in the last decade the invasive species *Rhynchophorus ferrugineus* (red palm weevil, RPW) and *Paysandisia archon* (palm borer moth, PBM) have caused considerable damage to palm trees in the Mediterranean Basin. The two native European palm tree species (*Phoenix theophrasti* and *Chamaerops humilis*) seem to be less susceptible to RPW than the other common palm species (Kontodimas *et al.* 2006; Dembilio *et al.* 2011; Giovino *et al.* 2012). On the other hand, *C. humilis* is highly susceptible to PBM (Fig. 9.34). To date, there has been only one record of infestation of *P. theophrasti* by PBM (Psirofonia and Niamouris 2013) (Fig. 9.17).

The cryptic behavior of these pests is the major obstacle to early identification of the infestation and characterization of infestation severity. Nevertheless, visual examination of palm trees is the most common practice for infestation detection. The common practice is to inspect the palm's shape, in particular crown symmetry, and leaf color and shape, with a focus on the condition of the spur leaf (Soroker *et al.* 2013, 2014). The stipe is also inspected for any wounds/tunnels, dry secretions, or oozing. However, not all commonly observed symptoms are pathognomonic (i.e. definitive indications of a certain infestation/infection or condition) of these pests. Some are shared with physiological deficiencies, pathogenic diseases, or other pests. Some symptoms are more specific to particular palm species but not others. This chapter describes the visual pathognomonic and non-pathognomonic symptoms in most common and economically important palm species in the Mediterranean Basin.

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Edited by Victoria Soroker and Stefano Colazza.

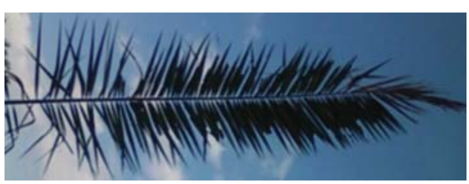
9.2 Non-Pathognomonic Symptoms

Palm infestation by RPW and PBM is associated with aberrant growth of the crown and leaf discoloration. However, these same symptoms may also be caused by other pests. In a search for infestation symptoms, the palm needs to be inspected slowly and carefully, with special attention to the symptoms presented in Boxes 9.1 and 9.2. Box 9.1 describes non-pathognomonic symptoms and their alternative causes.

Box 9.1

Non-pathognomonic symptoms observed in palms

Symptoms	Figure	Alternative reason
The crown lacks the typical round and symmetrical shape	 **Figure 9.1** Flattened crown of a Canary palm (*P. canariensis*). (*See color plate section for the color representation of this figure.*)	Physiological deficiency, e.g. lack of nutrients
A gap between the inner and outer leaves	  **Figure 9.2** Gap in the crown of Canary palm. (*See color plate section for the color representation of this figure.*)	Fruit bunch weight

Symptoms	Figure	Alternative reason
Some leaves are broken at the base	 **Figure 9.3** Canary palms with broken leaves (arrows). (*See color plate section for the color representation of this figure.*)	Wind, occasional damage by gardeners
Some leaves are damaged at the periphery	 **Figure 9.4** Leaf of Canary palm with damaged leaflets. (*See color plate section for the color representation of this figure.*)	Wind, occasional damage by chewing pests (e.g. locusts)

(Continued)

Box 9.1 (Continued)

Symptoms	Figure	Alternative reason
Outer leaves are dry	 **Figure 9.5** Dry outer leaves on date palm (*P. dactylifera*). (*See color plate section for the color representation of this figure.*)	Physiological problems, e.g. water stress, high temperature, or pathogen infection, e.g. *Diplodia phoenicum* (Sacc.)
Discolored leaf tips	 **Figure 9.6** Canary palm. (*See color plate section for the color representation of this figure.*)	Non-parasitic disease, e.g. water or nutrient deficiency
Wilted leaves in the crown of young trees	 **Figure 9.7** Date palm. (*See color plate section for the color representation of this figure.*)	Infection by fungi, e.g. *Fusarium* sp., *Thielaviopsis paradoxa* (Polizzi *et al.*, 2006)

Figure 9.8 Inspection window cut in the crown of *P. canariensis*.

The probability of these symptoms indicating the presence of RPW and/or PBM is high in areas where the pests have already been confirmed. In these areas, to validate the pests' presence in the center of the crown, an "inspection window" in the suspected palms (especially *P. canariensis*), made by cutting some leaves (Fig. 9.8), is strongly recommended. The "window" allows detecting evidence for the presence of any of the pest developmental stages (larvae or pupae in fiber-made cocoons, frass or tunnels; for description see Chapters 4 and 6, this volume).

9.3 Pathognomonic Symptoms

Pathognomonic symptoms of RPW and/or PBM infestation are described in Box 9.10. The most specific symptoms are those caused by larval chewing of the developing leaves at the center of the crown of the very susceptible palm *P. canariensis*. The symptoms depend on the location, size and number of pest larvae, and leaf developmental stage during their attack. When the leaf fronds are chewed at their bases, mature leaves dry out. At initial stages of the infestation, just the tips of the leaves dry out (Fig. 9.6). The crown may appear asymmetrical (Fig. 9.13) if larval feeding is concentrated on a specific side of the palm. Once the palm center ("the heart") is chewed up or destroyed by secondary infection, spur leaves no longer appear, and the palm has a typical "umbrella" shape (Fig. 9.16). This "umbrella" is initially green but, as infestation continues, the outer leaves become disconnected from the vascular system in the stipe by the developing larvae and dry, turning yellow. Although these symptoms are most commonly visible in *P. canariensis* infested by RPW, in heavily infested areas, crown leaf collapse has also been observed in other palm species, e.g. *P. dactylifera* and *Washingtonia* (Fig. 9.17).

Box 9.2

Pathognomonic symptoms of RPW and PBM observed in palms.

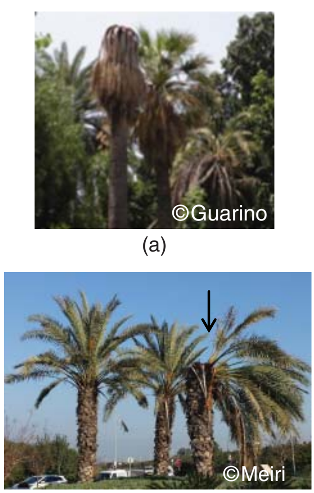
Symptoms	Figure	Pest
"Sewing" holes in the leaves caused by RPW adults	 **Figure 9.9** Holes in Canary palm leaves. (*See color plate section for the color representation of this figure.*)	RPW
Chewing symptoms from RPW larvae	 **Figure 9.10** Damaged leaves of Canary palm. (*See color plate section for the color representation of this figure.*)	RPW

Symptoms	Figure	Pest
Chewing symptoms from PBM larvae. Specific in infested zone	 **Figure 9.11** Damaged leaf of *Trachycarpus fortunei* showing a series of consecutive perforations in a circular pattern. (*See color plate section for the color representation of this figure.*)	PBM
Collapsed leaves and presence of holes, galleries, larvae, cocoons, and adults at the leaf base	 **Figure 9.12** Collapsed leaves on Canary palm. (*See color plate section for the color representation of this figure.*)	RPW

(Continued)

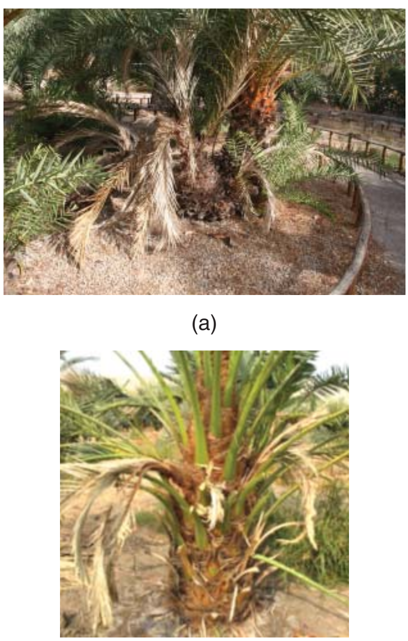
Box 9.2 (Continued)

Symptoms	**Figure**	**Pest**
Asymmetric inner leaf growth	 **Figure 9.13** Asymmetric inner leaf growth on Canary palm. (*See color plate section for the color representation of this figure.*)	RPW
Crown partially collapsed	 **Figure 9.14** Partially collapsed crown of Canary palm. (*See color plate section for the color representation of this figure.*)	RPW
Absence of young leaves	 **Figure 9.15** Absence of new young leaves in Canary palm. (*See color plate section for the color representation of this figure.*)	RPW

Symptoms	Figure	Pest
Symptoms of the infestation in the upper area of the stipe	 **Figure 9.16** Canary palms with the typical "umbrella" shape crown. (*See color plate section for the color representation of this figure.*)	RPW
Symptoms of the infestation in the upper area of the stipe	 (a) (b) **Figure 9.17** Collapsed infested crowns of (a) *Washingtonia* sp. and (b) *P. dactylifera* (infested palm marked with an arrow). (*See color plate section for the color representation of this figure.*)	

(Continued)

Box 9.2 (Continued)

Symptoms	Figure	Pest
Wilted inner leaves	 **Figure 9.18** Wilted inner leaves in date palm. (*See color plate section for the color representation of this figure.*)	RPW
Dry offshoot(s)	 (a) (b) **Figure 9.19** Dry offshoots in (a) Cretan date palm (*P. theophrasti*) and (b) *P. dactylifera*. (*See color plate section for the color representation of this figure.*)	RPW, PBM

Symptoms	Figure	Pest
Dry or fresh sawdust	 **Figure 9.20** Dry sawdust emitted from infested date palm. (*See color plate section for the color representation of this figure.*)  **Figure 9.21** Dry or fresh emission of sawdust from *Washingtonia* sp. stipe. (*See color plate section for the color representation of this figure.*)	RPW, PBM

(Continued)

Box 9.2 (Continued)

Symptoms	Figure	Pest
	 **Figure 9.22** Fresh sawdust extruding from larval galleries in *Howea forsteriana* stipe. (*See color plate section for the color representation of this figure.*)  **Figure 9.23** Abundant sawdust extruding from larval galleries in the crown of *T. fortunei*. (*See color plate section for the color representation of this figure.*)	PBM

Symptoms	Figure	Pest
Oozing from the stipe	 **Figure 9.24** Liquid oozing from the stipe of *Washingtonia* sp. (*See color plate section for the color representation of this figure.*)  **Figure 9.25** Liquid oozing from the stipe of *H. forsteriana*. (*See color plate section for the color representation of this figure.*)	PBM

(Continued)

Box 9.2 (Continued)

Symptoms	Figure	Pest
Oozing from the stipe	 **Figure 9.26** Dry or wet material oozing from the stipe of *P. dactylifera*. At this stage, the crown usually remains green with no obvious symptoms. (*See color plate section for the color representation of this figure.*)	RPW
Burrow at the base of the stipe	 (a) (b) **Figure 9.27** *Washingtonia* sp. palm tree infested (a) at the top and (b) at the bottom of the stipe. (*See color plate section for the color representation of this figure.*)	

Some symptoms can be caused by both RPW and PBM: collapsed leaves, asymmetric inner leaf growth, absence of new inner leaves, partial collapse of the crown, wilted leaves of offshoots, dry offshoots, oozing from the stipe. However, there are also differences: symptoms which specifically indicate infestation by the weevil include the "sewing" holes in the leaves or chewing symptoms that follow a ">" shape (Figs. 9.9 and 9.10).[1] On the other hand, the presence of "chewing" symptoms in the leaves or sawdust (Figs. 9.11 and 9.21) are more likely to indicate infestation by the moth. Specific visual detection protocols for each of these pests in their most sensitive hosts are described below.

9.4 Identification of RPW Infestation

Depending on the palm species and age, the abovementioned symptoms appear different. In general, in young palms (1 – 5 years old), infestation can be detected at early stages as dry or wilted leaves. In older palm trees, symptoms vary according to palm species, as described below.

9.4.1 Infestation in Canary Palm

In Canary palm, the most common infestation is at the level of the crown. It often seems that there were no symptoms before the crown collapsed. However, it is usually possible to detect gradual changes in canopy symmetry, such as: flattened crown, gap between the inner and outer leaves, asymmetric inner leaf growth, absence of new inner leaves, partial collapse of the crown (Figs. 9.1, 9.2, 9.13 – 9.15). In addition, some symptoms can usually be observed on the leaves: broken leaves, dry outer leaves, discolored leaves or leaf tips, damage at the periphery of the leaves (Figs. 9.3 – 9.6). Irrefutable evidence for RPW infestation in Canary palm trees includes holes in the leaves resembling holes made by sewing (Fig. 9.9), chewing symptoms in a ">" shape (Fig. 9.10) and collapsed leaves (Fig. 9.12) with RPW residue at the bases (galleries, larvae and/or palm fiber cocoons). The latter can already be empty or contain larvae, pupae or adult RPW that are ready to emerge.

9.4.2 Infestation in Date Palm

In young date palms, the most common infestation appears in the lower part of the plant, in the offshoots. Symptoms can remain hidden behind offshoots, leaf bases and stipe fibers but often dry or wet ooze, thick, dry or fresh sawdust, dry offshoot(s), and wilted leaves of some offshoots or the inner spur can be seen (Figs. 9.7, 9.17 – 9.20). It is advised that the dry offshoots be removed to expose the suspected area, with the aim of finding more obvious symptoms of weevil damage, such as cocoons or larvae. In old palms, as often seen in urban environments, the infestation of date palm by RPW can occur in other parts of the palm tree, i.e. in the crown (as in Canary palms) or along the stipe; in these cases, oozing and cavities are sometimes visible (Fig. 9.26).

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1 It is important to note that these symptoms were caused during leaf development and thus indicate the pest's presence within the central part of the palm, endangering the single growing point of the palm located deep within the developing leaves (Chapter 2, this volume).

Figure 9.28 Infested by RPW: (a) *Brahea* (= *Erythaea*) sp. (b) *Ravenea* broken below the crown. (c) *Syagrus* stipe with marks of oozing, cocoons, and larvae. Reproduced with permission from Yaakov Nakach. (*See color plate section for the color representation of this figure.*)

9.4.3 Infestations in Other Palm Species

Although 25 palm species are listed in the literature as hosts of RPW, not many are real hosts under natural conditions (see Chapters 1 and 4, this volume). Visual symptoms have been reported for those that seem to be the most susceptible. In palm species, such as *Washingtonia* sp., *Syagrus* sp., *Brahea* (= *Erythaea*) sp. and *Ravenea* sp., RPW usually attacks the upper part of the palm (Fig. 9.28). Ooze running down the stipe is usually a symptom of infestation. Infestations are also reported at the base of the stipe (Fig. 9.27).

9.5 Identification of PBM Infestation

As with RPW, infestation by PBM is not easy to detect. Symptom expression depends on palm species and age, and in some cases infested palms remain asymptomatic until palm collapse (Drescher and Dufay 2001; Riolo *et al.* 2004; Sarto i Monteys and Aguilar 2005;

EPPO 2008). Many symptoms may indicate PBM activity, but they might not be specific to PBM, such as: presence of sawdust extruding from larval activity on the crown, stipe (Figs. 9.20, 9.22 and 9.23), or axillary buds; oozing of thick brown liquid (Fig. 9.24 and Fig. 9.25); holes at the rachis base observed during sanitary operations; abnormal development of axillary leaf buds; deformation and abnormal twisting of stipe; and abnormal drying up of the palms, especially the core leaves. These symptoms are very similar to the presence of RPW (Figs. 9.32–9.34).

As in the case of RPW, PBM first-instar larvae can bore into the young packed fronds, and feeding damage on the leaves becomes evident as they develop, open, and expand. More specific symptoms for pinnate-leaved palms, such as *Phoenix* spp., are scattered chewing perforations on the leaves. Infested palmate-leaved palms—such as *T. fortunei*, *C. humilis*, *Washingtonia filifera*, and *Trithrinax campestris*—show a series of consecutive perforations along a circular sector, due to the morphology of the palm leaves (Fig. 9.11). Moreover, damage due to larval boring behavior can be observed on different parts of the palm tree: leaves, inflorescences, immature fruit, crown, leaf rachis, and stipe, depending on the palm species. In *C. humilis*, young larvae are found mainly in the stipe, inflorescences, and fruit, whereas in *P. canariensis* and *W. filifera*, they are found mainly within the leaf rachis. Nevertheless, in tall *P. canariensis* and *W. filifera* palms, larval galleries occur in the palm stipe as well as the leaf rachis. Distinctive oval holes can be observed in leaf petioles when they are cut (Fig. 9.29). In *T. fortunei*, the first-instar larvae can bore into the young packed fronds. In 2- to 10-year-old *T. fortunei* and *C. humilis*, large larvae are found only in the stipe, where humidity is higher and temperature more stable (Riolo, Isidoro, and Nardi 2005; Sarto i Monteys and Aguilar 2005).

The finding of PBM life stages, such as eggs, larvae, cocoons, and pupal exuviae, undoubtedly indicates PBM infestation. Eggs usually appear near or on the crown within the palm fibers (Fig. 9.30). The pupal exuviae often protrude from the palm stipe, crown, or leaf rachis (Fig. 9.31), and are sometimes observed in palms with no other symptoms. Cocoons and pupal exuviae are also sometimes found on the ground, next to asymptomatic palms.

Figure 9.29 Distinctive oval gallery holes caused by the activity of PBM larvae in the leaf petiole of Canary palm. (*See color plate section for the color representation of this figure.*)

Figure 9.30 *P. archon*: small egg cluster and egg chorion on the stipe (indicated by arrow). (*See color plate section for the color representation of this figure.*)

Figure 9.31 *P. archon*: pupal exuviae protruding from the stipe. (*See color plate section for the color representation of this figure.*)

Figure 9.32 *T. fortunei* infested by *P. archon*.

9.6 Simultaneous Infestation of Both Pests and Co-Occurrence with Other Pests or Diseases

The contemporaneous dispersal of RPW and PBM in the Mediterranean has created conditions for co-occurrence of the two pests in the same host. This has usually been recorded in *P. canariensis* and *Washingtonia* sp. in Attica (Greece) (Kontodimas, personal observation). In this case, the infestation by PBM was recorded in the peripheral

Figure 9.33 Dead *T. fortunei* as a result of severe PBM larval infestation.

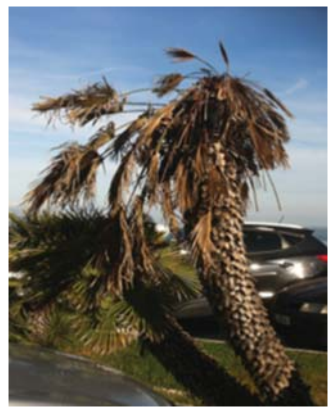

Figure 9.34 *C. humilis* infested by *P. archon*.

zone of the palm tree stipe, whereas RPW occupied the central section. In small palm trees (<1 m in height), RPW developed in the upper part of the plant and PBM was found at the periphery of the base as well as in the subterranean root parts (Kontodimas, personal observation). Simultaneous infestation of both pests has also been found on *Phoenix roebelenii* in the city of Marsala (Trapani, Italy) (Colazza, personal observation).

Two new palm pests have been recorded in the Mediterranean region and may make the identification of a new infestation more complicated: the borer *Diocalandra frumenti* F. (Coleoptera: Curculionidae) was reported in the Canary Islands in 1998, causing small holes and galleries at the leaf bases (Fig. 9.35); the hispid *Octodonta nipae* (Maulik) (Coleoptera: Chrysomelidae) was more recently reported in Cyprus (2009) infesting and gradually desiccating the leaves of queen palm (*Syagrus romanzoffiana*) (Fig. 9.36) (Vassiliou, Kazantzis, and Melifronidou-Pantelidou 2011).

In addition, larvae of two Lepidopteran species native to the Mediterranean region, *Ostrinia nubilalis* (Hübner) (Lepidoptera: Crambidae) and *Sesamia nonagrioides* (Lefèbvre) (Lepidoptera: Noctuidae), have been occasionally observed to bore into palms (*P. canariensis* and *T. fortunei*) and to produce leaf perforations similar to those described for PBM (Sarto i Monteys and Aguilar 2005; Riolo *et al.* 2007). However, the larvae of these pests do not bore into the bases of the older leaves or stipe, and the perforations on the leaves are smaller than those made by PBM and are found only in the young packed fronds. In date palm plantations, the rhinoceros beetle *Oryctes*

Figure 9.35 Holes caused by *D. frumenti* (in Canary islands).

Figure 9.36 New leaves of queen palm damaged by *O. nipae* (in Cyprus). Reproduced with permission of V. Vassileiou Cyprus, 2012.

Figure 9.37 Damage to date palm fronds by *O. agamemnon*.

agamemnon (Burmeister) (Coleoptera: Scarabaeidae) bores into the palm stipe and is occasionally observed attacking developing fronds, with symptoms resembling those of RPW (Fig. 9.37). Infestation of *O. agamemnon* also occurs with that of RPW. In this case, the scarabeid usually occupies the periphery of the stipe, thus further compromising stability of the palm, which has already been weakened by RPW infestation in the central part of the stipe (Beaudoin-Ollivier *et al.* 1999).

The co-occurrence of fungal pathogens with RPW and PBM infestations has also been recorded. *Ceratocystis* sp., which causes dark discoloration in leaf bases and rachis, has often been recorded simultaneously with RPW or PBM infestation. *Gliocladium* sp., which causes pink rot, has been recorded. In these cases, insecticidal treatment is probably not enough to save the palm.

9.7 Conclusion

Despite the cryptic behavior of the RPW and PBM, regular visual examination of palm trees for infestation detection by experts trained to distinguish pathognomonic symptoms of these pests can contribute to accurate detection and identification of the infestation. This is especially true for the most common hosts of these species, Canary palms for RPW and *Chamaerops* for PBM, providing the ability to take appropriate phytosanitary measures. Still, detection of visual symptoms of RPW in mature date palms without offshoots is extremely difficult, and often impossible. In addition, the Mediterranean ornamental landscape is very rich in a variety of palm species, and infestation symptoms may vary. Therefore, a study of the early visual symptoms and susceptibility in most of these species is urgently needed.

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10

Surveillance Techniques and Detection Methods for *Rhynchophorus ferrugineus* and *Paysandisia archon*

Victoria Soroker[1], Pompeo Suma[2], Alessandra La Pergola[2], Vicente Navarro Llopis[3], Sandra Vacas[3], Yafit Cohen[4], Yuval Cohen[5], Victor Alchanatis[4], Panos Milonas[6], Ofri Golomb[4], Eitan Goldshtein[4], Abd El Moneam El Banna[7] and Amots Hetzroni[4]

[1] Department of Entomology, Agricultural Research Organization, The Volcani Center, Rishon LeZion, Israel
[2] Department of Agriculture, Food and Environment, Applied Entomology Section, University of Catania, Italy
[3] Universitat Politècnica de València, Center for Agricultural Chemical Ecology, Mediterranean Agroforestal Institute, Spain
[4] Institute of Agricultural Engineering, Agricultural Research Organization, The Volcani Center, Rishon LeZion, Israel
[5] Department of Fruit Tree Sciences, Institute of Plant Sciences, Agricultural Research Organization, The Volcani Center, Rishon LeZion, Israel
[6] Department of Entomology & Agricultural Zoology, Benaki Phytopathological Institute, Greece
[7] Agriculture Research Center, Egypt

10.1 Introduction

Management of any pest requires accurate monitoring of its population, forecasting its dispersal, and evaluating the success of eradication efforts. As the best management is prevention, preclusion of further spread of invasive pests requires tools for monitoring, especially at ports of entry and at new infestation foci. Early detection of the infestation by the red palm weevil (RPW), *Rhynchophorus ferrugineus* (Olivier 1790), and the palm borer moth (PBM), *Paysandisia archon* (Burmeister 1880), is particularly challenging as both pests develop inside the palm, well hidden from the human eye. Especially challenging are those situations in which not all of the palms are accessible for individual assessment as is common in urban areas or parks, natural habitats such as Canary palm or Cretan date palm groves, and date palm plantations where the areas to be monitored are too large. Various methods and approaches have been evaluated over the years for early detection, particularly of RPW infestations. The most obvious approach for infestation detection is visual examination of the tree. Visual symptoms in Canary, date, and some other palm species are detailed in Chapter 9, this volume. Briefly, visual detection of RPW activity depends mainly on infestation stage, the site of infestation, palm height, and species. For example, crown infestation by RPW is easiest to detect as the palm crown loses its symmetry and inner fronds show chewing symptoms. This situation is common with Canary Island date palm (*Phoenix canariensis*) and coconut (*Cocos nucifera* L.), but rather rare in date palms (*Phoenix dactylifera* L.). In the latter, the infestation occurs mostly in the lower part of the stem; if offshoots are present, the symptoms appear either on the offshoots themselves or as tunnels and cavities within the stem, often in places of previously removed offshoots. The palm may appear healthy, without

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Edited by Victoria Soroker and Stefano Colazza.

any visible symptoms, until the damage to the trunk tissues overpowers the tree and it collapses, exposing large cavities. Hidden activity of these pests makes visual detection of the infestation problematic and inaccurate. On the other hand, pest development within the palm tissue is associated with both pest-specific traces (such as distinct odors or sounds) and specific physiological changes in the palm that are invisible to the naked eye, but can be identified by other means.

Here we aim to review detection methods based on chemical, acoustic, and thermal cues, as well as pest monitoring by semiochemicals. Essentially, all of the methodologies are expected to provide sensitive, specific, and non-destructive detection. Advantages, possibilities, pitfalls, and potential future implementations of each detection method are discussed.

10.2 Acoustic Detection

10.2.1 Assumptions

Acoustic detection of RPW larval activities has been suggested based on distinct sounds reported from the pest-infested palms. The same can be assumed to hold true for PBM. The larvae of both species, with especially large last instars, produce chewing and moving sounds. These sounds, propagated through the fibrous tissue, can be captured by a suitable sensor and are candidates for acoustical and vibrational detection and monitoring.

10.2.2 Main Detection Tools, General Features, and Challenges

Typical RPW larval activity sounds like a train of clicks with strong energy, between 0.4 and 8 kHz (Mankin *et al.* 2008; Herrick and Mankin 2012). When a number of large larvae (~1 g or more) reside inside palm tissue, larval sounds can even be detected by trained experts without any special equipment. However, detection is problematic at early infestation stages (larvae < 100 mg) when the generated sound is too low to distinguish from the background. Even without external noise, the palm's internal environment is not quiet (Box 10.1). Sounds derive from the activities of palm pests—such as feeding, moving, secreting, or spinning—or from the tree as air bubbles, and environmental effects—such as leaf rubbing, and even light draft winds.

Acoustic detection of specific pest sounds is not limited to the large larvae of the RPW. It has been implemented to monitor termites in wood (Scheffrahn *et al.* 1993), grubs in soil (Mankin *et al.* 2000), and adult insects and larvae in stored products (Mankin, Shuman, and Conffelt 1997; Potamitis, Ganchev, and Kontodimas 2009). The presence (or absence) of RPW larvae has been monitored in suspected coconut palm trees (Siriwardena *et al.* 2010) and in date palm offshoots (Hetzroni *et al.* 2004; Soroker *et al.* 2004). Recently, PBM acoustic activity was monitored in artificially infested *Chamaerops humilis* L. (Suma and La Pergola, unpublished). El-Sebay *et al.* (2004) used a condenser microphone to successfully detect sounds from the 2nd to 4th instar stages in sugarcane cuttings (single larvae each) under laboratory conditions and in palm trees.

The incidental signals that small cryptic insects produce while moving and feeding can be very low in amplitude but still detectable (Mankin *et al.* 2011). Therefore, sensor

Box 10.1

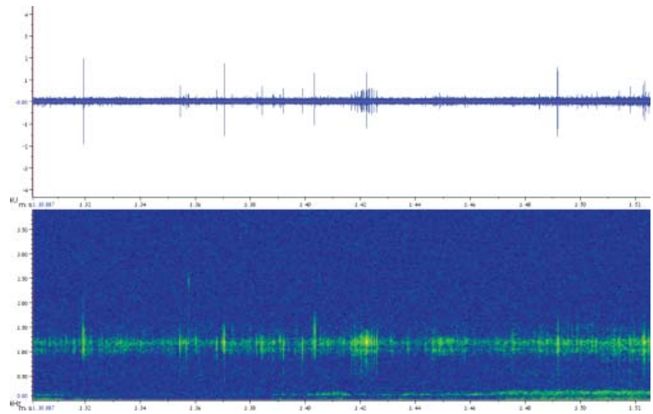
Sources of sounds that can be recorded from infested date palm

a. Weevil-derived:

- feeding
- movement
- secreting
- spinning

b. Palm-derived:

- Air bubbles
- Water movement
- Fiber friction
- Tear of fibers



Typical acoustic signal acquired from RPW-infested palm tree. Top: signal energy (kU – signal intensity); bottom: signal frequency (kHz); horizontal axis: time (s)

technology plays a significant role in capturing the larval sounds. Various types of microphones can be used for the acoustic detection of insects. Commonly used and reasonably priced sensors for insects that produce low-frequency sounds (such as the RPW and PBM) are piezoelectric transducers (Potamitis, Ganchev, and Kontodimas 2009; Siriwardena *et al.* 2010; Schofield 2011; Lampson *et al.* 2013) and accelerometers (Lampson *et al.* 2013).

Effective attachment of a sensitive microphone to the soft tissue of the palm tree is a challenge (Mankin *et al.* 2011). A laser vibrometer is a non-tactile sensor that has been used to investigate sexual communication signal traits between plant-eating insects transmitted as they propagate through the stem (Rodríguez, Ramaswamy, and Cocroft 2006). A laser vibrometer was tested by conducting parallel recordings from Canary and date palm trees using contact (microphone) and laser sensors. Some of the palm trees were infested by small 1–3 larvae (up to 100 mg each) while others were left uninfected as control. This enabled testing the ability to remotely sense acoustic signals that manifest at the outer surface (EU final report project number: FP7 KBBE 2011-5-289566). Others have indicated that the recordings made from infested palms by digital laser vibrometer exhibit a good signal-to-noise ratio, comparable or superior to other acoustic methods tested in previous studies (Mankin *et al.* 2011).

An acoustic probe inserted 10 cm into the stem was proposed as a bioacoustics sensor for early detection of the RPW. Detection was based on the acoustic intensity around 2.25 kHz. It was reported to detect infestation of 2-week-old larvae in a controlled environment, avoiding natural ambient noises (Gutiérrez *et al.* 2010). Others inserted a fixed nail/screw into the trunk and attached the microphone to it magnetically (Fig. 10.1) (Herrick and Mankin 2012; Hetzroni 2012; Jalinas *et al.* 2015).

Figure 10.1 Microphone fixed magnetically to a nail inserted into the palm trunk. (Source: Hetzroni 2012)

Various research groups have proposed a selection of bioacoustic features based on analysis in the frequency domain (Mankin *et al.* 2011). Hetzroni *et al.* (2004) recognized and isolated several dominant frequencies that indicate typical larval activities. Hussein, Hussein, and Becker (2010) indicated 94% detection in a cut infected trunk in quarantine, with the absence of any other apparent inhabitants. Sounds of the RPW were automatically detected from noise with up to 98.8% accuracy using Gaussian mixture modeling (GMM) as the classification method and mel-frequency cepstral coefficients as features, augmented with techniques adopted from the speech-recognition domain, namely "text-independent speaker identification" (Pinhas *et al.* 2008). Others reported 99.5% accuracy for RPW and sounds of the rice weevil were detected with 100% accuracy with GMM classification using dominant frequency and 23 linear frequency cepstral coefficients (LFCCs) as features (Potamitis, Ganchev, and Kontodimas 2009). Spectral features of stinkbug sounds were extracted and signals were then classified using the generalized method of moments and probabilistic neural network (Lampson *et al.* 2013).

A study by Pinhas *et al.* (2008) evaluated human labeling of audio clips and found that human detection can be unreliable, depending on the listener. Some of the problems in achieving adequate acoustic detection included: identification of the specific acoustic patterns associated with larval activities, detection of young larvae in the stem, and discriminating larval sounds from physiological sounds produced by the host plants (Jolivet 1998) augmented by sounds produced by other inhabitants, such as other arthropods, rodents, or ambient noise such as birds and wind.

The magnitude of the sound produced by a boring insect decreases significantly as it passes through a substrate. The attenuation coefficient is affected by the nature of the substrate and the frequency of the sound. Low frequencies are less attenuated and wood has a low attenuation coefficient (compared to grain, for example), and therefore the low frequencies produced by RPW infestations could be detected 2–4 m away from the source. Signals with higher frequencies are attenuated, thus sensors placed apart from each other will detect signals of different frequencies and amplitude (Mankin 2011).

Massive destruction of the stem interior (by the borers' activity) might affect the attenuation (Mankin *et al.* 2011).

Sensitivity of detection also varies with the site of the infestation and palm structure: as already mentioned, young date palms usually bear offshoots and the infestation is usually centered in those or in the stem close to the base of their attachment. On the other hand, Canary palms do not have offshoots and are usually attacked in the crown.

Most of the relevant studies have been conducted under isolated/enclosed conditions. However, a study conducted on *Rhynchophorus cruentatus* indicated no significant difference in larval burst rates between enclosed and exposed conditions, suggesting that large boring larvae can be detected acoustically without the need for isolation or confinement (Dosunmu *et al.* 2014).

Both a trained listener (within 3 min of monitoring) and the machine (developed algorithm) were able to accurately detect the hidden activity of RPWs inside young Canary palms shortly after infestation (less than 3 weeks), long before any visual symptoms appeared. Although human detection was somewhat better than machine detection (TP = 100% vs. 80%, respectively), either a trained listener or a machine can potentially be employed in quarantine to detect RPW infestation in young Canary palms. The acoustic detection of RPWs in date palm was less efficient. The observer achieved 100% true positive detection at a later stage of the infestation, while machine detection at that stage was only 50%, but was able to reach 100% as the larvae developed and grew bigger. These data indicate that automated/machine detection requires further improvement (Hetzroni, Soroker, Cohen 2016).

Understanding the diurnal activity of the borer is a key to locating the insect based on its behavior. This activity affects system design for inspection quarantines and for scouting in plantations, natural areas, and gardens. One has to be aware of feeding and movement patterns during the day and during the pest's life cycle. Quantification of expected temporal pauses in activity is important to determine the minimal time and schedule for monitoring sessions.

Very little is known about the diurnal activity of the RPW, especially the feeding activity of the larvae. A study of diurnal activity of adult RPWs using food-baited pheromone traps indicated that the insects are active in the evening and early-morning hours (Faleiro and Satarker 2003). However, these data did not provide an understanding of the concealed larvae's behavior. Observation of the RPW's diurnal activity in young potted palms that were placed in isolation indicated monotonous feeding activity rather than a diurnal pattern (Fig. 10.2).

10.2.3 Advantages and Pitfalls

The various approaches and efforts indicate that acoustic identification of concealed activity within the palm trunk is feasible. The active RPW larvae produce detectable sounds as early as 2 weeks after the palm tree has been infested. Acoustic detection provides a non-destructive technique to sense the presence of active larvae within minutes.

The acoustic technique has a few flaws: (a) it is limited to the detection of active larval instars, while egg and pupa stages cannot be detected, thus high rate of false-negative diagnoses; (b) ambient conditions interfere with the low energy emitted by younger larvae. Therefore, this method is particularly applicable in a controlled environment such as in quarantine facilities at ports of entry and as a method for confirmation in palm trees that are already suspected of being infested by other means.

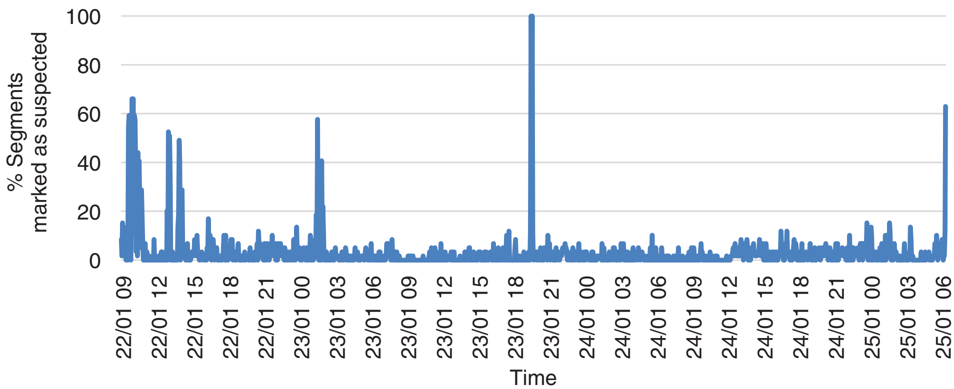


Figure 10.2 Percentage of segments suspected of being beetle activity over a period of 3 days. (Source: Hetzroni *et al*., unpublished data)

We are still limited in our knowledge of insect activity. We are not yet certain if the larvae exhibit diurnal and/or annual cycles or pauses of activity. Both diurnal and seasonal larval activity patterns and length of the developmental cycle under different climatic conditions should be taken into consideration prior to mass implementation of acoustic detection, as dormant insect stages, such as eggs, pupae, or inactive larvae cannot be detected acoustically. In quarantine facilities, sufficient quarantine time with repeated monitoring should ensure accurate and efficient detection.

10.3 Chemical Detection

10.3.1 Assumptions

The possibility of chemical detection is based on the assumption that weevil- and PBM-infested palms emit characteristic volatile cues. These may be derived directly from the insect or their frass, the wounds in the infested palm, or they may be herbivore-induced. Thick brown and bad-smelling oozing liquids are well known from RPW- and PBM-infested palms. Moreover, the male RPW releases aggregation pheromone (Hallett *et al.* 1993). A list of compounds from RPW-infested *P. canariensis* has been recently reported (Vacas *et al*. 2014). None of the specific cues emitted by palms infested by PBM has yet been identified.

10.3.2 Main Detection Tools, General Features, and Challenges

Chemical detection can be performed using automatic target detection on large scale by applying olfactory sensors (electronic nose or tongue). Automatic olfactory detection is being increasingly implemented in industry for quality control, environmental monitoring, health, and security (Sindhuja, Lav, and Suranjan 2012). The sensory system typically relies on pattern recognition to isolate the chemical signature from an array of sensors. Although still far from practical implementation for the detection of RPW infestation, this approach seems plausible for routine inspection as a smelly liquid often oozes from the infested palms. Future application of such tools—direct contact with the suspected tree by "electronic tongue" or remote sensing by an "electronic nose"—depends on the identity/volatility of the cues. A preliminary study was conducted in Italy to determine whether gas sensors (eNose) can be used for the early detection of RPW in *P. canariensis*. Tests carried out under semi-field and field conditions showed a discrimination probability of close to 95% between healthy and infested palms (Littardi *et al.* 2013; Rizzolo *et al.* 2013). The analyzer consisted of a sensory unit for gas sampling, a series of sensors, and a computer for calculations and final assessments. The sensors were sensitive to a wide range of gases, and the reaction mechanism was based on oxygen exchange between the volatile molecules and the metal film, causing an exchange of resistance that is recorded and correlated to the adsorbed compounds (Pozzi and Villa 2010). The air sampling was carried out with the use of a lung pump that enabled aspirating samples of atmospheric air near the palm stem. The main advantage of this type of pump is the total absence of contact between it and the gases to be analyzed, and thus the sample to be analyzed is not contaminated in any way. The electronic nose used was Demetra-Nose® and the analyses were carried out using the PEN3 portable electronic nose produced by Airsense. In general, the instrument consists of a sampling device, 10 MOS-type chemical sensors, and a software package for data collection and analysis. Semi-field tests were performed in a greenhouse with 20 healthy Canary palms of the same age. The air (gas) was sampled before and 3 weeks after artificial infestation with two, four, or eight RPW larvae by inserting each RPW larva through a hole drilled in the palm stem. Field tests (urban environment) were performed on Canary palms (3 m height in average) located in different locations and selected according to infestation symptoms: palms free of infestation symptoms, palms with obvious infestation symptoms, and highly infested palms close to crown collapse. The aspiration was performed with a special telescopic tube connected to the pump. Using this method, it was possible to discriminate between healthy and infested palms with a precision of close to 95% (Littardi *et al.* 2013; Rizzolo *et al.* 2013). This technique requires a rigorous methodology for air sampling to minimize interference from the external environment, and high sensitivity to detect and discriminate between groups of specific molecules that are present in minute quantities in the sampled air. Application of the instrument can potentially allow early detection of infestation and provide valuable assistance in RPW control in palm nurseries and thus rapid eradication of infestations (Pozzi and Villa 2010; Rizzolo *et al.* 2013). As already noted, despite advances in the development of electronic noses and tongues, these instruments are still far from operational, particularly in plant monitoring and palm inspection. However, the chemical detection approach for RPW-infested palms has been successfully tested using sniffer dogs.

Domestic dogs (*Canis familiaris*) are well known for their superior chemodetection abilities. They are able to detect scents of various origins, such as explosives, drugs, and invasive species. Their area of olfactory epithelium is much larger than that of humans, allowing them to detect very low concentrations of both biological and non-biological scents (Browne, Stafford, and Fordham 2006). Dogs have been previously reported to detect infested plant material (Wallner and Ellis 1976; Welch 1990; Schlyter 2012). A variety of dog breeds have been employed in the past for diverse sniffer tasks. Breeds such as Labradors, Rottweilers, Beagles, and Golden Retrievers are often preferred for these tasks thanks to their proven performance, easy disposition, and good interaction with the public. In relation to palm pests, and in particular RPW, the feasibility of this approach has been proven at least twice. Nakash, Osem, and Kehat (2000) confirmed the ability of Golden Retrievers to successfully detect the oozing secretion collected from RPW-infested date palms, but the trained dogs' ability to detect the infested palm *in situ* was not shown. Suma *et al.* (2014a) proved the ability of one Rottweiler and two Golden Retrievers to detect various numbers of RPW larvae and/or adults partially buried in vented containers at the base of potted Canary palms under semi-field conditions (Fig. 10.3). After a 6-month training period, dogs were more than 70% accurate in finding the artificially infested Canary palms with either larval instars or adult weevils of both sexes (Suma *et al.* 2014b).

As palm species are likely to vary in their volatile profiles, thereby affecting detection sensitivity, we compared RPW detection in two host species: *P. canariensis* and *Trachycarpus fortunei*. A trained dog was able to accurately detect infested Canary palms sooner than infested *Trachycarpus* palms (Fig. 10.4). The accuracy for the major host, the Canary palm, was above 80% as early as 4 weeks after infestation and reached 100% with only 6% false negatives.

In our recent studies (Suma *et al.*, unpublished), trained female Labrador Retrievers were able to identify 10 *P. canariensis* palms artificially infested with one RPW larva (<1 cm) in the plot with 90 similar but non-infested palms under open nursery conditions (Fig. 10.5). All of the palms were inspected three times at four time intervals starting from the infestation (after 2, 24, 48, and 120 h). The dog was able to detect the

Figure 10.3 Dog detection tests carried out under semi-field conditions: Left: one Rottweiler and two Golden Retrievers inspect *P. canariensis*. Right: German Shepherd "marks" detection of infested *P. dactylifera*.

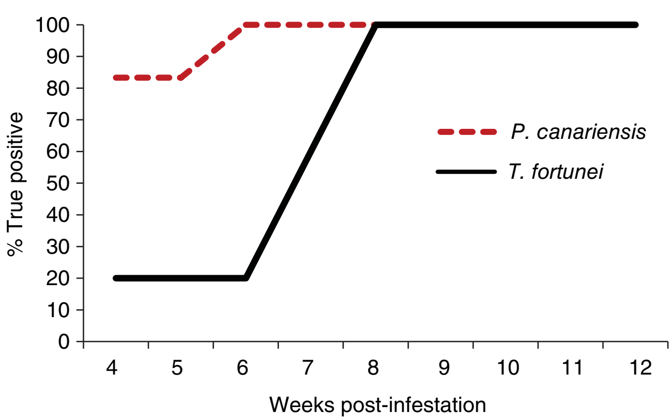


Figure 10.4 Dogs' ability to detect infested palms as a function of infestation development in *P. canariensis* and *T. fortunei*.

Figure 10.5 Inspection of nursery-grown palms by sniffer dogs. Detection of a *C. humilis* infested by PBM during field tests (right). Potted *P. canariensis* palm, artificially infested with one RPW larva (bottom).

RPW-infested palms with an average accuracy of 86% and 99% for the true-positive and true-negative responses, respectively (unpublished data from 2014) (Table 10.1).

The dog's ability to detect PBM infestation was tested in several experiments. Table 10.2 presents the results of two of them: one in a greenhouse with 12 potted *C. humilis* with different types of infestation, and another in a public garden (open area) with 20 *C. humilis* (10 infested by PBM and 10 non-infested). The dog showed good sensitivity and precision with both natural and artificially infested palms having only one PBM larva (Table 10.2).

Table 10.1 A female Labrador Retriever's ability to discriminate between palms infested with one young RPW larva and non-infested palms in an open nursery. True positive (TP); false negative (FN); false positive (FP).

Response categories	Time interval after infestation			
	2 h	**24 h**	**48 h**	**120 h**
TP	90%	77%	90%	87%
FN	10%	23%	10%	13%
FP	2%	1%	1%	0%
TN	98%	99%	99%	100%

Table 10.2 Labrador Retriever's detection of PBM-infested *C. humilis*.

Type of infestation[a)] (tot no. of palms)	Responses (%)[b)] Greenhouse		Open area	
AI ($n = 3$)	91.7 (TP)	8.3 (FP)	—	—
TI ($n = 3$)	83.3 (TP)	16.7 (FP)	—	—
NI ($n = 3$)	100 (TP)	0 (FP)	90 (TP)	10 (FP)
UP ($n = 3$)	100 (TN)	0 (FN)	86.7 (TN)	13.3 (FN)

a) AI: artificially infested with 1 PBM larva; TI: small stem of infested *C. humilis* hidden in the canopy of non-infested potted palms; NI: naturally infested with early symptoms of infestation; UP: non-infested palm.
b) TP: true positive, when the dog correctly responded in the presence of the pest; TN: true negative, when no response was correctly obtained with a non-infested palm; FP: false positive, when the dog responded to a non-infested palm; FN: false negative, when no response was obtained with an infested palm.

Regarding the influence of environmental conditions on the dogs' searching ability, no difference in working ability was recorded within a temperature range of 22–32 °C (recorded during the experimental period). However, windy days often negatively affected the accuracy of the responses.

10.3.3 Advantages and Pitfalls

Trained sniffer dogs have several advantages as detectors: they are highly sensitive and reliable and relatively easy and cheap to train and operate, and they can significantly reduce the amount of time spent searching for a target object. Dogs can detect all of the infestation stages independently of weevil activity. Dogs can be trained to detect many different smells, and therefore the same dog can be used to detect both RPW and PBM. Once well trained, the dogs remember the smell they were trained for throughout their lives.

Pitfalls in the implementation of dog detection include the requirement for professional training and variations in dogs' odor sensitivity, detection, and working ability. Training to detect infested palms is not as simple as the smell emitted from those palms is still undefined and probably varies with infestation stage. It is not yet clear if dogs are able to discriminate between actively infested palms and treated palms with past infestation. The dogs' working ability suffers from climatic constraints, which limit their implementation in large-scale operations and on windy and hot days (e.g. in date plantations with hundreds or even thousands of palms). Most of the information on dogs' detection abilities has been gathered in experiments with small palms. The effectiveness of sniffer dogs in detecting infestation in crowns of tall trees is still questionable.

10.4 Thermal Detection

10.4.1 Assumptions

Since direct visual detection of the infestation is quite difficult, alternative approaches have been suggested. A study by Bokhari and Abuzuhairah (1992) indicated the possibility of detecting physiological changes in RPW-infested palms. Several observations reported temperature elevation in the trunks of RPW-infested palms as detected by infrared cameras.

Pest feeding within the palm trunk causes intensive fermentation of plant tissue, which increases the local temperature inside the crown/trunk above ambient levels (24 °C to above 40 °C (4–26 °C above the ambient level) (Abe *et al.* 2010; Soroker *et al.*, personal observations). Although rather dramatic, the temperature rise at the center of the crown of heavily infested palms could only be thermally detected when viewed from above following removal of damaged fronds. The natural insulation of the palm tissue prevented detection in lateral view. Moreover, solar radiation interferes with the thermal imaging. Therefore, at this stage, direct trunk temperature cannot be considered a confirmed application for identification of damaged palms (ARO Palm Protect team, personal experience).

On the other hand, the tunneling insects damage the palm's vascular system and create local water-stress conditions. This change in "crop water status" can be sensed through inspection of the thermal portion of the spectrum of the emitted radiation (Tanner 1963; Gates 1964; Ehrler 1973). Recent technological advances in remote thermal imaging offer the potential to acquire spatial information on surface temperature, and thus facilitate the mapping of canopy temperature variability over large areas. Thermal imaging is a viable alternative to point measurements, since the temperature of the whole plot/orchard/garden can be acquired at one aerial imaging campaign, and a map of the plants' water-status distribution can be produced.

10.4.2 Main Detection Tools, General Features and Challenges

High-resolution thermal imaging systems have been used to evaluate the water status of various crops. We have recently shown that aerial thermal images are a promising tool to map water status of date palm trees on a commercial scale (Cohen *et al.* 2012). For this purpose, Cohen *et al.* (2012) developed a semi-automated procedure based on watershed segmentation analysis, which allowed detection of all palm trees in the thermal image (with insignificant overestimation), and the extraction of canopy temperatures of individual palm trees. Similarly, detection of canopy temperature based on aerial thermal images using semi-automated procedures can be used to identify potential infestation in palm trees in homogeneous plantations over a wide area.

In potted Canary palms, infestation with RPW larvae was reflected by both higher canopy temperature (extracted from thermal images) and lower stomatal conductance compared with healthy trees (Fig. 10.6). The water stress was detected as early as 25 days after infestation, 3 weeks before any visible symptoms appeared. Measurements can also be conducted in plantations using cranes, or specially designed poles (Fig. 10.7). The ability to detect PBM infestation by the same method has not yet been reported.

10.4.3 Advantages and Pitfalls

Initial research has shown that aerial thermal imaging can be used to detect RPW-infected trees in a wide area, making this methodology more cost-effective than others requiring assessment of each individual palm, such as dogs or acoustic tools. Nevertheless, mapping suspected infected palm trees within commercial plantations through thermal imaging is a complex task. When covering a large area, the water status of trees can be highly variable due to differences in irrigation, age, sun exposure, diseases, or genetic variability, and can cause inaccurate detection of infestation.

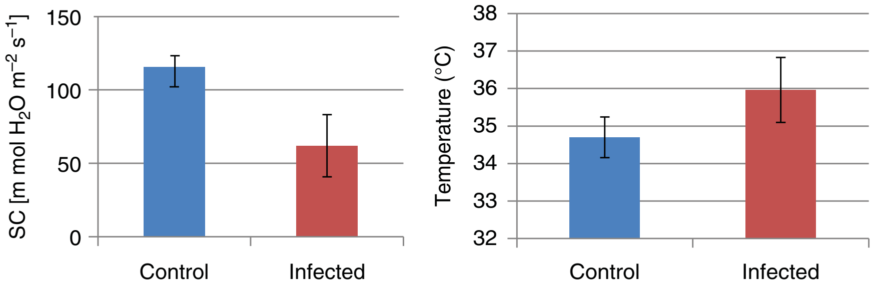


Figure 10.6 Stomatal conductance (SC; left) and canopy temperature (right) of infested and non-infested Canary palm seedlings. Bars represent confidence intervals of 95%.

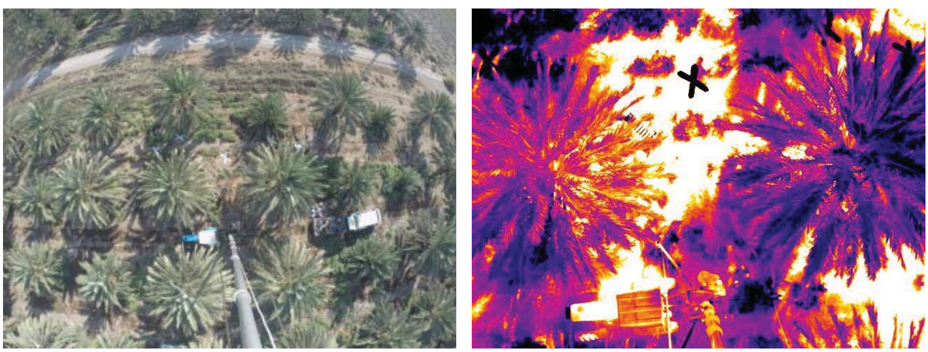


Figure 10.7 RGB (left) and thermal (right) images of date palm trees in a commercial plantation using a specially designed mast. In the thermal image, higher temperatures are observed (yellowish color) in part of the canopy of an infested tree (on the left) compared with lower temperatures (bluish colors) in the canopy of a healthy tree. The images were captured from cameras attached to a 20 m high pole. (*See color plate section for the color representation of this figure.*)

Additional data layers can resolve these ambiguities, when combined in a GIS system. In addition, the accuracy and reliability of the detection is threshold-dependent and more research is needed to develop an adaptive algorithm.

10.5 Detection of Pest Distribution by Monitoring Traps

10.5.1 Assumptions and Methodology

Semiochemical-based monitoring traps have several main purposes: the detection of pest introductions, evaluation of population densities, and determination of pest dynamics and pest distribution in a territory. Often, decisions to implement area-wide management of RPW are also based on weevil captures in surveillance traps (Faleiro 2006). In general, detection of pest introductions requires highly attractive traps, mainly based on optimized lure composition and emission. These factors are not so crucial for studies of pest dynamics, intended mainly to determine flight periods, for example once the pest is commonly detected. Optimization of this monitoring system includes bait composition and life span, trap structure, and spatial distribution.

The most essential characteristic for the detection of pest presence and outbreaks is the sensitivity of the monitoring system. The attractant must be highly specific and effective and should be optimized to reach maximum sensitivity. Although chemically mediated attraction to host plants has been suggested, no attractants are available for PBM (see Chapters 6 and 7, this volume), making semiochemical-based monitoring of this pest impossible at this stage. In the case of palm weevils, semiochemical-based detection relies on the use of the species-specific aggregation pheromone. Male-produced aggregation pheromones have been documented for several Rhynchophorinae weevils, including *R. ferrugineus* (Chapter 5, this volume). Hallett *et al.* (1993) reported the presence of two male-specific compounds—4-methyl-5-nonanol (ferrugineol) and 4-methyl-5-nonanone (ferrugineone)—in a 10:1 proportion, respectively, in the RPW aggregation pheromone. The mixture is only produced by males but attracts both sexes, which is a great advantage for trapping-based management strategies. It is known to have a long-range attraction effect, covering several kilometers (unpublished results). On the other hand, the RPW is capable of rather distant flights (Abbas *et al.* 2006; Avalos Masó *et al.* 2014; and see Chapter 5, this volume) and its distribution is often clumped (Faleiro, Kumar, and Rangnekar 2002) (see Chapter 5, this volume). Pheromone emission level is crucial for a sensitive detection system and must be optimized for the highest trapping efficacy. It has been widely reported that the pheromone release rate must be controlled because insect response to the attractant can decrease at emission values that are below or above the optimum. Although ferrugineol emission can vary over a wide range without affecting RPW response, captures tend to be fewer with emission rates of 1 mg/day relative to emission rates of over 5 mg/day (Rochat and Avand-Faghih 2000). Higher release rates, of up to 50 mg/day, did not have a negative effect (Vacas *et al.*, 2016).

Weevil-trapping systems also include natural kairomones (host plant material and/or molasses) to boost trap attractiveness. The composition of the host bait is a considerable drawback to providing standardized detection protocols as trap catches are directly related to the quality of this bait. As part of integrated pest management (IPM) strategies, reported host baits included in traps for RPW were parts of date palm stems, coconut pieces, dates + sugar-cane molasses + ethyl acetate, dates + yeast + date extract (Abraham *et al.* 1998; Hallett, Oehlschlager, and Borden 1999; Soroker *et al.* 2005; Abbas *et al.* 2006), with quantities ranging from 200 g to 1 kg of food bait (Faleiro 2006). The optimal plant material (dates and palm stem pieces) is often expensive or inaccessible, and therefore implementation of this practice over wide areas is unmanageable. It has also been reported that the attractiveness of natural lures changes with time as maximal catches are obtained several days after renewing the plant material in the trap and decrease considerably after 3 or 4 weeks (Hallett *et al.* 1999; Faleiro 2006). Thus, the best solution for this matter is to replace the natural kairomones with a synthetic mixture, for example synthetic palm esters of similar or higher attractant activity (Guarino *et al.* 2011).

10.5.2 Optimal Traps

The proportion of weevils captured relative to the total number of weevils attracted to the trap's vicinity is another important factor. Trap design plays an important role in this proportion; inside certain trap types, only 50% (or even less) of the attracted weevils are effectively captured (Rubio, Hidalgo, and Ortiz 2011).

Prior to reported trap developments, traps made of palm stems or leaf petioles were used to capture palm weevils (*Rhynchophorus* spp.) (Morin *et al.* 1986; Abraham *et al.* 1998; Hallett *et al.* 1999). For example, Morin *et al.* (1986) reported the construction of traps consisting of small heaps of cubed oil palm stems. Although, the heaps needed to be renewed every week, the efficacy of these traps was superior to metal ones (Abraham *et al.* 1998), probably due to the higher attractant power of the lures coming from the heaps or cubes compared to the food bait provided in the metal traps. Oehlschlager *et al.* (1993) evaluated the effectiveness of four trap designs for trapping *Rhynchophorus palmarum* adults: (1) the McPhail trap, (2) a 45 cm × 20 cm (length × diameter) PVC pipe, (3) a multiple funnel (16 nested plastic funnels with a receiver at the bottom), and (4) a 19 L white plastic bucket, with four 3 cm × 8 cm entry holes in the walls just below the lid, which also has four openings. The bucket trap was significantly more effective than the other designs. In different experiments, these plastic buckets were also compared with traps made of palm material: (5) a stem sandwich (palm stem sections covered with palm fronds), (6) single stems (50 cm long stem sections with 1 cm wide right-angle cuts), and (7) a pit trap covered with palm fronds. They found that bucket traps were as attractive as the stem traps if the stem surfaces and food baits were renewed weekly, whereas pit traps were very inefficient.

Until recently, bucket-type traps were the most widespread model employed to trap RPWs, as they are inexpensive and easy to handle. Nevertheless, several studies revealed that their efficacy can still be improved. Following concern raised by Oehlschlager *et al.* (1993) that 20% of the trapped *R. palmarum* adults were able to escape from the bucket traps after 24 h, RPW-capture efficacy of the standard insecticide-baited white bucket traps was compared to that of two insecticide-free trap designs based on modified buckets (Hallett *et al*. 1999): a funnel trap, with a funnel inserted below side entry slots, and a vane trap with funnel—two metal vanes at right angles and a funnel fitted below them. All three types of traps were equally effective, indicating that RPWs can be captured effectively in an insecticide-free trap with an easy modification—the fitting of a funnel inside the standard bucket. To facilitate weevil entry into the trap, the smooth bucket walls can be easily roughened by various means, including covering them with mesh or other material as described in Abuagla and Al-Deeb (2012). Gentle slopes also appear to play an important role due to RPW crawling behavior (Hallett *et al.* 1999).

Another factor studied to improve trapping efficacy was trap color. Reddish-brown buckets were found to achieve significantly more RPW captures than white traps or traps camouflaged with palm fiber (Sansano *et al*. 2008), but there was no discrimination between partially buried white and yellow buckets that were 2 m apart (Tapia *et al.* 2010). The importance of using dark colors has also been recently reported in relation to bucket traps by several authors. Partially buried red buckets captured significantly more RPWs than blue, green, orange, pink, yellow, or white traps in a trial reported by Al-Saoud, Al-Deeb, and Murchie (2010); the red traps caught approximately 1.8 times as many weevils as the white traps. Similarly, Abuagla and Al-Deeb (2012) found that red traps capture significantly more weevils than white or yellow traps, but the maximum number of RPWs was obtained in black traps, differing significantly from the rest. These data fit well with our recent information on color vision of the RPW (see Chapter 5, this volume).

Taking into consideration previously discussed requirements of shape, color, and texture, a new trap design (Picusan®, Sansan Prodesing SL, Valencia, Spain) was developed by Universitat Politècnica de València (Fig. 10.8). It consists of a cylindrical base (25 cm in diameter, 6 cm in height) to house the captures, a rough (1 mm between grooves) black pyramid with a 66% slope to facilitate weevil climbing, a funnel inserted into the upper side to prevent escapes, and a green cover on the top, leaving a 4 cm aperture between the upper side of the pyramid and the top where the weevils can enter the trap

Figure 10.8 The Picusan® trap.

(Vacas, Primo, and Navarro-Llopis 2013). The black pyramidal Picusan traps offer better trapping efficacy than non-buried bucket traps, white or black, achieving 45% more weevil catches than regular buckets. The efficacy of the newly developed Picusan trap was also evaluated relative to locally implemented traps of different designs by other Palm Protect project participants (ARC, ARO, BPI, UNIPA) (Table 10.3). The obtained data clearly indicated that the new Picusan trap is generally superior to traditional black and white bucket traps.

10.5.3 Optimal Lures

As already noted, aside from trap design, improvement of attractants is essential for successful trapping systems. Traps for weevils used to be baited with the specific aggregation pheromone, a food bait and/or fermentation volatiles. The RPW's response to its aggregation pheromone has been previously reported (Hallett *et al.* 1993, 1999; Rochat and Avand-Faghih 2000) and confirmed in the experiments conducted within the Palm Protect project. Accordingly, ferrugineol emission can vary over a wide range without affecting RPW-trapping efficacy, and release rates higher than ~4 mg/day do not produce significantly higher captures (Vacas *et al.*, 2016). Thus, any commercial dispenser optimized to emit ferrugineol at mean release rates close to this threshold will be suitable for RPW-trapping systems. However, traps baited with only aggregation pheromones are only moderately attractive. The combined use of pheromone and host volatiles increases attractiveness to palm weevils synergistically, thereby increasing trapping efficiency. It is also important to highlight that the addition of water to these traps was proved to be essential with catches increasing more than threefold compared with dry traps (Soroker *et al.* 2015; Vacas *et al.* 2013).

Fermentation volatiles are only poorly attractive by themselves, but they can enhance trap efficacy by increasing the attractant radius, improving the short-range orientation toward the traps, arresting weevils near traps, and, finally, increasing the number of captured weevils. The fermentation volatiles of different palm tissues, palm oils, coconut,

Table 10.3 Trap comparisons carried out within Palm Protect project[a].

Partner	Trap designs/colours evaluated	No. of sets
UPV (Spain)		5
BPI (Greece)		4
ARC (Egypt)		5
ARO (Israel)		7
UNIPA (Italy)		7

a) Efficacy of Picusan® trap was compared with: Polytechnical University of Valencia (UPV) white and black buckets; Benaki Phytopathological Institute (BPI) pitfall and funnel; Agriculture Research Center (ARC) black bucket with a funnel inserted on the top, regular black bucket and inverted black bucket with two rectangular windows 2.5 × 15 cm; Agricultural Research Organization (ARO) white bucket; University of Palermo (UNIPA) red bucket.

and pineapple are attractive to *Rhynchophorus* weevils (Giblin-Davis *et al.* 1996). These include a series of esters, such as ethyl acetate. Jaffé *et al.* (1993) reported that the addition of ethyl acetate to traps baited with pheromone and sugar cane increases *R. palmarum* catches. Moreover, Rochat *et al.* (2000) reported that ethanol and ethyl acetate blends have a moderately synergistic effect with the pheromone of *R. palmarum*. However, results published by Oehlschlager (Oehlschlager and González 2001; Oehlschlager 2006) did not confirm this effect as they found no significant differences between traps baited with only pheromone or with pheromone + ethyl acetate. Regarding RPWs, El-Sebay (2003) reported that traps baited with pheromone and ethyl acetate captured more adults than those baited with pheromone plus food bait. However, the role of ethyl acetate in RPW-trapping protocols is controversial. Electrophysiological studies of host volatiles have revealed that RPW antennae are responsive to many compounds, including the so-called palm esters (Guarino *et al*. 2011; Vacas *et al.* 2014; Chapter 3, this volume); however, improved captures can only be proven by field assessment. Guarino *et al*. (2011) concluded that a blend of the esters ethyl acetate and ethyl propionate improves catches in traps baited with pheromone and molasses better than individual esters. The trials included in Vacas, Primo, and Navarro-Llopis (2013) suggested that ethyl acetate alone does not significantly increase the efficacy of the traps baited with only pheromone. However, the combination of molasses with ethyl acetate is able to synergize the attractant effect of the pheromone (Vacas *et al*. 2016).

Vacas *et al.* (2014 and 2016) found that the addition of 1:3 ethyl acetate/ethanol blend increases RPW catches twofold compared to aggregation pheromone alone, achieving as much as 76% efficacy when compared to the total weevil catches obtained with a natural kairomone composed of *P. canariensis* palm stem and sugar molasses. These results, obtained within the Palm Protect project, suggest that a simple synthetic mixture of fermentation volatiles, released at 100–300 mg/day, can boost pheromone attractiveness, similar to the kairomone blend employed in the trials, avoiding the frequent replacement and manual labor required to service the traps.

10.5.4 Trap Position and Distribution for Monitoring RPW Dispersion

Although the monitoring of RPWs by trapping is rather efficient and some recommendations can be found in the literature (Faleiro 2006), much remains to be considered with respect to optimal trap distribution. Being a rather expensive operation in terms of the involved labor cost, decisions on trap distribution are mostly based on economics and not on the pest's spatiotemporal behavior. For example, in Israel, routine monitoring in some infested urban areas and high-risk agricultural areas is operated by the Israeli PPIS (Plant Protection and Inspection Services) at a variable density from about 1 trap/ha to 1 trap/50 ha. A different approach was adopted in Greece, where traps were operated only for a limited time and period of the year (Aggelakopoulos *et al.* 2012). Based on a study conducted in Saudi Arabia, Faleiro, El-Saad, and Al-Abbad (2011) suggested that in plantations with low weevil activity (<1% infested palms) a density of 1 trap/ha is sufficient for mass trapping of adult *R. ferrugineus*, whereas in plantations with infestation levels > 1% a density of 10 traps/ha provided the best weevil captures. However, in area-wide mass-trapping programs, the pest could be effectively trapped at 4–7 traps/ha depending on available resources. The potential area effectively covered by each trap is hard to define. Geostatistical tools have been implemented to try to cope with this challenge, mainly for monitoring purposes. Within the Palm Protect project, distribution and abundance of the RPW catches were mapped using ArcGIS software (ESRI, Ltd.) in an urban environment and in date palm plantations. The major conclusions were that, ideally, within a bulk of date palm plantations, traps should be distributed at a density of at least 1 trap per 0.35 ha (60 × 60 m), in urban environments, traps should be distributed at a density of 1 trap per 0.5 ha or spaced no less than 75 m apart mainly because of the high spatial autocorrelation nature of the distribution of RPW.

10.5.5 Advantages and Pitfalls

Given that both male and female weevils are attracted to the pheromone baited trap, the monitoring of RPW adults is a basic tool to detect the presence of the pest, so as to act with preventive chemical treatments as soon as adults are detected. The main advantage of RPW detection with semiochemical-baited traps is that it is based on a specific and powerful attractant. It allows detecting a single adult located several kilometers away and, therefore, is the best method to detect the introduction of RPWs into new areas. It is especially useful for large and partly inaccessible areas.

The main disadvantage of trap monitoring for RPWs is that it requires a continuous labor investment, while it is impossible to deduce the number and position of the infested palms in the area. Moreover, given that aggregation pheromone attracts only adults, other developmental stages are simply not detected.

10.6 Conclusion

10.6.1 Perspectives for Accurate Early Detection of RPW and PBM

In the last few years, intensive efforts have been made toward development of various detection techniques, especially for the detection of RPWs, and to a lesser extent PBMs, mainly in their major host plants *P. canariensis* and *C. humilis*, respectively. All of these approaches have yielded very promising results, particularly for trade and quarantine facilities where each and every palm can be inspected. It has been proven possible to detect RPW infestation in quarantine facilities and nurseries with reasonable accuracy (above 75%) before any symptoms become visible, using acoustic and thermal technologies, as well as sniffer dogs. Acoustic activity of both RPW and PBM can be detected by sensitive microphones and human experts, and trained dogs can detect palms infested by either of these pests and can discriminate between them and other insects. The pros and cons of the various detection methods presented above are summarized by different parameters in Table 10.4. Algorithms have been developed for automated acoustic detection of RPWs, but these require further development to reach the accuracy of human experts. Although no single method provides 100% detection of RPWs, a combination of detection tools can provide reasonable solutions. For example, palms containing acoustically undetectable stages (eggs or pupae) can be detected by sniffer

Table 10.4 Pros and cons of the three main detection methods.

Parameter	Acoustic	Sniffer dogs	Thermal remote sensing
Individual examination	Required	Required	Not necessary
Special equipment	Yes	Not necessary (dogs)	Yes
Labor	Low if automated	Medium[a)]	Low if automated
Trained labor	No	Yes	Yes
Sensitivity	80–95% under controlled environment	64–75%[b)] Depends on breed and training	Still unknown
Cost	Affordable	Affordable	Affordable if aerial images are used
Suitability	Controlled environment/ quarantine	Mostly for local detection	Open areas

a) Main effort is related to the training process.
b) Both accuracy and sensitivity are expected to be improved once appropriate training protocol is implemented.

dogs, or by thermal sensing if the palm's vascular system has been sufficiently damaged. In the case of PBM, the possibility of thermal detection has not yet been reported but nevertheless cannot be refuted.

Inspection of palms in open spaces and gardens, and particularly in larger areas such as urban, agricultural, or natural habitats, for risk assessment remains a challenge. The task is especially difficult in non-agricultural regions, where a large number of trees, often several thousands in an inspected region, of various species, ages, and growth conditions need to be routinely monitored for pest infestation and treatment success. Access to the palm stem is often limited and reaching the crown is difficult and expensive. In these cases, for acoustic monitoring one can either use a laser vibrometer or apply a fixed sensor as part of the monitoring strategy. Dogs can also be used under these conditions, while thermal-sensing may also be suitable but only in plantations with palms of similar type and age, cultivated under standard conditions or with the aid of a geographical information system (GIS) that contains complementary information. Even if the early symptoms of the infestation are impossible to detect, the risk of RPW infestation can be determined by using traps. Yet, implementations of this technique still need to be developed for PBMs. Based on the knowledge accumulated on chemosensing and vision characteristics of PBM (see Chapter 7, this volume), the design of traps combining specific chemical and visual cues is feasible.

Regardless of the selected detection means, acquired data on RPW dispersal and infestations in these areas requires rapid positioning and visual management. Such a system might be based on Internet and web applications, and a graphical user interface (GUI) to produce and display spatial and temporal information to support application decisions. Electronic field-data acquisition has been recently widely adopted (Montoya 2003). Moreover, mobile GIS enables the development of location-aware monitoring and facilitates the collection of real-time agro-environmental data and in particular distribution patterns of an insect pest population (Sciarretta, Trematerra, and Baumgartner 2001; Papadopoulos, Katsoyannos, and Nestel 2003; Hetzroni *et al.* 2009). Systematic accumulation of information concerning pest distribution and host (palm) distribution and condition, along with treatment history, is the basis of the decision-making process.

A palm location database is extremely important in non-agricultural areas for monitoring, treatment, and risk assessment. About 20 palm species are considered hosts of the RPW (see Chapter 4, this volume). Palm evaluation is rather simple in mono-cultural plantations, but not in other sectors. In Mediterranean areas, palms of various species are extremely common in landscaping, making individual evaluation of all potential hosts impossible. The most commonly affected species are *P. canariensis* and *P. dactylifera*, followed by *Washingtonia*. In particular, *P. canariensis* can be used as an infestation indicator. A combined location-aware system (CPLAS) and decision-support system was recently developed for RPW infestation (detailed in Chapter 11, this volume). This system utilizes web services and incorporates various layers of spatial data (including monitoring and visual palm assessment) to generate spatial risk maps for monitoring, risk assessment of the RPW dispersal/infestations, and decision support for control of the pest. The system has already been evaluated under real-time conditions in Canary palms (Pontikakos, Kontodimas, and Tsiligiridis 2015). However, to be implemented in areas with different and mixed palm species, this system will require adjustments and modifications. Moreover, the information gathered by various detection modalities should in future be combined with other GIS information by dedicated programs to be used for risk assessment in decision support systems.

10.6.2 Future Challenges

Even if it is possible to discriminate between RPW- or PBM-infested and healthy palms by a number of parameters—such as acoustic, chemical, and thermal—considerable effort is still required to improve the efficacy and sensitivity of these methods to make them field-operational and affordable. Whether RPWs and PBMs can be discriminated acoustically remains to be further studied. In both cases, major future challenges lie in the automation of the detection process, and further development and perfection of specific sensors (acoustic and chemical). The system and equipment should be suitable for the different settings. Although palms in plantations, nurseries, or quarantine units are accessible and gathered within defined areas, they differ in size, species, and water content. A systems approach might employ scouts (human or robot) to examine each tree. Similarly, an autonomous bioacoustic and/or chemical sensor can be installed in every palm tree under study to capture and analyze the data over long periods. The results could be reported wirelessly to a control station via a communication network, to be subsequently processed and conveniently stored (Rach *et al.*, 2013). The challenge is to promote the implementation of such detection tools by decision-makers. This requires more than sensitivity; they need to be reliable, easily accessible, and cost-effective in terms of time and labor. Cloud technology combined with automated data-gathering from numerous sensors, data processing, and timely risk status reports to the end user for each monitored palm could serve this function.

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11

CPLAS Information System as a Monitoring Tool for Integrated Management of Palm Pests

Costas Pontikakos[1], Filitsa Karamaouna[2], Amots Hetzroni[3], Dimitris Kontodimas[2], Victoria Soroker[3], Frosa Samiou[4], Yuval Cohen[3], Stella Giorgoudelli[2], Ourania Melita[2], Stavros Papageorgiou[5], Paul Benjamin[6] and Eitan Goldshtein[3]

[1] *Department of Agricultural Economy and Development, Informatics Laboratory, Agricultural University*
[2] *Benaki Phytopathological Institute, Athens, Greece*
[3] *Institute of Agricultural Engineering, Agricultural Research Organization, The Volcani Center, Rishon LeZion, Israel*
[4] *Directorate of Parks and Landscaping, Region of Attica, Athens, Greece*
[5] *Bytelogic, Athens, Greece*
[6] *Bahá'í Gardens, Bahá'í World Center, Haifa, Israel*

11.1 Introduction

The red palm weevil (RPW), *Rhynchophorus ferrugineus*, is one of the most dangerous palm pests: its cryptic behavior makes its detection and control extremely difficult (see Chapters 4 and 10, this volume). Inspection of plant material for quarantine pests on a large scale (i.e. urban, agricultural, or natural habitat areas) and decision-making for control management are extremely challenging, as a large number of trees, often several thousands of potential hosts, need to be routinely evaluated for possible pest infestation, management decisions have to be made, and the situation has to be routinely monitored and assessed for treatment success. This complicated task requires a location-aware system (LAS) that integrates many services and needs to be fed by several data types—pest and palm condition and position (Cohen *et al.* 2008; Li *et al.* 2010; Pontikakos Tsiligiridis, and Drougka 2010, Pontikakos *et al.* 2012). This chapter describes the upgraded version of the LAS by Bytelogic termed CPLAS (upgrade produced by the Benaki Phytopathological Institute during the FP7 Project Palm Protect) as a tool for monitoring and risk assessment of the dispersal of RPW and infestations of palm trees (Pontikakos, Kontodimas, and Tsiligiridis 2015). The CPLAS enables monitoring in large areas and diverse environments (i.e. urban, agricultural, and natural), as well as in complex scenarios such as a large number of palm trees or species, monitoring traps, and management options.

The CPLAS relies on a redesigned database architecture and qualifies for use with many of the available background geographic information system (GIS) information layers, a spatial multimedia decision support system (DSS) for infestation risk assessment of palms by RPW in real time and selection of the most appropriate control strategy, a web-mapping site with the spatial data, cost-efficient hardware (handheld devices) and

Handbook of Major Palm Pests: Biology and Management, First Edition.
Edited by Victoria Soroker and Stefano Colazza.

software (operator system, user interface, etc.) for *in situ* data acquisition. The DSS of the CPLAS reports the infestation risk of individual palm trees of three palm species, the Canary palm *Phoenix canariensis*, the date palm *Phoenix dactylifera*, and the Cretan palm *Phoenix theophrasti*, based mainly on symptoms of visual observation, with recommendations for their management. The CPLAS and DSS were implemented and evaluated under real-time conditions in five areas: three urban parks having numerous palm trees (the Central Park "Pedion Areos" and the "National Garden" in Athens, Greece, the "Bahá'í Gardens " in Haifa, Israel), two date palm tree orchards (Maale Gamla and Ramot plantations on the shore of Lake of Galilee, Israel), and the Preveli palm tree forest (*P. theophrasti*), prefecture of Rethymno, Crete.

11.2 CPLAS Architecture and Functions

11.2.1 CPLAS Architecture

The CPLAS has a client-server architecture that uses web services and integrates mobile GIS, DSS, and multimedia content to develop and implement location-aware services for efficient monitoring of RPW infestations (Pontikakos *et al.* 2015). The server is used to synchronize data with mobile GIS, desktop GIS, and web mapping; it provides the necessary functionality for storage, analysis, and distribution of the data. The client side of CPLAS comprises the mobile GIS, web mapping, and desktop. The mobile GIS enables acquiring data from the field.

Mobile and desktop GIS experts are responsible for collecting, managing, and analyzing the data. Mobile GIS users are trained to operate the CPLAS software via handheld devices such as personal digital assistants and to collect field data on the infestation risk of palms according to the classification system of the CPLAS. The desktop GIS experts can process and convert the field data by creating the necessary geo-databases and information layers for the infested area, analyze the GIS data, and make decisions on the management practices for the RPW in collaboration with entomologists.

The CPLAS mobile GIS architecture supports plugins and extensions that enable customization, adding new functionalities and system enhancement (e.g. the GPS can find the user's position and locate palms and traps). The GIS module implements processes such as mapping and creating or editing new spatial objects.

11.2.2 CPLAS Database

The database contains the spatiotemporal data, the attribute information, and the system parameters. The database engine is Microsoft SQL Server Compact (SQL CE) 3.5 used in combination with a compact relational database for applications that run on mobile devices and desktops. Data for collection include characteristics of palms, actions, findings, remarks, photos, the infestation risk, and reports, such as of symptoms on palms (see Chapter 9, this volume). Palm characteristics include information such as species, location, and height. The actions refer to data on management practices, such as dendro surgery (sanitation), sprayings, and information on the removal of dead/heavily infested palms. The findings concern records of the RPW individuals (adults, pupae, larvae, cocoons) found in the infested palms or in traps located in the infested area. The system has the capability to store multimedia content, such as digital photographs of palms, and to export data on selected palms. GIS data, infestation risk

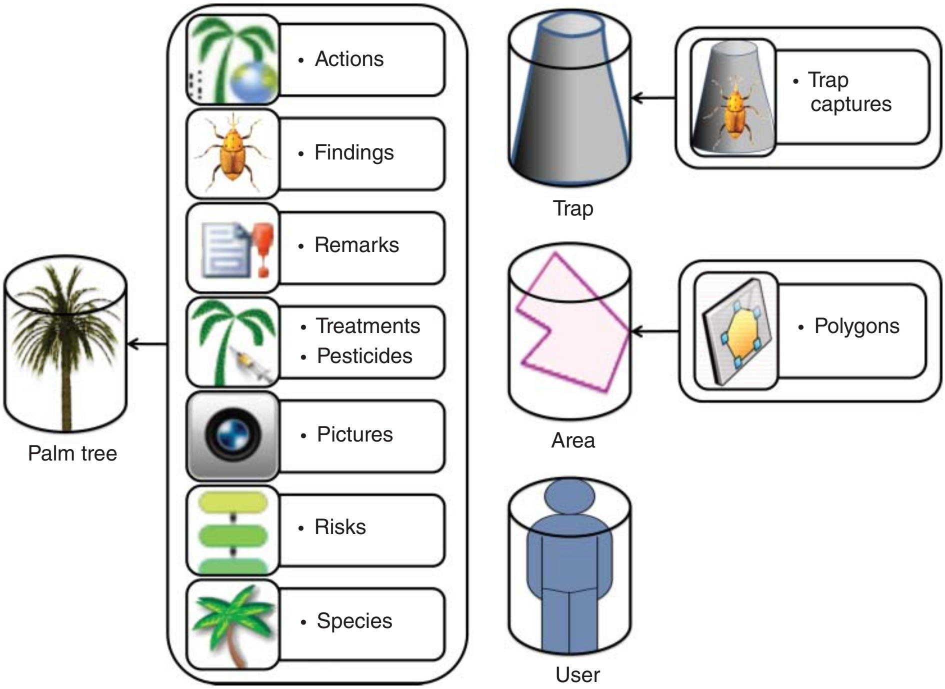


Figure 11.1 General architecture of CPLAS database.

classification, and species data need to be managed by GIS experts, while data on palm characteristics, treatments, findings, and infestation risk can be collected by non-expert personnel in the field. The database architecture is shown schematically in Fig. 11.1.

Based on the proposed database architecture, the CPLAS supports the following GIS information layers: points indicating the position of the palms, demarcated areas with the palms, background maps of the monitored area, photo layers, and infestation risk maps indicating low to high infestation risk of palm trees by the RPW with a gradation of colors from cold to warm, respectively.

11.2.3 DSS for Infestation Risk Assessment and Spatiotemporal Risk Analysis

Comprehensive mapping of the infestation risk caused by a pest is an essential aspect of rapid risk assessment. Infestation risk maps can be created using interpolation methods. To examine many spatial phenomena, variables at unknown locations must be estimated from measured values at limited sample locations. Among the many interpolation methods, inverse distance weighting (IDW) interpolation is one of the most commonly used deterministic ones. Spatiotemporal analysis of the infestation risk to palm trees by RPW in the implementation areas can be performed using the IDW interpolation method—the Shepard method (Shepard 1968), with power = 2, distance = 100 m. The DSS enables the identification of those palm trees with the highest risk and consequently the areas that should be considered for treatment. Such maps display hot spots in the infested area, taking into account the infestation risk level and the density of the infested palms. The recommendations of the DSS correspond to the infestation risk to the individual palms (i.e. the first management priority is to safely remove the palms that have died but are still actively infested). These palms are dangerous in terms of pest dispersal and public safety due to potential stability problems. The next priority of the DSS recommendations is to schedule the next inspections of the infested palms. For the infestation risk assessment for Canary palms in urban areas, the DSS described by Pontikakos *et al.* (2015) is used. In Fig. 11.2 the graphical user interface (GUI) and multimedia content of the DSS of the CPLAS are presented. The design of the DSS used for the infestation risk assessment of the date palm, *P. dactylifera*, and the Cretan palm, *P. theophrasti*, is shown in Table 11.1.

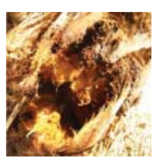
Figure 11.2 GUI and multimedia content of the decision support system of the CPLAS.

Table 11.1 CPLAS decision support system for infestation risk assessment for *P. dactylifera* and *P. theophrasti*.

Risk	Question/ symptom description	Picture	Actions to be taken
0	No inspection conducted		
1	No symptoms in non-infested area		If the country is infested then regular inspections are required twice a year
2	No symptoms in infested area (infestation recorded within 1 km range)		Regular inspections, once a month
3	Outer leaves are dry and curved		Removal of dry fronds Careful inspection of the stem for any fruss or oozing Careful inspection of offshoots Regular inspections, once a month
4	Crown curved		Careful inspection of the stem and offshoots Dendro surgery or phytosanitary removal of the palm Regular inspections, once a month
5	Leaves of some offshoots are wilted Dry offshoot(s)		Offshoot removal and dissection Careful inspection of mother plant under the offshoot Regular inspections, once a month
6	Mother stem is infested, cavity is no more than a few centimeters into the soft tissue or dry sawdust-like material from offshoot or the main stem		Dissection, thorough inspection for cocoon presence and cleaning of the infested tissue Treatment with insecticide and fungicide in the cavity Regular inspections, every 15 days

(Continued)

Table 11.1 (Continued)

Risk	Question/ symptom description	Picture	Actions to be taken
7	Wet oozing and pungent or dry oozing from: the stem, the disconnected offshoots next to the aerial roots	 Wet oozing Dry oozing	Dissection, thorough inspection for cocoon presence, and cleaning of the infested tissue Treatment Regular inspections, every 2 weeks
8	Holes emitting secretions in the stem of palm trees without offshoots		Dissection, cleaning of the infested tissue Treatment Regular inspections, every 2 weeks
9	Spoor leaves are dead		Dendro surgery If the "heart" is intact: treatment and regular inspections, every 2 weeks If the "heart" is dead: safe phytosanitary removal of the palm and regular inspections of the neighboring trees once a month
10	Mother stem is infested Cavity large and deep, about 1/3 of trunk diameter		Safe phytosanitary removal of the palm Regular inspections in the neighboring trees once a month

The decision process is performed in a question/answer manner, following specific steps through a multimedia wizard. The GUI and the multimedia content supporting the decision process (DSS) of the CPLAS for the Canary palm are shown in Fig. 11.3 and Fig. 11.4, and for the date and Cretan palms are shown in Fig. 11.5 and Fig 11.6.

11.2.4 Data-acquisition Process

Data are acquired using graphical forms and the mobile GIS of CPLAS via the GUI. To make the data-acquisition process easy, fast, and reliable, predefined and "smart" text is used. In general, this text can be edited and enhanced by the user as needed. In many cases, this text is fitted to the user's actions so as to limit the text choices to those

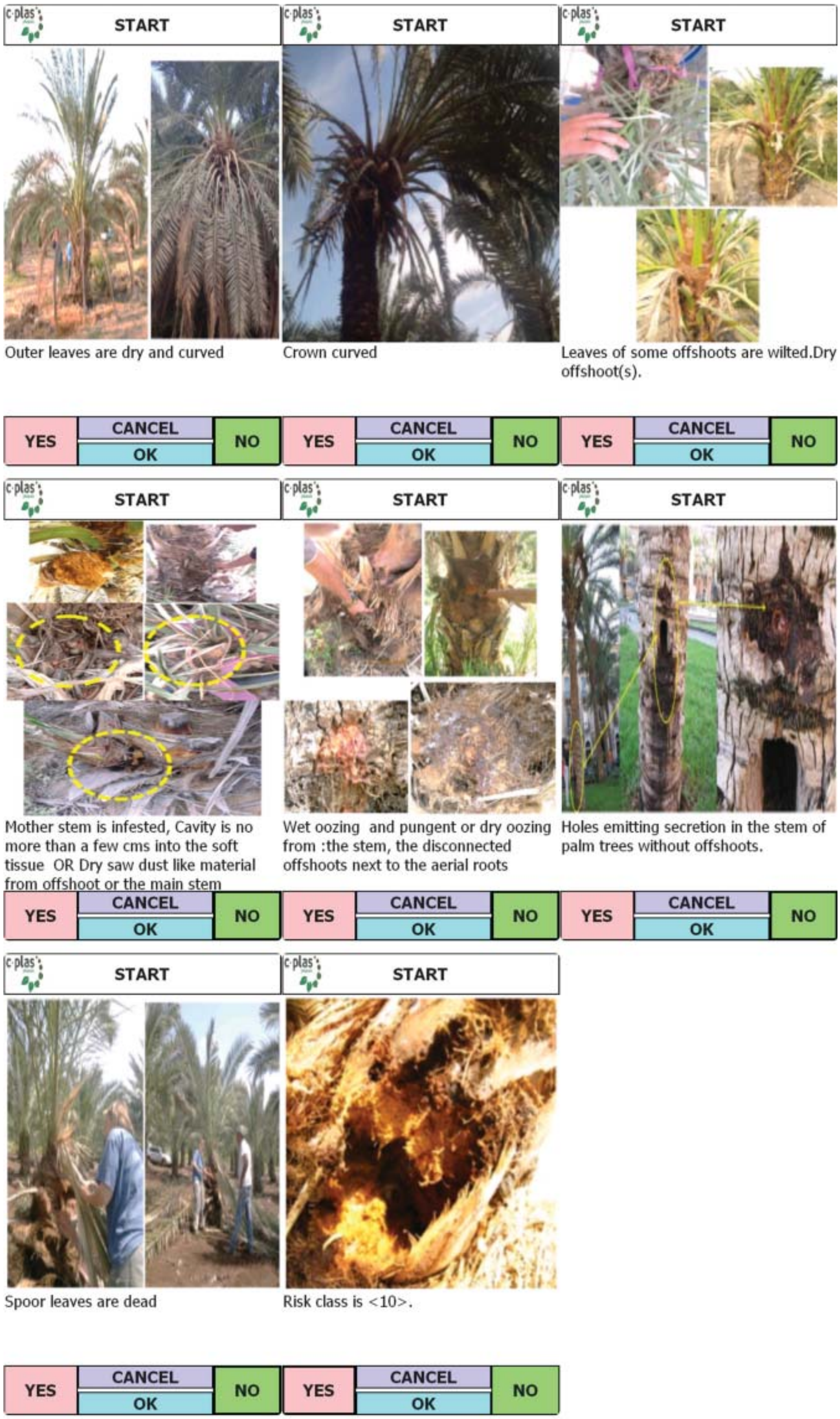


Figure 11.3 CPLAS GUI and multimedia content of the decision support system for infestation in the crowns of Canary palms.

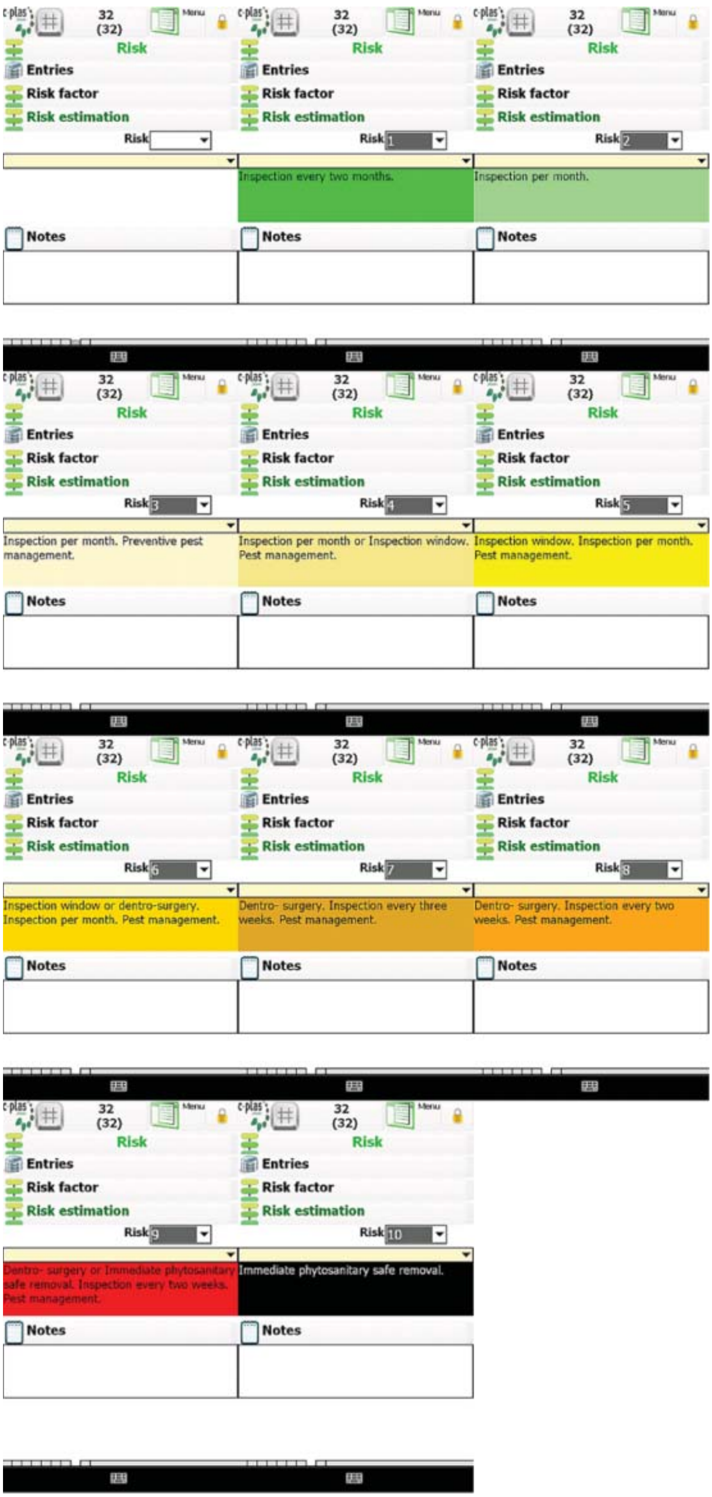


Figure 11.4 Decision process of the CPLAS decision support system.

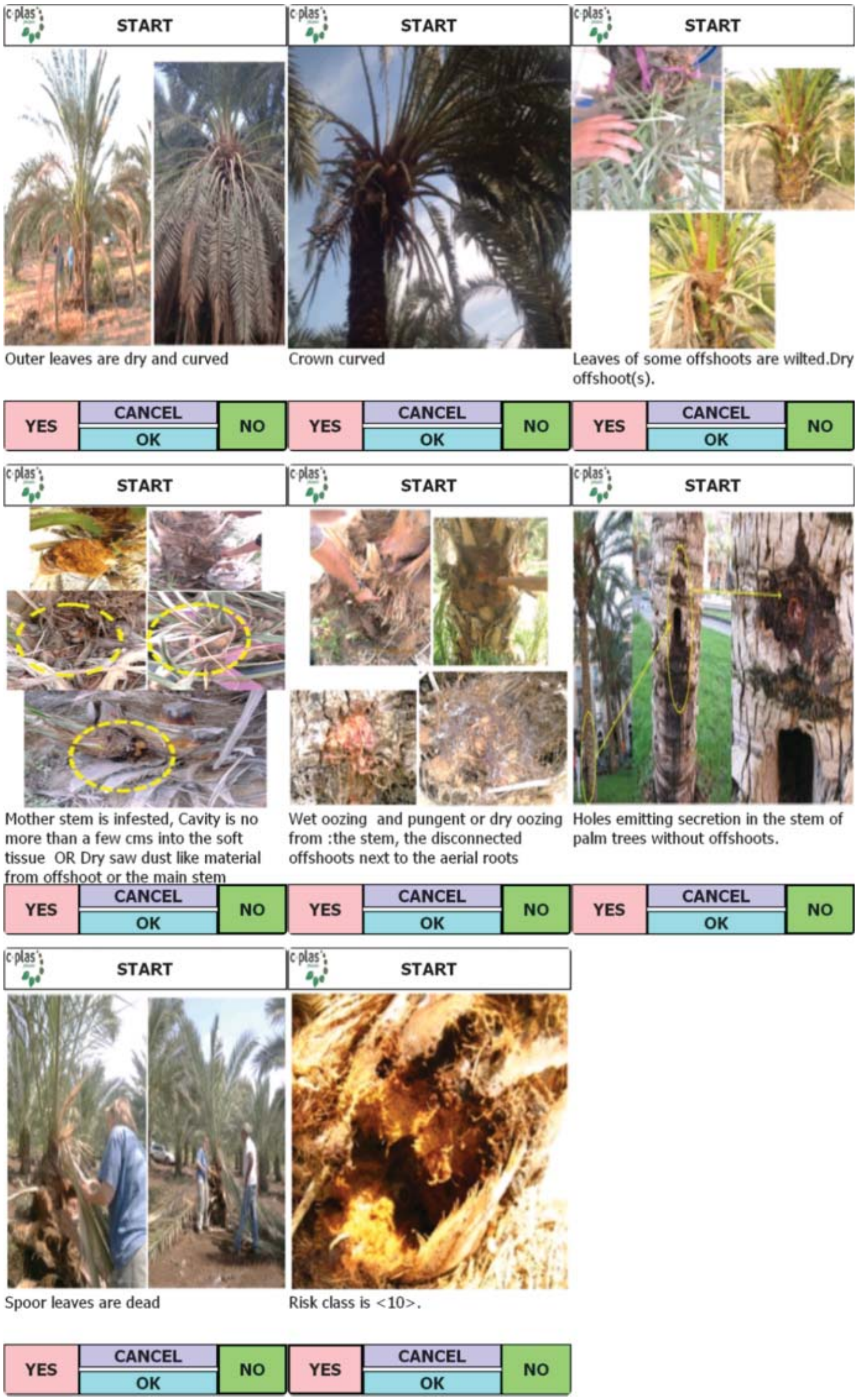


Figure 11.5 CPLAS GUI and multimedia content of the decision support system for date palms.

Figure 11.6 CPLAS GUI and multimedia content of the recommendations of the decision support system for date palms.

that are suitable or logical. For example, if the user finds out that a palm has minor infestation symptoms, then the system enables the user to select only those text notes that are relevant to those symptoms. Other text can be related with the palm or the user position.

To optimize the digitization process, a methodology that uses all available means—such as GPS, aerial images, and planting patterns—is implemented. The GPS receiver is used in most cases for digitization of the palms' positions in the implementation area. Because GPS accuracy is dependent on obstacles, weather, satellite geometry, and other factors, additional methods of digitization need to be used (e.g. satellite or aerial images and polygons of landscape architecture) to increase accuracy. A semi-automatic position finder function has been developed specifically for the case of agricultural areas, where the palms are planted at certain well-defined distances. In this function, only the first and last palm are digitized and the middle palms' positions can be automatically identified taking into account the known distance between palms in a row and between rows in the orchard. Further correction or modification of palm position can be performed manually later on.

Data are also acquired using the GIS mobile, which provides the user with capabilities to seek information using spatial data and attribute queries for statistical and navigational purposes. Using on-site navigation techniques, the navigator can relate any palm position with the user position, giving useful information on user location and the assigned palm. The navigation is enhanced with tracking functionalities and multimedia content, such as images (photographs) and voice commands. In the photo layer, the user can store photographs of each palm and any action taking place on the palms. These photographs are available to the navigator of the mobile client so that the user can easily identify a specific palm during the navigation. The user can see the images using an internal image viewer or directly upon the information layers of the CPLAS, in which case he/she can focus on the image using the mapping tools (zoom in, zoom out, pan, etc.).

11.2.5 Implementation of CPLAS in Real Time: Case Studies

The CPLAS was implemented under real-time conditions in five study areas. GIS layers were constructed, data were acquired, and spatiotemporal analysis was performed for three urban palm tree areas (the Central Park "Pedion Areos" and the "National Garden" in Athens, Greece, and the "Bahá'í Gardens" in Haifa, Israel), two date palm tree orchards (Maale Gamla and Ramot plantations on the shore of Lake of Galilee, Israel), and the Preveli palm tree forest (*P. theophrasti*), prefecture of Rethymno, Crete.

11.2.5.1 Pedion Areos Park

Pedion Areos Park is the central park of Athens, Greece (WGS87 longitude: 23.736540; latitude: 37.992946; elevation of approximately 90 m above sea level). There are more than 400 palms (primarily *P. canariensis*) in the park. Many of these palms were planted based on a landscape design, whereas others were self-sown. Infestation risk assessments of the palms were performed from 2010 to 2014. In Fig. 11.7, the GIS layers of the palms, the areas, and the background of the map for Pedion Areos Park are presented.

Infestation risk data of the palms of Pedion Areos Park for the years 2010 and 2011 were imported to the CPLAS system. Mean infestation risk of palms by the RPW at Pedion Areos Park was estimated for the years 2010–2014. The distribution of palms

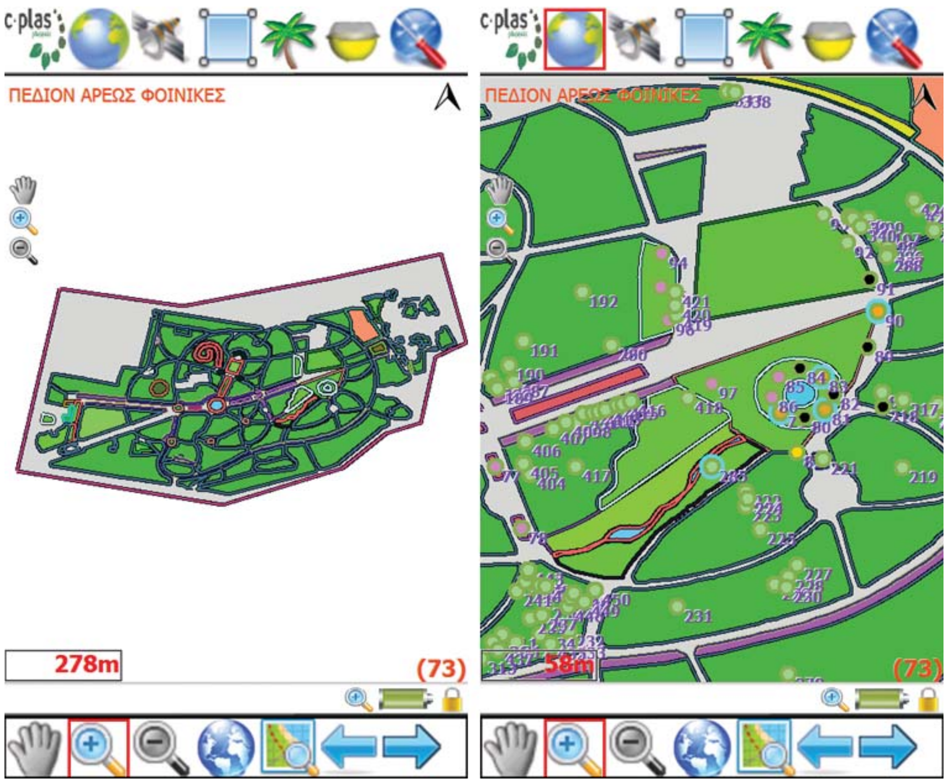


Figure 11.7 CPLAS mobile GIS layers of Pedion Areos Park, Athens, Greece. Points indicate the positions of palms; numbers correspond to the recorded number of palms in the monitored area; the color of the points indicates infestation risk of palm trees by RPW with a gradation of colors from cold to warm for low to high risk, respectively.

infested by RPW in infestation risk classes of CPLAS over time is presented in Fig. 11.8. Different colors specify different infestation risk levels according to the 10-class infestation risk scale of CPLAS with gradation from cold colors for low risk to warm colors for high risk.

The first loss of a palm tree due to infestation by RPW at Pedion Areos Park was recorded on January 10, 2010. Since then, the Competent Authority of the Park has used CPLAS for digitization of the palms, infestation risk assessment, and decision-making for the management of infestations. The data were analyzed and layers of interpolation of infestation risk were constructed. Decisions on management were based on the CPLAS DSS recommendations for sanitation, chemical-control treatments, or safe phytosanitary removal of the infested palms. However, this was not always feasible for technical and practical reasons. The last interpolation map in Fig. 11.8 indicates that the RPW has spread in the park and many palms have died as a result of infestation by the pest. Nevertheless, CPLAS has been a useful tool for infestation risk assessment and for decision support on the management of infestation at the individual palm tree level, as well as for focusing inspection on hot spots, contributing to more efficient control of the pest in the park, both spatially and temporally.

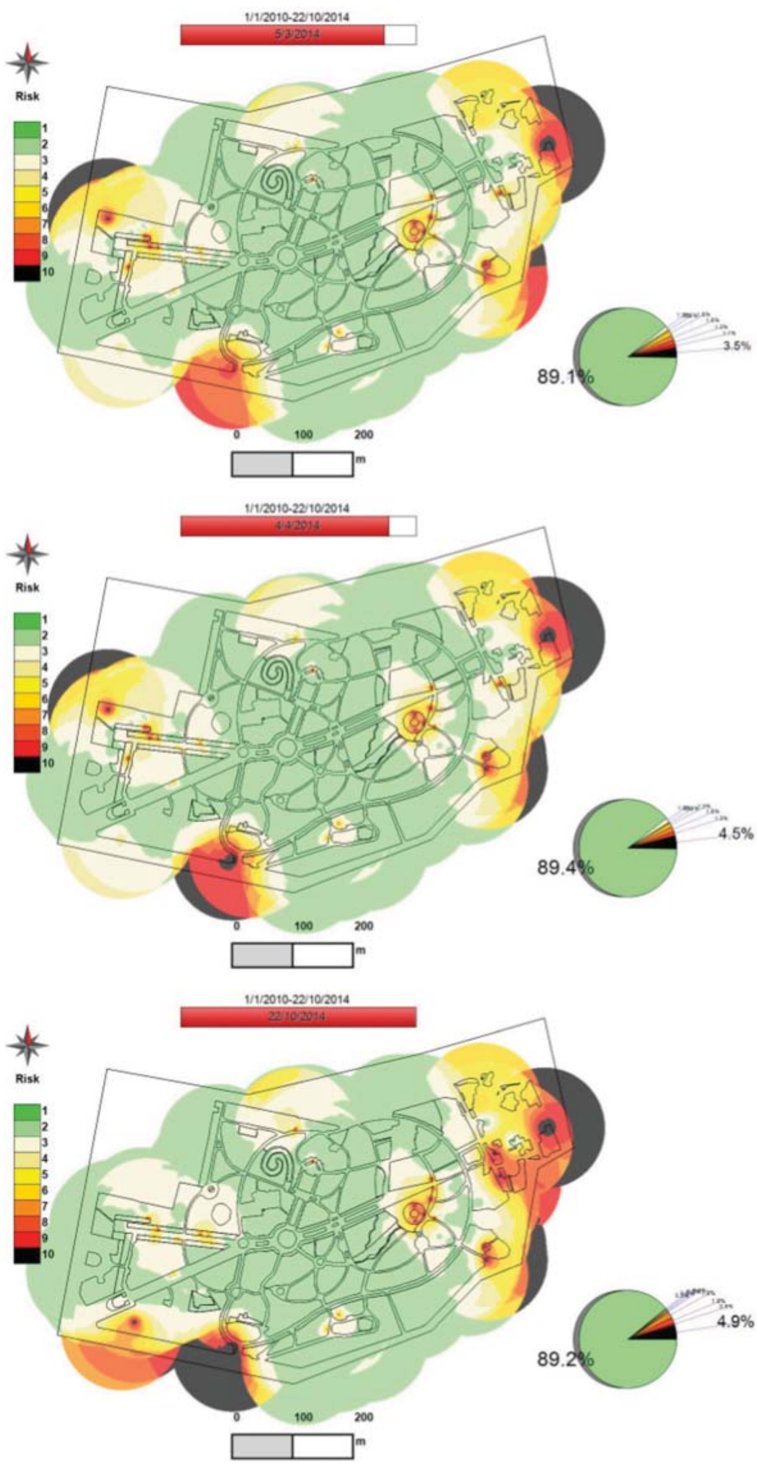


Figure 11.8 Spatiotemporal analysis of the infestation risk of palms by the RPW at Pedion Areos Park (March to October 2014); color indicates infestation risk according to the 10-class infestation risk scale of CPLAS with gradation from cold colors for low risk to warm colors for high risk; percentages in the pies represent palms classified at different risk levels out of the total number of palm trees in the park.

11.2.5.2 National Garden of Athens

The National Garden of Athens, Greece (longitude 23.737892, latitude 37.973450, height 93 m) has approximately 450 palm trees. Infestation risk assessments of the palms were performed during the years 2013 and 2014. In Fig. 11.9, the GIS layers of the palms, the traps, and the background of the map are presented for the National Garden of Athens.

In the National Garden of Athens, a trial was conducted to investigate the optimum trap distribution for the early detection of RPW in urban areas. A network of 40 Picusan® traps was deployed and served weekly from November 1, 2013 to the first week of November 2014. The attractants were *R. ferrugineus* pheromone (Pherosan RF (Sansan Prodesing S. L.) + ethyl acetate (Novagrica Hellas S.A.)) + sugar molasses. The CPLAS was used to record the locations of the traps and palms and to perform infestation risk assessment (March 2013 – November 2014). Interpolation spatial analysis of the infestation risk (IDW, power = 2, distance = 100 m) of the palm trees and the traps' captures at the National Garden of Athens are shown in Fig. 11.10.

11.2.5.3 Bahá'í Gardens

The Bahá'í Gardens are located in Haifa, Israel (WGS87 longitude: 35.0921131; latitude: 32.9436492; elevation of approximately 25 m above sea level). The gardens comprise a staircase of 19 terraces extending all the way up the northern slope of Mount Carmel. There are approximately 100 Canary palms in the gardens. Infestation risk assessments of the palms were performed from March 2012 to July 2014. In Fig. 11.11, the GIS layers of the palms, the position of the traps and the background map, an infestation risk map, and navigation tools/multimedia capabilities of CPLAS are presented for the Bahá'í Gardens.

Infestation risk assessments of the palms in the Bahá'í Gardens were performed from March 2012 to July 2014. Spatiotemporal analysis of the infestation risk (IDW,

Figure 11.9 Mobile GIS layers of the National Garden of Athens, Greece. Points indicate position of the monitoring traps for the RPW and numbers correspond to the traps' serial numbers; the color of the circles at the bottom of the palm tree sketches indicates the infestation risk of palm trees by the RPW with a gradation of colors from cold to warm for low to high risk, respectively; in the last layer, the palm tree species can be accessed.

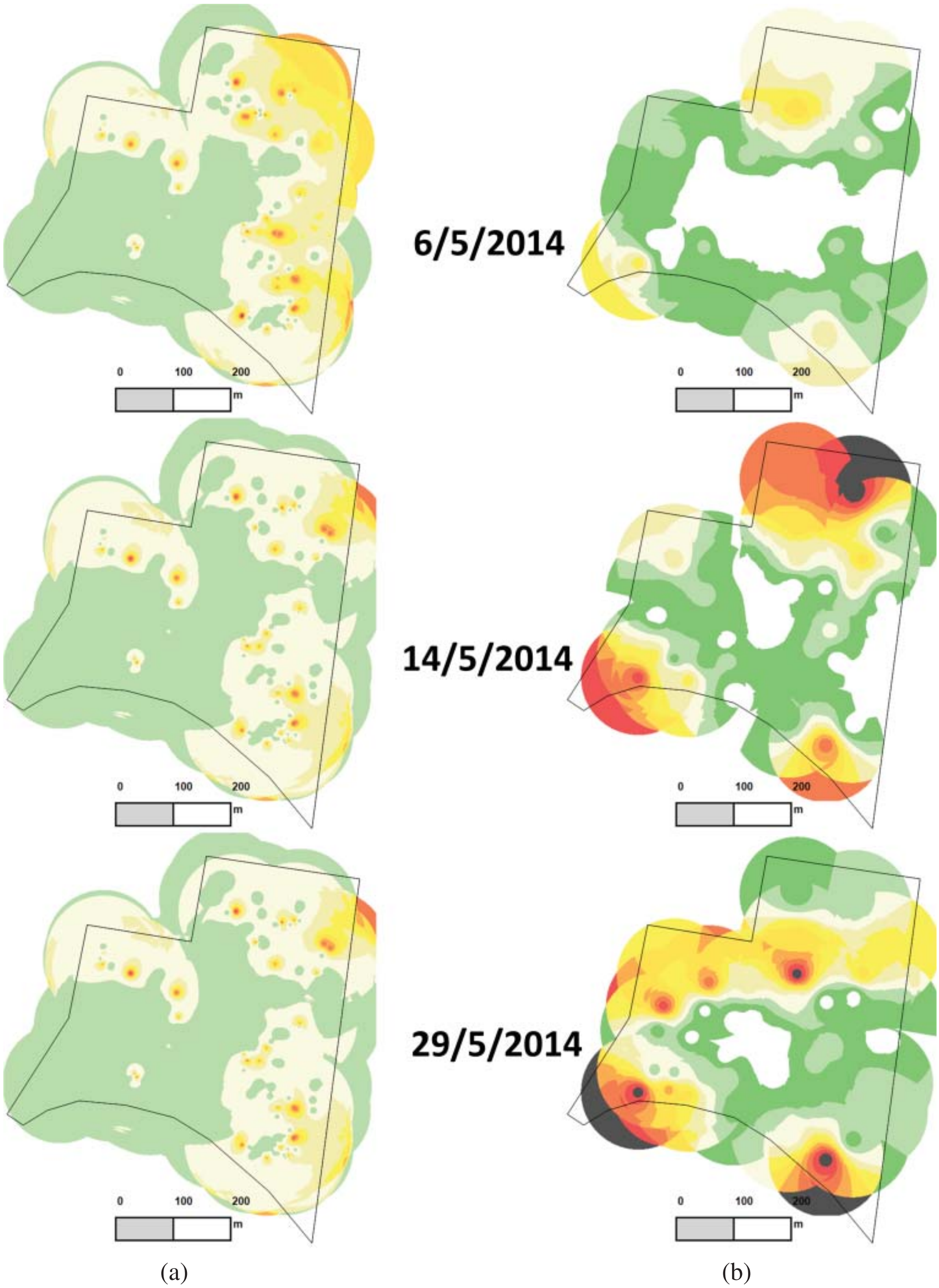


Figure 11.10 Spatiotemporal analysis of infestation risk (a) and trap captures (b) in the National Garden of Athens, Greece (May and June 2014). Color indicates infestation risk according to the 10-class infestation risk scale of CPLAS with gradation from cold colors for low risk to warm colors for high risk.

Figure 11.11 CPLAS mobile GIS layers of the Bahá'í Gardens, Haifa, Israel. In the first layer: small points indicate the position of the palms; numbers correspond to the recorded number of palms in the monitored area; the color of the points indicates infestation risk of palm trees by the RPW with a gradation of colors from cold to warm for low to high risk, respectively; large points indicate the position of the monitoring traps for RPW. In the second layer: demarcated areas indicate different infestation risk of palm trees by the RPW with a gradation of colors from cold to warm for low to high risk, respectively.

power = 2, distance = 100 m) was conducted for the same period, indicating an increase in the infestation risk with time (Fig. 11.12).

11.2.5.4 Date Palm Orchards in Maale Gamla and Ramot

CPLAS spatial information layers were created for the date palm orchard in Maale Gamla and Ramot (Fig. 11.13). Inspection and infestation risk assessment of date palms was conducted at the date palm plantation of Ramot on December 16, 2014 and January 13, 2015, according to the protocol for visual inspection of date palms (see Chapter 9, this volume). Spatiotemporal analysis of the infestation risk of date palms (IDW, power = 2, distance = 100 m) was conducted for the date palm orchard in Ramot (Fig. 11.14). No new infested palms were detected up until July 20, 2015. However, follow-up is still needed to evaluate the accuracy of the CPLAS for the infestation risk

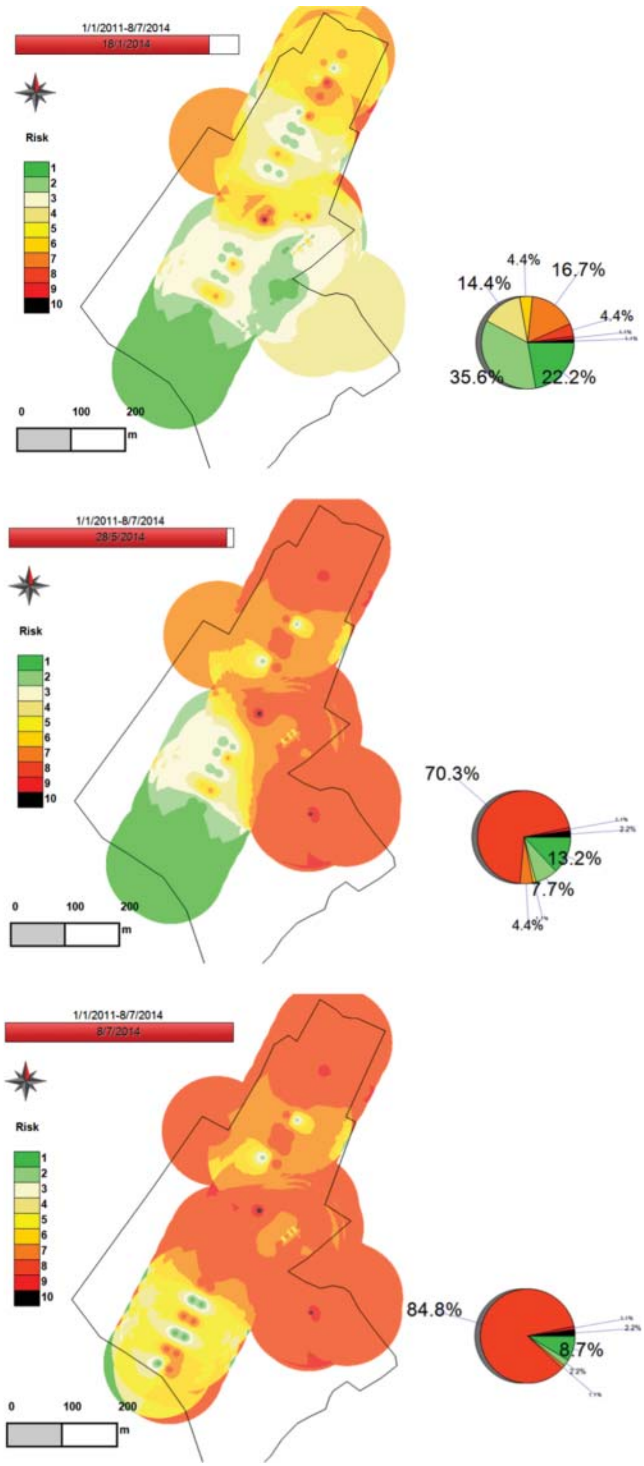


Figure 11.12 CPLAS spatiotemporal analysis of infestation risk to palms by the RPW at Bahá'í Gardens (January to July 2014); color indicates infestation risk according to the 10-class infestation risk scale of CPLAS with gradation from cold colors for low risk to warm colors for high risk; percentages in the pies represent palms classified at different risk levels out of the total number of palm trees in the gardens.

Figure 11.13 Mobile GIS layers of Maale Gamla and Ramot, Israel.

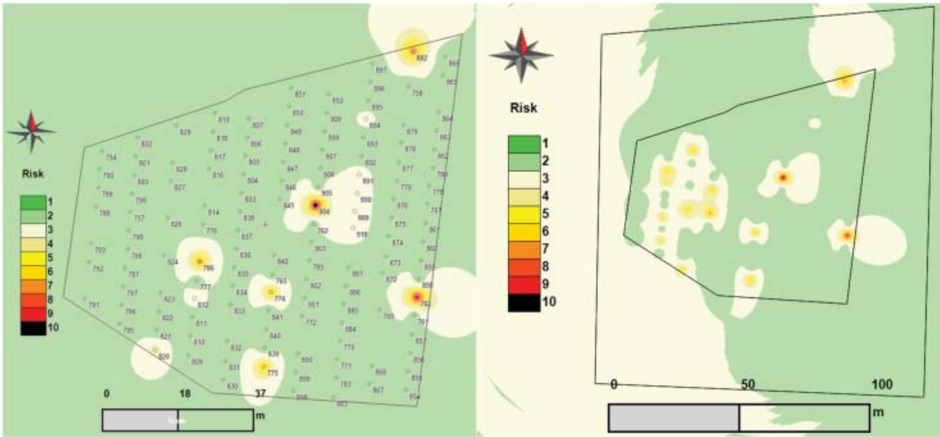


Figure 11.14 CPLAS spatial analysis of infestation risk of date palm in Ramot on December 16, 2014 (left) and January 13, 2015 (right); color indicates infestation risk according to the 10-class infestation risk scale of CPLAS with gradation from cold colors for low risk to warm colors for high risk.

assessment, because infestation by the RPW develops much more slowly in date palms and detection of symptoms in these palms is still challenging (see Chapters 9 and 10, this volume).

11.2.5.5 Preveli Palm Tree Forest

The Preveli palm tree forest (longitude 24.47282, latitude 35.15587, approximate height 40 m (20 – 60 m)) is a forest of approximately 300 native Cretan palm trees, *P. theophrasti.* It is located at the exit of the Kourtaliotiko Gorge on the southern coast of the prefecture of Rethymno on the island of Crete, Greece. The CPLAS spatial information layers were created for approximately one-third of the Preveli palm forest (102 palms) and infestation risk assessment was performed on December 18 and 19, 2014, when no infestation was found. In Fig. 11.15, the GIS layers of the palms and background map of the CPLAS in Preveli forest are presented.

11.3 Web-mapping Service of CPLAS

The CPLAS web-mapping site was designed to support authorized CPLAS users with a web service of the system. The site includes static and dynamic web pages. The static web pages demonstrate static multimedia and text information content. The dynamic web pages show data content and mapping information according to the user's actions, profiles, and preferences, for example the report's web page facilitates data interpolation and their presentation with animation or in 3D, 3D mapping, offline reports, and photo gallery (Fig. 11.16 and Fig. 11.17).

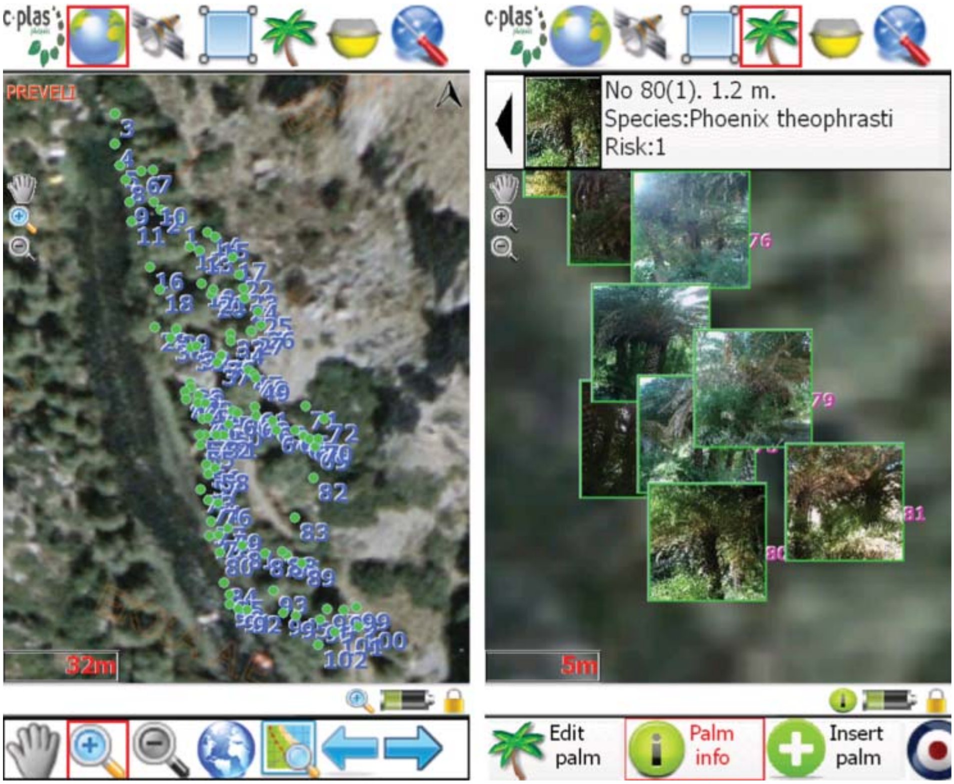


Figure 11.15 CPLAS mobile GIS layers where Cretan palms are indicated with green points on the background map at Preveli forest, Crete, and individual photos of each palm can be accessed.

11.4 Conclusion

The new version of CPLAS is an LAS that facilitates rapid systematic assessment of the infestation risk of palms by the RPW (Canary palm, date palm, and Cretan date palm) in urban, agricultural, and natural environments with large numbers of trees, traps, and treatment options. The system includes monitoring, network, web, and communication functions, data handling and ease of use. It supports real-time classification capabilities of the infestation risk of individual palms and provides spatiotemporal analysis of the infestation risk in the study area.

The CPLAS was evaluated in three urban areas with infested palms and proved to be easy to use and useful for systematic infestation risk assessment of Canary palms. It was also adopted for application in date and Cretan palms. Owing to the slower development of RPW infestation in these palm species, however, no clear conclusion can be drawn about its potential for the evaluation and accuracy of infestation risk assessment, and follow-up is still necessary.

Overall, the CPLAS is an efficient tool for the meticulous collection of a very large volume of data that would otherwise be difficult or unfeasible. Furthermore, it enables analysis of very large data volumes on a geographical scale. It provides interpolation maps for infestation risk, which can be the basis for prediction modeling and can support

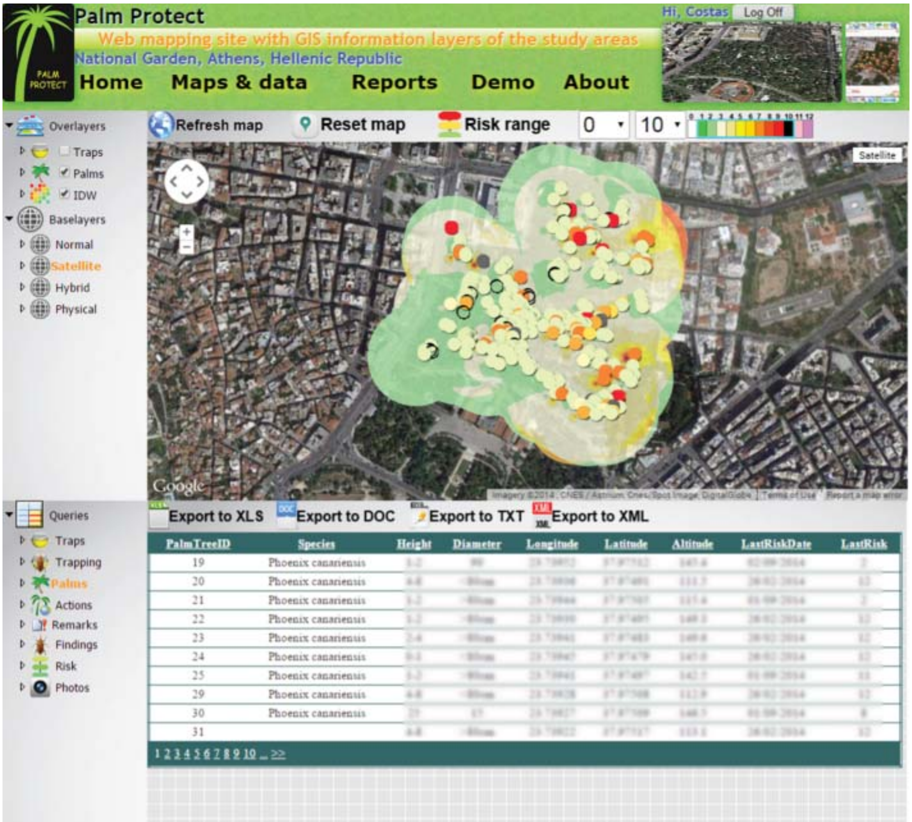


Figure 11.16 A web page of the CPLAS web-mapping site for the National Garden of Athens, Greece. In the upper middle portion of the web page, the web mapping is presented; in the lower middle portion of the web page, the queries menu is shown together with the recorded data (table).

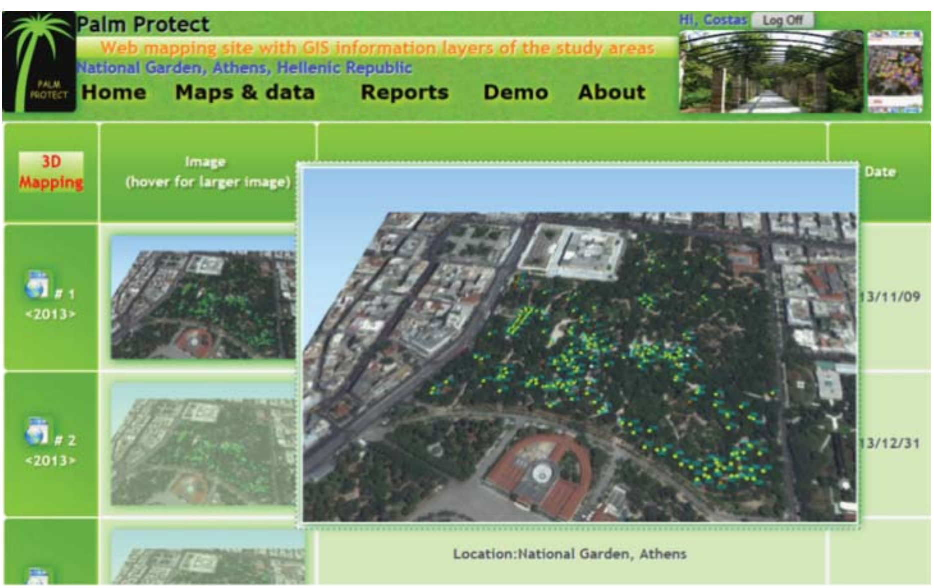


Figure 11.17 The 3D web-mapping page of the CPLAS web-mapping site for the National Garden of Athens, Greece.

decision-making for the management of large areas. Nevertheless, more work needs to be done to determine the accuracy of CPLAS in date palm plantations. Since risk assessment is dependent on the availability of detection methods, updates will be necessary in the future according to innovations in the methods available in the regions for implementation. The CPLAS can also be adapted to address the infestation risk assessment of RPW in other palm species and palm pests.

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12

Control Measures Against *Rhynchophorus ferrugineus* and *Paysandisia archon*

Josep A. Jaques[1], Paola Riolo[2], Neil Audsley[3], Joan Manel Barroso[4], Oscar Dembilio[1], Nunzio Isidoro[2], Roxana Luisa Minuz[2], Sandro Nardi[5], Vicente Navarro Llopis[6], Laurence Beaudoin-Ollivier[7] and Enrique Quesada Moraga[8]*

[1] *Universitat Jaume I, Department of Agricultural and Environmental Sciences, Campus del Riu Sec, Spain*
[2] *Department of Agricultural, Food and Environmental Sciences, Marche Polytechnic University, Italy*
[3] *Fera Science Ltd, Sand Hutton, York, United Kingdom*
[4] *Endoterapia Vegetal SL, Girona, Spain*
[5] *Servizio Fitosanitario Regionale, Agenzia Servizi Settore Agroalimentare delle Marche, Italy*
[6] *Universitat Politècnica de València, Center for Agricultural Chemical Ecology, Mediterranean Agroforestal Institute, Spain*
[7] *Centre de coopération internationale en recherche agronomique pour le développement (CIRAD), Biological System Department, Research Unit Bioagresseurs, France*
[8] *Unidad Entomologia Agricola, Dpto. Ciencias y Recursos Agricolas y Forestales, Campus de Rabanales C4 2 planta, Spain*

12.1 Why Control of *R. ferrugineus* and *P. archon* is so Difficult: Reasons to Deal with Both of these Pests Together

The economic impacts of *R. ferrugineus and P. archon* are completely different. On the one hand, *R. ferrugineus* is a pest of economic importance worldwide (Faleiro 2006; EPPO 2008a, 2008b; Dembilio and Jacas 2011; Giblin-Davis *et al.* 2013), mainly due to its impact on agriculturally important crops, including date and coconut palms, and ornamental palms such as *Phoenix canariensis*. On the other, *P. archon* has not been reported to be a significant pest in its native area (South America) (Bourquin 1933; Sarto i Monteys and Aguilar 2005). However, in Europe, it has caused serious damage and plant mortality in both palm nurseries and urban areas (EPPO 2008b). The larvae of these pests penetrate deep into the stem, damage the internal tissues, and disrupt nutrient transport, which can even lead to tree collapse and death (Murphy and Briscoe 1999; Sarto i Monteys and Aguilar 2005), with serious consequences for cultivated and native palm species.

The amount of information available on control methods against *R. ferrugineus* has increased exponentially in recent years. These methods include physico-mechanical, biotechnological, biotechnical, chemical, and biological control (Faleiro 2006; EPPO 2008a; Giblin-Davis *et al.* 2013). Conversely, there is little information available regarding the control of *P. archon*. Nevertheless, it is possible to use biological, physical, mechanical, and chemical methods against this moth (Sarto i Monteys and Aguilar 2005; Nardi *et al.* 2009; Chapin *et al*. 2013; Peltier 2013).

*J.A. Jaques was formerly J.A. Jacas

Handbook of Major Palm Pests: Biology and Management, First Edition.
Edited by Victoria Soroker and Stefano Colazza.

R. ferrugineus and *P. archon* are extremely difficult to control because their larvae are mostly endophagous, and therefore chemical control has only limited efficacy. Moreover, the availability of chemical products as pesticides varies nationally, and the withdrawal of pesticides from the re-registration processes under EU Directive 91/414/EEC and further with EU Directive on Sustainable Use of Pesticides (2009/128/EC) has restricted the number of authorized active substances (OJEU 1991). However, at present, preventive integrated management that carefully combines all of the available methods appears to be the best approach to controlling these pests.

Containment and eradication measures against *R. ferrugineus* have been implemented in several countries, including those in the EU (OJEU 2007, 2008, 2009a, 2010). Protective measures against the introduction and spread of *P. archon* in the EU have been adopted with Directive 2009/7/EC (applied only to plants intended for planting) (OJEU 2009a). In general, National Plant Protection Organizations (NPPOs) face difficulties in implementing compulsory measures against *R. ferrugineus* promptly because citizens, municipalities, nurseries, and other involved stakeholders frequently strongly oppose the destruction of infested palm trees due to their economic (nurseries and date orchards), cultural (historic palm groves and forests and monumental palms), touristic, and emotional value, and because of the high cost of this measure (Nardi *et al.* 2011). Herein, we discuss some of the pros and cons of the available control methods, mainly, but not exclusively, for *R. ferrugineus*.

12.2 Current Control Methods

12.2.1 Legal Control

As both *R. ferrugineus* and *P. archon* are invasive but well hidden within their host, quarantine is of high importance in the control of their spread. Both of these species are now included in the European and Mediterranean Plant Protection Organization (EPPO) quarantine A2 list (EPPO 2014), and diagnostic EPPO standards (PM. 7) are available. The EU legislation now lists the susceptible host plants for each of these two pest species. These regulations apply to palms, excluding fruit and seeds, with a stem-base diameter of over 5 cm (OJEU 2007, 2009a). The rationale for this regulation is that *R. ferrugineus* cannot complete its life cycle in smaller palms. As a consequence, infestation in such palms is easily detected with the naked eye. However, as *P. archon* can complete its whole life cycle in palms with a basal diameter of less than 5 cm (P. Riolo, personal observation), the exclusion of these palms should probably be revisited. Import requirements from non-EU countries are very similar for both *R. ferrugineus* and *P. archon* (OJEU 2007, 2009a). Susceptible plant hosts have to comply with one of the following compulsory measures: (1) have been grown throughout their life in a country where these pests are not known to occur; (2) have been grown throughout their life in a pest-free area established by the NPPO in accordance with relevant International Standards for Phytosanitary Measures; or (3) have, during a period of at least 2 years for *P. archon* and a period of at least 1 year for *R. ferrugineus*, been grown in a place of production: (a) which is registered and supervised by the NPPO in the country of origin, (b) where plants were placed in a site with complete physical protection (i.e. nets or screen-house) against the introduction of these pests or with application of appropriate preventive treatments, and (c) where, during the periodic official inspections, no signs of these pests have been observed. Post-entry quarantine requires complete physical protection for 1 year from their arrival into the EU for palms imported from areas where *R. ferrugineus* is known to occur (OJEU 2010). Only when these palms have been shown to be healthy after their quarantine period can they receive a plant passport that permits their movement within the EU (OJEU 2007, 2008). However, the efficacy of these procedures remains unknown, and would greatly increase if accompanied by a suitable quarantine treatment.

The main procedures for eliminating arthropod pests from a commodity are classified broadly as chemical and physical. Chemical treatments include fumigants, such as methyl bromide and phosphine, which can penetrate into the commodity and are toxic to pests. Methyl bromide was the most commonly used post-harvest and quarantine treatment worldwide. However, with the phasing-out of ozone-depleting substances according to the United Nations Montreal Protocol, methyl bromide is currently forbidden as a post-harvest treatment and its use is not permitted within the EU, even for quarantine purposes (OJEU 1991). For the immediate future, phosphine will continue to be an important and economically viable fumigant for widespread use against insect infestation (Bell 2000; Donahaye 2000). Data obtained by Saleh *et al.* (1996), Hussein (1998), and Mesallam (2010) under field conditions, and those reported by Llácer and Jacas (2010) in a hermetic container, suggest that low doses of aluminum phosphide can kill all stages of *R. ferrugineus*. Furthermore, the use of phosphine fumigation applied to infested *P. canariensis* crowns has resulted in complete mortality of this pest (Llácer and Jacas 2010). Furthermore, additional infested and non-infested palms exposed to phosphine fumigation have survived for up to 1 year after the treatment with no phytotoxic symptoms and no infestation (Dembilio and Jaques in press). These data form the basis for the development of a quarantine treatment against *R. ferrugineus* which could be easily applied in the sealed containers that are used to prepare and ship the plant material. Quarantine treatments could significantly reduce the enormous phytosanitary risks that palm movements currently pose worldwide (Llácer and Jacas 2010; Dembilio and Jaques in press).

12.2.2 Cultural Control

Field sanitation is one of the major components of integrated pest management (IPM) programs against *R. ferrugineus* for coconut palms in India (Abraham, Koya, and Kurian 1989; Faleiro 2006). It has also been used in relatively young *Phoenix dactylifera* orchards in the Middle East, where infestation is most common at the junctions between off-shoots and the mother stipe, within 2 m of the ground (Azam and Razvi 2001; Cohen *et al.* 2012). This technique involves the removal of infested or dry offshoots, and the removal of the infested palm tissues and pest specimens by filling the cavities with soil or pesticide-treated sawdust. The stipe is then wrapped with plastic sheets to prevent further attraction of weevils and new infestation of the wounded tree. If the damage is not too severe, the palm usually recovers by filling the cavity with adventitious roots.

Sanitation has also been applied to *P. canariensis*, where infestation usually occurs in the crown. In this case, the technique is based on the process used for the traditional production of palm syrup on La Gomera Island (Canary Islands, Spain). This technique is adopted as a last resort for the recovery of damaged palms. The objective is to clean up the entire infested canopy by removing nearly all of the fronds, galleries, and specimens without damaging the meristematic tissues (Ferry and Gómez 2008; Nardi *et al.* 2011; Faleiro *et al.* 2012). Crown sanitation (Fig. 12.1 and Fig. 12.2) is a complicated technique, and it requires highly skilled application. Once the palm has been pruned, the stipe must be thoroughly washed. Then a spray treatment (chemical and/or biological) that includes a fungicide is applied, to prevent subsequent fungal infection. These treatments are repeated on a monthly basis. In some cases, the stipe of the palm is protected with a strong fine-meshed net that is not in contact with the apical zone, with the aim of reducing solar radiation and re-infestation. This method is extremely time-consuming and thus especially suited for old, high-value, monumental specimens. As the infested material contains developing weevils, all of the material removed from the palm needs to be shredded. Field sanitation has been applied to *P. canariensis* in urban areas of several European regions, and a reduction in the number of infested palms has been reported in Italy (La Mantia, Lo Verde, and Ferry 2008; Nardi *et al.* 2011). In general, both as private citizens and public institutions, palm owners prefer to invest money in sanitation rather than destruction. However, treated palms have a high risk of asymmetric development, and re-infestation has been reported to vary from a few cases to more than 80% of the plants (La Mantia, Lo Verde, and Ferry 2008; Nardi *et al.* 2011). Moreover, adverse climatic conditions (e.g. low temperatures during the winter) increase the mortality of

(a) (b) (c) (d)

Figure 12.1 Crown sanitation: different steps of the integrated approach applied to *P. canariensis*. A. Spherical pruning operation. B. Washing of the crown with water at high pressure. C. Crown after pruning. D. Spray treatment (chemical and/or biological) including a fungicide to prevent subsequent fungal infection.

(a) (b)

Figure 12.2 Crown sanitation: apical bud growth in *P. canariensis* 2 weeks (a) and 2 months (b) after spherical pruning and sanitation.

the treated plants (Nardi *et al.* 2011). As a consequence, palm owners in some European regions (e.g. southeastern France) have become highly reluctant to perform sanitation.

A microwave device has been designed to reduce all of the developmental stages of *R. ferrugineus* populations directly inside the palm. Microwaves can penetrate the stem and crown tissues and transfer energy to the water molecules, which make up most organic materials, resulting in heated water molecules, including those making up internally feeding insects. Overheating and hyperthermia kill them. The highest temperatures applied this way in palms are believed not to exceed 57 °C. This treatment can be applied as a curative treatment. However, there are no reliable studies on the effects of these microwave treatments on palm physiology and survival. A study carried out by Massa *et al.* (2011) in artificially infested palms under greenhouse conditions showed that irradiation with a 2.45 GHz magnetron produces a rapid increase of the temperature in the tissues, reaching up to 70 °C in some parts of the palm, just 2 min after the radiation is applied.

While other cultural techniques, such as irrigation or pruning, cannot be considered control methods, their effects on *R. ferrugineus* and *P. archon* cannot be neglected, and should be considered in any IPM program against these pests. Adult *R. ferrugineus* appear to use moist soil as a temporary shelter, and there are reports of flood irrigation increasing infestation in date-palm orchards (Aldryhim and Al-Bukiri 2003; Aldryhim and Khalil 2003). The same might be true for sprinkler irrigation, and therefore farmers have been advised to prevent wetting the stipe next to the offshoots (Cohen *et al.* 2012). *R. ferrugineus* is preferentially attracted by wound-emitted volatiles and oviposits in soft tissue, such as the cut ends of fronds and other wounds and cracks. Therefore, removal of live green fronds and offshoots, and other trimming practices, should be followed by

Figure 12.3 Glue application on a *P. canariensis* palm stipe.

thorough treatment with an appropriate insecticide, and preferably be restricted to the winter season (Dembilio and Jacas 2011), especially in areas where a wintering no-flight period has been observed. For *P. dactylifera*, it has been suggested that wounds be covered with pitch or with chemicals that efficiently seal and dry the wounded tissue (Cohen *et al.* 2012).

An original approach that was recently proposed through research at INRA consists of coating the sensitive parts of the stipe with glue that acts as a physical barrier between the palm and *P. archon* (Fig. 12.3). In particular, this glue affects both the penetration by young larvae (guaranteeing a re-infestation rate below 10%) and the flight of emerging adults (90% decrease in flight activity) (Peltier 2013).

12.2.3 Biological Control

Biological pest control relies on the use of natural enemies, either entomophagous arthropods (predators and parasitoids) or entomopathogenic microorganisms (bacteria, fungi, and viruses) and nematodes. A few studies have been conducted on the natural enemies of *R. ferrugineus* and other *Rhynchophorus* species (Murphy and Briscoe 1999; Faleiro 2006; Mazza *et al.* 2014) and scant data are currently available for *P. archon* (see Chapter 8, this volume). In this chapter, only those natural enemies that have shown evidence of biological control potential in semi-field or field experiments will be discussed.

Among the entomopathogenic microorganisms, nematodes and fungi have shown promise for *R. ferrugineus* and *P. archon* control. Few studies have dealt with viruses and bacteria. Indeed, naturally occurring cytoplasmic polyhedrosis viruses (CPV) of *R. ferrugineus* in India and Egypt have not been reported to be effective in either inoculative or inundative strategies (Gopinadhan, Mohandas, and Nair 1990; El-Minshawy, Hendi, and Gadelhak 2005). Similarly, there are several reports of entomotoxic bacteria isolated from larvae and adults of *R. ferrugineus* with uncertain laboratory effects (Alfazariy 2004; Manachini *et al.* 2009). Mitosporic ascomycetes have been reported to naturally regulate *R. ferrugineus* populations (Dembilio *et al.* 2010a) similar to entomopathogenic nematodes (EPN), and both have shown potential for *R. ferrugineus* control (Llácer, Martinez, and Jacas 2009; Dembilio *et al.* 2010b). Moreover, their effect is self-amplifying. In the case of EPN, they can actively find and infect the target host with their symbiotic pathogenic bacteria (Dolinski and Lacey 2007; Lacey and Shapiro-Ilan 2008). However, Manachini, Schillaci, and Arizza (2013) noted the key role of the *R. ferrugineus* immune system on the multiplication of EPN in the host. Although *Steinernema carpocapsae* (Weiser) (Nematoda: Steinernematidae) could avoid encapsulation by *R. ferrugineus* hemocytes, high defensive abilities of the *R. ferrugineus* humoral and cellular defense system toward *S. carpocapsae*'s symbiotic bacterium *Xenorhabdus nematophila* (Enterobacteraceae) were detected.

EPN are safe for non-target vertebrates and for the environment, and production costs have been significantly reduced by their mass production in liquid media (Ehlers 2001, 2003). EPN have been repeatedly tested against the red palm weevil (Abbas, Saleh, and Akil 2001; Abbas *et al.* 2001; Saleh and Alheji 2003; Elawad *et al.* 2007; Llácer, Martinez, and Jacas 2009; Dembilio *et al.* 2010b; Nardi *et al.* 2011). Although field experiments in date palms conducted several years ago produced inconsistent results (Abbas *et al.* 2001), more recent laboratory, semi-field, and field assays using *S. carpocapsae* with chitosan showed efficacies of around 80% in *P. canariensis* (Llácer, Martinez, and Jacas 2009; Dembilio *et al.* 2010b) and *Phoenix theophrasti* (Dembilio *et al.* 2011). Interestingly, the same species has proven effective against *P. archon* (Nardi *et al.* 2009). Trials in France showed similar results but also indicated important variability and the need to define optimal application standards (Perez *et al.* 2010; André and Tixier-Malicorne 2013). Because efficacies obtained by Dembilio *et al.* (2010b) when combining treatments of imidacloprid (Confidor® 240 OD; Bayer Crop Science, 2.4 g a.s. per palm) and *S. carpocapsae* (Biorend Palmeras®, Idebio, 5×10^6 Dauer Juveniles (DJ) per palm) were not significantly different from those obtained with the same products when applied alone, the use of EPN should be considered when developing guidelines for treatments against *R. ferrugineus* and *P. archon*.

Similar to EPN, entomopathogenic fungi (EPF) fulfill all of the criteria of a sound approach when looking for sustainable alternatives to chemical control. Unlike other insect pathogens, EPF infect the host by contact, penetrating the insect cuticle. The host can be infected by both direct treatment and horizontal transmission from infected insects or cadavers to untreated insects or to subsequent developmental stages via the new generation of spores. Passive mechanical transmission of fungi within insect populations has been observed for various EPF, for example *Beauveria bassiana*, *Metarhizium anisopliae*, and *Isaria fumosorosea* (Lacey *et al.* 1999; Quesada-Moraga *et al.* 2004, 2008). These unique characteristics make EPF especially important for the control of concealed insects. Some of these species have been isolated from field-collected *R. ferrugineus* (El-Sufty *et al.* 2009; Sewify, Belal, and Al-Awash 2009; Dembilio *et al.* 2010a), while different strains of *M. anisopliae* and *B. bassiana* have been tested against *R. ferrugineus* (Gindin *et al.* 2006; El-Sufty *et al.* 2009; Sewify, Belal, and Al-Awash 2009; Dembilio *et al.* 2010a). El-Sufty *et al.* (2009) obtained a mortality rate of 13–47% of adult *R. ferrugineus* in field assays using a strain of *B. bassiana* isolated in the United Arab Emirates. Sewify, Belal, and Al-Awash (2009) successfully reduced the incidence of *R. ferrugineus* under field conditions in Egypt using a native strain of *B. bassiana* isolated from a *R. ferrugineus* cadaver. In addition, a *B. bassiana* strain isolated from pupae of infested date palms in Spain was shown to infect eggs, larvae, and adults of *R. ferrugineus* (Dembilio *et al.* 2010a). Mortality was not the only indicator of treatment efficacy because adults of either sex inoculated with the fungus efficiently transmitted the disease to untreated adults of the opposite sex and significantly reduced fecundity (up to 63%) and egg hatching (33%), resulting in an overall 78% reduction in progeny. Semi-field preventive assays on potted 5-year-old *P. canariensis* palms, with efficacies of up to 86%, confirmed the potential of this strain as a biological control agent against *R. ferrugineus*.

Different strategies are currently being evaluated to optimize the field application of EPF and to satisfy the more recent sustainable principles of pesticide use in the EU, with an emphasis on strategies promoting reductions in the amount of inoculum applied by localizing it, and the search for auto-dissemination strategies. Among them, it is important to highlight the use of different lure-and-kill devices and of sterile males as natural spreaders.

Although the sterile insect technique (SIT) (Lance and McInnis 2005) has been tested against *R. ferrugineus* (Ranavara, Harwalkar, and Rahalkar 1975; Rahalkar *et al.* 1977), its extremely high cost makes it barely sustainable. However, the potential of gamma-irradiated males to spread an entomopathogenic microorganism offers new possibilities for exploiting these biological control agents. The potential of using a pathogenic strain of the EPF *B. bassiana* dispersed by *R. ferrugineus* sterile males has been studied (Llácer, Santiago-Álvarez, and Jacas *et al.* 2013). First, the effects of gamma irradiation (15 and 25 Gy) on the mating success and performance of adult males irradiated at the age of 1 day were studied in the laboratory, revealing that irradiation does not affect male sexual competiveness but rather sperm quality. In a semi-field assay carried out to evaluate infestation in young *P. canariensis* caused by different combinations of couples with irradiated and/or *B. bassiana*-challenged males, it was shown that irradiated males could act as a vector for *B. bassiana* and should be considered as a new method of improving the biological control of *R. ferrugineus*.

An experimental auto-contamination trap was devised to infect *R. ferrugineus* adults with *Beauveria* and *Metarhizium* species (Francardi *et al.* 2013). This trap was evaluated under laboratory conditions using different cereal substrates and showed higher activity of the *Metarhizium* species. These authors also measured persistence and germination of the fungus under field conditions in traps in sunny and shaded locations in spring, summer, and fall. The traps preserved fungal inoculum stability longer in spring and summer than in fall, with no significant differences in conidial persistence between sunny and shaded conditions. However, the efficacy of the trap as an auto-dissemination device remains to be proven and some attempts have been made in this direction within Palm Protect (see Section 12.2.5).

All of the methods reported so far have to deal with a severe handicap: pest accessibility to biocontrol agents. As most of *R. ferrugineus* and *P. archon* life cycles are concealed within the host, systemic distribution of the natural enemy would be highly desirable. It has been shown that fungal endophytes play an important role in protecting plants against herbivorous insects (Jallow, Dugassa-Gobena, and Vidal 2004, 2008) and plant pathogens (Ownley *et al.* 2008). *B. bassiana* has been reported as an endophyte in a variety of plants from the Gymnospermae (Ganley and Newcombe 2006) and Angiospermae

(Bills and Polishook 1991; Evans, Holmes, and Thomas, 2003; Quesada-Moraga *et al.* 2006; Posada *et al.* 2007), including monocotyledonous species such as maize (Bing and Lewis 1991, 1992; Wagner and Lewis 2000) and *Pinus monticola* (Ganley and Newcombe 2006). In some cases, use of these endophytic fungi has resulted in complete control of the target pest (Quesada-Moraga *et al.* 2006). However, the use of strains of EPF with endophytic behavior is still a poorly explored tool for systemic protection of palms against *R. ferrugineus* and *P. archon*. Overall, to improve *R. ferrugineus* control by entomopathogenic microorganisms, a deeper investigation of the interaction between them and *R. ferrugineus*'s immune system is required.

Entomopathogenic microorganisms, and particularly EPF, may also provide a poorly explored source of new insecticidal compounds of natural origin for the control of *R. ferrugineus*. The insecticidal activity of a semi-purified extract from *Metarhizium brunneum* against larvae and adults of *R. ferrugineus* was assessed (Garrido-Jurado *et al.* 2013). Two fractions of this extract were evaluated against *R. ferrugineus*, both adults and larvae, and they showed high oral toxicity at 24 h (Garrido-Jurado *et al.* 2013). The possible application of this crude extract, targeting adults by crown spray and larvae by stem injection, is under evaluation.

12.2.4 Chemical Control

Many preventative and curative procedures have been designed with more or less success to limit and contain the spread of *R. ferrugineus*. Chemical control is the most conventional and practical measure, which is commonly based on the repeated application of large quantities of pesticides that are employed to ideally suppress the spread of infestation. An effective insecticide against *R. ferrugineus* and *P. archon* should have either systemic properties to reach these concealed pests within the palm tissue or contact activity to prevent establishment in a new host. Moreover, pesticide residues in fruit are a critical concern in date-producing areas. Finally, issues about the environmental pollution caused by these treatments are important not only in commercial orchards and nurseries but also, and especially, in public areas where ornamental palms are grown (Faleiro 2006; Dembilio *et al.* 2010b; Llácer, Dembilio, and Jacas 2010; Dembilio *et al.* 2014). Implementation of Directive 2009/128/EC on sustainable use of pesticides (OJEU 2009b) has further restricted the available active substances that are authorized for use against both *R. ferrugineus* and *P. archon* in the EU (Table 12.1) from mid-2015.

Because of the hidden nature of the immature stages of *R. ferrugineus* and *P. archon*, effective methods for the management of these pests have been difficult to develop and insecticides have to be applied frequently and over a long period of time for the effective management of established populations (Murphy and Briscoe 1999; Nardi *et al.* 2009). Treatments are often performed without sufficient information on the pesticide's mobility and persistence within the palm tissue. Therefore, one of the objectives of Palm Protect was to identify new environmentally safe insecticides and new delivery tools to make insecticides not only physiologically selective but also ecologically selective and user-friendly (Hernández-Marante *et al.* 2003; Dembilio *et al.* 2010b; Llácer, Dembilio, and Jacas 2010).

Highly effective active substances used against *R. ferrugineus* include insecticides such as chlorpyrifos, diazinon, phenthoate, and methomyl. However, most of these molecules have been, or will be, banned in the EU (Abbas *et al.* 2005; Lo Verde *et al.* 2008). As a consequence, today only a few pesticides are authorized in the EU

Table 12.1 Active substances, doses, and application techniques authorized for use against *R. ferrugineus* and *P. archon* in different EU countries.

Active substance	Country	Dose of commercial specialty	Application technique/s	Additional information
Abamectin 1.8 EC (W/V)	Spain[a)]	20–80 ml/palm	Stem injection. One single application or two (half dose) at 15–45 day interval. Application by authorized companies only	Authorized in public gardens
	Greece[b)]	20–80 ml/palm	Crown or Stipe injection. Two applications at 15–45 day interval. Application by authorized companies only Additionally: crown or Stipe injection are authorized	Against *R. ferrugineus* only Authorized under expert surveillance; restricted authorization
	Italy[c)]	25 ml/palm	Stipe injection	Authorized in public gardens, nurseries, and open field
Beauveria bassiana	France[d)]	5 10^8 conidia gr^{-1}	Foliar spray 8–10 g/palm for *Phoenix* spp. 3–10 g/palm for *Washingtonia* spp. 35–100 g/m stipe for *Trachycarpus* spp. and *Chamaerops* spp.	Against *P. archon*
Cyfluthrin 2.4 % + Imidacloprid 7.1 % EC	Italy[c)]	120 ml hl^{-1}	Foliar spray	Authorized in public gardens, nurseries and open field Repealed in August 2014
Chlorpyrifos 48 % EC (W/V)	Spain[a)]	150–200 g hl^{-1}	Foliar spray	
Chlorpyrifos-methyl 22,1% EC	Italy[c)]	500 ml hl^{-1}	Foliar spray	Authorized in public gardens, nurseries and open field
Clothianidin 50% WG (W/W)	Greece[b)]	15–20 g hl^{-1} 10 g ml^{-1}/palm 30 g 50 ml^{-1} of water/50 m[b)]	Foliar spray; Applications at 15–20 day interval Stipe injection. Applications at 15–20 day interval Authorized use for palms in nurseries. Spray of the ground area under the foliar. Applications at 15–20 day interval	Authorized under expert surveillance; restricted authorization
Emamectin benzoate 42,9 G/L	France[d)]	0.05 l/palm	Stipe injection (2–4 holes/palm) once a year in spring	Against *R. ferrugineus*

Imidacloprid 20 % OD (W/V)	Spain[a)]	50–75 ml hl^{-1}	Foliar spray	Stipe injection authorized in public gardens
		8–10 l ha^{-1}	Drench application allowed in nurseries only. Maximum of two applications 30–40 days apart/year	
			Stipe injection every 45–55 days from March to November	
		4–10 ml/palm	Injection 1.5–2.0 m below the crown by authorized companies only	
Phosmet 50 % WP (W/V)	Spain[a)]	150–250 g hl^{-1}	Foliar spray	
Spinosad 120 g l^{-1} EC	France[d)]	3 l ha^{-1}	2 applications with a maximum of 3/year	Against *P. archon* only; authorized in public gardens and nurseries
Thiamethoxam 25% WP (W/W)	Spain[a)]	40 g hl^{-1}	Foliar spray	Authorized in public gardens
		400 g ha^{-1}	Maximum of two applications 7–14 days apart	
		400 h ha^{-1}	Drench application. Maximum dose/application	
		5–20 g/palm	Stipe injection	
	Greece[b)]	40 g hl^{-1} (Max 400 g ha^{-1}/application)	Foliar spray. Maximum of two applications at 7–14 day interval. Also authorized for preventive use in nurseries (maximum of two applications)	Against *R. ferrugineus* only; authorized under expert surveillance; restricted authorization
		5–20 g	Drench application at palms of low height. Maximum one application	
		20–200 ml/palm	Crown or stipe injection. Minimum dose for low palms- maximum dose for high palms. Maximum of two applications at 7–14 day interval. Additionally: foliar spray, drench application and crown or stipe injection are authorized. Spray authorized for treatment of palm parts for disposal	

Sources:

a) MAGRAMA (2015) Registro de Productos Fitosanitarios, http://www.magrama.gob.es/es/agricultura/temas/medios-de-produccion/productos-fitosanitarios/registro/menu.asp (January 2015).

b) MARDF (2012) Data base of Authorized Plant Protection Products (September 2012).

c) Assessorato Regionale delle Risorse Agricole e Alimentari. Prodotti autorizzati per la lotta al punteruolo rosso della palma, http://www.regione.sicilia.it/agricolturaeforeste/assessorato/ServizioFitosanitarioRegionale.htm (January 2015).

d) MAA (2015) Le catalogue des produits phytopharmaceutiques et de leurs usages des matières fertilisantes et des supports de culture homologués en France, http://e-phy.agriculture.gouv.fr/.

against *R. ferrugineus* (Table 12.1). Among them, neonicotinoids (e.g. imidacloprid and thiamethoxam) constitute one of the most effective insecticidal groups. Nevertheless, the use of these products is under severe scrutiny because of their effects on pollinators and other non-target species (EFSA PPR Panel 2013; van der Sluijs *et al.* 2013). At present, their use in palms has several restrictions (Table 12.1), including removal of the male inflorescences of treated palms. Laboratory and glasshouse experiments have demonstrated the high toxicity of imidacloprid against different stages of *R. ferrugineus* (El-Sebay 2004; Soroker *et al.* 2005; Kaakeh 2006; Llácer, Negre, and Jacas 2012; Dembilio *et al.* 2014). Moreover, application of imidacloprid through drip irrigation was successful in date palm plantations (Soroker *et al.* 2005) and a palm nursery (Dembilio *et al.* 2010a). In a field assay, two soil applications of this pesticide (Confidor® 240 OD, 2.4 g a.s. per palm) per year successfully reduced mortality of 6- to 7-year-old *P. canariensis* palms to less than 27%, compared to more than 84% for untreated control (Dembilio *et al.* 2010b). This product can be applied as a foliar spray, a drench (usually only in nurseries), or by injection into the stem (Table 12.1).

Stem injection is an interesting application method used against *R. ferrugineus* (Hernández-Marante *et al.* 2003). Experiments carried out by El-Sebay and Abbas (2008) revealed that low-pressure injection is effective and safer for palms than high-pressure injection. A mixture of abamectin and neem oil was tested in ornamental Canary palms by drilling the palm stipe and injecting at 1.5 atmospheres (Polizzi *et al.* 2009). In Egypt, El-Sebay (2003) used this method to test 15 insecticides against the weevil in date palm. During the EU Palm Protect project, low-pressure injection systems and specific stem-injection formulations have been developed to reduce palm injuries during injection (Fig. 12.4), and increase uptake and enhance movement of the active substance in the palms. Owing to the vigorous debate on the pros and cons of the application of this technology to palms (Speranza 2008), we studied the efficacy of two insecticides, abamectin (Vertimec® 1.8 EC, Syngenta, 80 ml per palm) and imidacloprid (Confidor® 20 LS, 10 ml per palm), using different application methods, including stem and frond injection and crown spray, in *P. canariensis* (Dembilio *et al.* 2014). Stipe injection of imidacloprid resulted in better distribution within the palm and higher persistence, especially as compared to crown spray. Once injected, abamectin moved

Figure 12.4 New injection device developed during the Palm Protect project.

and accumulated in the fronds to concentrations that were expected to cause 50–90% mortality in young instars and below 50% mortality in older ones in the crown for 1 month after treatment. In contrast, upon injection, imidacloprid remained in the stipe, where concentrations resulted in more than 90% mortality in young instars and 50–90% in older ones for more than 2 months after the treatment (Dembilio *et al.* 2014). As a consequence, better performance of imidacloprid relative to abamectin against *R. ferrugineus* under field conditions was observed. These studies also demonstrated that the injection area using the new prototype developed during Palm Protect heals and looks compact and healthy 24 months after injection (Dembilio *et al.* 2014).

Recent strategies aimed at identifying compounds for the replacement of classical neurotoxic pesticides have focused on exploiting naturally occurring toxins such as arthropod-derived hormones and venoms, and EPF-derived insecticidal compounds (Quesada-Moraga, Ruiz-García, and Santiago-Álvarez 2006; Ortiz-Urquiza *et al.* 2009; Ortiz-Urquiza *et al.* 2010; Mazet, Huang, and Boucias 1994; Fitches *et al.* 2010; Quesada-Moraga and Vey 2004). These molecules are typically proteins or peptides showing specific antibiotic or insecticidal activities against invertebrates, and as such are ideal candidates for the development of new insecticides with improved target specificity, and therefore reduced environmental impact compared to conventional neurotoxic insecticides. In a prospective complementary direction, it would also be possible to target the weevil by disrupting its endosymbiotic bacteria, which contribute to its fitness and developmental success (Login *et al.* 2011). Because this approach has not been evaluated against *R. ferrugineus* or *P. archon*, further research is needed.

12.2.5 Control Methods Based on the use of Semiochemicals

Semiochemicals, which are often the main cues that trigger insect behavior, play a well-known role as specific and environmentally compatible tools in pest management. First of all, they are used to monitor pest populations, to adjust management practices for changes in density and distribution pattern. Second, semiochemicals can be used directly for control, in various ways: either for mating disruption or combined with insecticide and/or traps. The commonly known methods are: mass trapping, lure-and-kill, lure-and-infect, and push-pull. The latter combines both attractants, such as pheromones and host attractants/repellents, which orient the target insects away from the host toward the control agents, either biological or conventional (Ridgway, Silverstein, and Inscoe 1991; Bjostad, Hibbard, and Cranshaw 1993; Oehlschlager *et al.* 2002; El-Sayed *et al.* 2006; Oehlschlager 2006; Cook, Khan, and Pickett 2007; Witzgall, Kirsch, and Cork 2010). Although these concepts are not new, positive results and worldwide application are not yet the rule. This is due to the complexity of developing strategies that are economically profitable only in the mid- to long term, and basically depend on many biological and technical parameters pertaining to the target pests, semiochemicals, traps, and insecticide/biocontrol agents. Overall, biological information indicates the suitability of mass trapping for beetles as their intraspecific communication is mostly based on aggregation pheromones (El-Sayed *et al.* 2006). In contrast, mating disruption cannot be employed, as no sex pheromone that is attractive in the long range is involved in *R. ferrugineus*.

In *R. ferrugineus*, a mixture of 4-methyl-5-nonanol (ferrugineol) and 4-methyl-5-nonanone (ferrugineone) has been described as the aggregation pheromone (Hallett *et al.* 1993). Currently, these compounds are used in monitoring and mass-trapping traps combined with natural sources of kairomones (molasses, dates, or palm stems) to improve attraction. Ethyl acetate, as a component of the natural kairomones, has been used to improve the attraction for palm weevils such as *Rhynchophorus palmarum* (Jaffé *et al.* 1993) and *R. ferrugineus* (El-Sebay 2003). However, the previously published efficacy of ethyl acetate for *R. ferrugineus* has been called into question. Indeed, field trials carried out in Spain found that the release of ethyl acetate in a range of 450–2200 mg/day does not significantly increase the attraction to traps baited with ferrugineol only (Vacas, Primo, and Navarro-Llopis 2013). Guarino *et al.* (2011) showed that mixed ethyl acetate and ethyl propionate enhance capture in traps baited with molasses and the aggregation pheromone relative to one or the other "palm ester" alone. More than 100 volatile compounds were further identified from freshly cut leaves, palm stem, and fermented palm stem tissues (Vacas *et al.* 2014). Several of those compounds, including the esters evaluated by Guarino *et al.* (2011), showed high electroantennogram activity in *R. ferrugineus* (i.e. they were detected by the insect and likely to affect its behavior). Various mixtures of these compounds were assessed for efficacy in field trials but only a blend of ethyl acetate and ethanol proved to significantly enhance attraction to the pheromone (Vacas *et al.* 2014). This blend (*ca.*100 mg/day) enabled as many captures as a source of natural kairomone (molasses + palm pieces) in a ratio of 1:3, but not 3:1. Thus, additional assays are needed to improve the current synthetic kairomone, possibly with the addition of other components, and to finalize a substitute for plant tissues that will decisively improve trapping and thus monitoring/control efficiency.

Mass trapping of adult *R. ferrugineus* with food-baited and later with pheromone/food-baited traps has been recommended as a component of the *R. ferrugineus* IPM program since 1975. Some success with this approach, enforced by female-biased captures, has been reported in coconut and date palm plantations (India: Faleiro 2006; Israel: Soroker *et al.* 2005). Moreover, in Italy, mass trapping used within IPM strategies against *R. ferrugineus* in urban areas has shown positive results (Lo Bue *et al.* 2009; Nardi *et al.* 2011).

Various trap densities for mass trapping have been suggested (El-Sebay 2004; Faleiro 2006). While implementing traps is labor-intensive and often suboptimal, there is some concern about endangering palms by inappropriate trap setting, excessive trap densities, or setting traps too close to the palms (Rochat *et al.* 2006). Moreover, as in the case of monitoring, the density and distribution of traps are largely pragmatic and limited by economic constraints rather than based on scientific data.

Improvement of trap design is necessary to increase the efficiency of mass-trapping and monitoring techniques. Dark-colored traps seem to be most attractive to *R. ferrugineus* (Hallett, Oehlschlager, and Borden 1999) and new designs have been recently developed (Alfaro *et al.* 2011). An efficacy assessment demonstrated that a black pyramidal trap catches significantly more weevils than the traditional white bucket trap (Vacas, Primo, and Navarro-Llopis 2013). Additional improvements are necessary to increase the ratio of weevils caught vs. weevils attracted, thereby avoiding the infestation of healthy palms adjacent to the traps by weevils that have been attracted over long distances. Studies on the requirement of moisture inside the trap, pheromone-release rate, new synthetic kairomones, and exposure of traps to sunlight have been carried out during the EU Palm Protect project. Results demonstrated that traps located in the shade catch significantly more weevils than those in the sunlight, probably due to the negative phototropic behavior of weevils or the mild temperatures in shady places. Another conclusion was that traps with water capture three times more weevils than dry traps (Vacas, Primo, and Navarro-Llopis 2013). This result suggests the convenience of using water in traps, although servicing is more expensive. An important factor for trapping efficacy is the pheromone release rate. Results obtained from the EU Palm Protect project showed that release rates over 5 mg of ferrugineol per day do not result in higher weevil captures. Therefore, optimization of pheromone dispensers to achieve this release rate can reduce mass-trapping costs. Finally, as mentioned above, the use of kairomone can increase trap efficacy. We should take into account that a percentage of the weevils attracted from long distances by ferrugineol are not effectively captured in the traps. The addition of a kairomone might increase the ratio of captured weevils to those that are merely attracted, thereby reducing the number of weevils that are attracted but do not fall into the traps and are free to attack neighboring palms. Although ethyl acetate does not significantly improve attraction of only pheromone in pyramidal traps, field trials carried out in the EU Palm Protect project in Egypt, France, Greece, Italy, Israel, and Spain have demonstrated a broad variety of ecological situations in which the use of a synthetic kairomone composed of ethanol + ethyl acetate in a 3:1 proportion significantly enhances trap catches, as reported by Vacas *et al.* (2014).

Another control method based on the use of semiochemicals developed during the EU Palm Protect project is the attract-and-infect technique. In this method, weevils are attracted to a trap that contains an infective agent. The weevils that fall into the trap escape through an infective tunnel and are contaminated. When the weevils leave the infective device, they carry the spores and transmit the pathogen to other individuals during mating or just through contact. In the EU Palm Protect project, a strain of *B. bassiana* isolated from an infected pupa in Spain (accession no. CECT-20752) (Dembilio *et al.* 2010a) was used for the infective device. An oil formulation with conidia of this strain was applied in the tunnel that connects the entrance of the trap to the exit. Field and semi-field trials conducted with these devices demonstrated that more than 90% of the weevils that went through the tunnel became infested and died in less than 15 days. In addition, infection transmission was detected in more than 40% of the weevils that mated with the infested weevils that had gone through the infective tunnel. Finally, a field trial demonstrated a significant reduction in the number of weevils reaching the center of a 1 ha plot by placing four traps in the corners of this square plot. Moreover, damage in the palms placed in the center of each plot was significantly reduced relative to control plots (58% attack reduction). The conclusion from these experiments was that the attract-and-infect strategy is a potential tool for reducing *R. ferrugineus* populations.

Methods combining mass trapping and chemical or biological control have offered promising results in *R. ferrugineus* management (Benvenuti, Barzanti, and Roversi 2013). Sewify, Belal, and Qaed (2014) demonstrated that combining mass trapping using 1.5 traps per hectare and insecticide treatments significantly decreased populations of *R. ferrugineus* compared to untreated controls, and their numbers were half those observed in mass trapping or insecticide treatments alone. In the same work, the percentage of affected palms was reduced from 3.73% in control plots to 2.03 and 2.05% in mass trapping and insecticide treatments respectively, and to 0.77 and 0.82% when mass trapping was combined with EPF or chemical application, respectively. A combination of mass trapping and insecticide treatments reduced populations in Israel, where *R. ferrugineus* was suppressed in 3 years (Soroker *et al.* 2005), and it has proven to be a valuable method for *R. ferrugineus* control in the United Arab Emirates (Faleiro 2006). Other authors (Muralidharan, Vaghasia, and Sodagar 1999; Oehlschlager 2006) have suggested a 70–80% reduction of the population using mass trapping at a density of only 1 to 3 traps per hectare. However, this reduction was not obtained in field trials carried out in Spain, even when the density was increased to five traps per hectare. In the case of *P. archon*, there is limited published information on the use of semiochemicals for its management (Delle-Vedove *et al.* 2012; Sarto i Monteys *et al.* 2012; Frérot *et al.* 2013; Riolo *et al.* 2014; Ruschioni *et al.* 2015). In particular, none of the putatively reported chemicals, such as sex pheromone, has shown the potential for long-range attraction. Further research is therefore urgently needed to develop management approaches based on their use.

12.3 Future Needs and Trends

Many scientific documents covering different perspectives of *R. ferrugineus* and *P. archon* bio-ecology and control have been recently published. Further research, carried out in part within the framework of the Palm Protect project, has provided important tools to improve the management of these pests. The following areas have been studied:

- *Plant quarantine*. Assays performed during Palm Protect with aluminum phosphide (Dembilio and Jaques in press) successfully eliminated all developmental stages of *R. ferrugineus* from infested palms with no phytotoxic effects up to 1 year post-treatment. These results may pave the way for a quarantine treatment against palm borers, which would greatly reduce the enormous risks that palm movements currently pose worldwide.
- *Chemical control*. The application of chemicals against *R. ferrugineus* and *P. archon* is difficult because of the concealed nature of their larvae (Dembilio and Jacas 2011). Frequent pesticide applications do not usually reach *P. archon* larvae or cocoons (Sarto i Monteys and Aguilar 2005; Nardi *et al.* 2009). Although there are highly effective pesticides available for *R. ferrugineus* control (Table 12.1), there are many problems related to both product delivery to the target and the eco-toxicological profile of these biocides. New environmentally friendly products are urgently needed (such as those derived from fungal secondary metabolites), and more refined application methods (e.g. improved stipe injection) (Dembilio *et al.* 2014) may definitively improve the safety of this type of control.
- *Biological control*. Although many different strains of EPF affecting *R. ferrugineus* and *P. archon* have been identified during Palm Protect, knowledge of the natural enemies of these two pests in their native habitats is still incomplete. These EPF could be combined with other natural enemies, such as EPN (Llácer, Martinez, and Jacas 2009, Dembilio *et al.* 2010a, Nardi *et al.* 2009, 2011) and especially semiochemicals in traps developed to attract and infect *R. ferrugineus* adults that will go on to spread the disease within their populations (Llácer, Santiago-Álvarez, and Jacas 2013).
- *Semiochemicals and mass trapping*. IPM programs are moving more toward the use of semiochemicals, which may partially replace insecticides (mass trapping). Improved blends of attractants for *R. ferrugineus* have been developed during Palm Protect and they will no doubt enhance the efficiency of mass trapping and allow the implementation of attract-and-kill and attract-and-infect strategies using new biocides and EPF. For the moment, no traps or semiochemicals are available for *P. archon*, as it behaves like a butterfly rather than a moth (Sarto i Monteys *et al.* 2012; Riolo *et al.* 2014). This implies that sex recognition has a strong visual stimulus component (Sarto i Monteys *et al.* 2012; Frérot *et al.* 2013; Riolo *et al.* 2014). Visual and plant volatile cues can probably be exploited for detection and/or monitoring purposes (Ruschioni *et al.* 2015).

- *Resistance and induced plant defenses.* Although both antibiotic and antixenotic mechanisms of plant defense have been observed for *R. ferrugineus* (Barranco *et al.* 2000; Dembilio, Jacas, and Llácer 2009) and *P. archon* (André and Tixier-Malicorne 2013) in different palm species, the possible exploitation of these mechanisms under real field conditions warrants further attention for its potential usefulness in the future.

Although further research is still needed to clarify the basis of some of the control methods, knowledge generated within the framework of the Palm Protect project may be key to finding more sustainable ways of protecting our palms and continuing to enjoy our agricultural, natural, and cultural palm heritage.

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13

Action Programs for *Rhynchophorus ferrugineus* and *Paysandisia archon*

Pompeo Suma[1], Ezio Peri[2], Alessandra La Pergola[1], Victoria Soroker[3], Oscar Dembilio[4], Paola Riolo[5] and Sandro Nardi[6]

[1] Department of Agriculture, Food and Environment, Applied Entomology Section, University of Catania, Italy
[2] Department of Agricultural and Forest Sciences, University of Palermo, Italy
[3] Department of Entomology, Agricultural Research Organization, The Volcani Center, Rishon LeZion, Israel
[4] Universitat Jaume I, Department of Agricultural and Environmental Sciences, Campus del Riu Sec, Spain
[5] Department of Agricultural, Food and Environmental Sciences, Marche Polytechnic University, Italy
[6] Servizio Fitosanitario Regionale, Agenzia Servizi Settore Agroalimentare delle Marche, Italy

13.1 Introduction

Invasive alien species (IAS) present a growing environmental and economic threat worldwide. An IAS is any kind of living organism that is not native to an ecosystem but can change important ecosystem characteristics, resulting in harm to the environment, the economy, or human health (Ehrenfeld 2010). They can be members of any taxonomic group (i.e. animals, plants, fungi, or microorganisms). In 2001, Pimentel *et al.* estimated that as many as 480,000 IAS had been introduced worldwide. At the global level, IAS are considered to be the second greatest cause of species extinction after habitat deterioration (CBD 2005; Essel *et al.* 2011). Their impact is particularly large in evolutionarily isolated ecosystems (e.g. islands). The challenges from alien pest species have become more significant as natural bio-geographic borders, such as mountains and oceans, which previously inhibited spread, have been overcome by the desire for increased international travel and trade, aggravated by modern modes of transportation, and resulting in the increased probability of biological invasions. With the rise in international travel, the movement of exotic species and incidences of invasions have increased in both number and variety.

In Europe, quarantine measures adopted by legislative authorities are not always sufficient as they fail to prevent the accidental introduction of IAS. As a consequence, the number of invasions as well as the scale of the IAS' impact are very high for several countries, as reported by Hulme *et al.* (2009); those authors showed that approximately 10 new species become established each year, with a rising trend for invertebrate introductions, as reported by Williams *et al*. (2010). Among non-native terrestrial invertebrates, insects are the dominant group in Europe, representing 86% of the 1522 established species (Roques *et al.* 2009). This proportion is not unexpected, considering that 85% of the world's known invertebrates are insects (Keller *et al.* 2011). In Italy, for example, more than 500 alien insect species have been reported,

Handbook of Major Palm Pests: Biology and Management, First Edition.
Edited by Victoria Soroker and Stefano Colazza.

with the accession rate during a 60-year period increasing from approximately 0.5 species/year in the 1950s to more than seven species/year in the last two decades (Barbagallo *et al.* 2008). Effective management of IAS is particularly challenging because of the limited financial resources allocated to combating the initial invasion, while efficient management of established organisms is very difficult. Following their introduction, and considering that eradication is more likely to succeed in man-made habitats than in natural ones (Pluess *et al.* 2012), biological and integrated management methods, whenever applicable, are recommended. However, to cope with an immediate direct threat from an invasive alien insect pest on plants, the use of synthetic agrochemicals is often compulsory, despite possible negative ecological and toxicological effects.

This chapter provides a general overview of the problems, from prevention to control, posed by the two invasive palm pests *Rhynchophorus ferrugineus* (red palm weevil, RPW) and *Paysandisia archon* (palm borer moth, PBM). In particular, an integrated action plan aimed at coordinating containment, control, and management activities is provided, based on scientific and socio-economic information.

13.2 General Measures against all IAS

Although 12,000 IAS are known in the environment of the European Union and in other European countries, approximately 10–15% have become established and spread, causing environmental, economic, or social damage resulting in a significant impact on biodiversity. The remaining alien species have not caused problems in the invaded areas to date (DAISIE project 2008; Kettunen *et al.* 2008; EU Reg. no. 1143/2014). The main legislative framework for the plant health regime in the EU is Council Directive 2000/29/EC (May 8, 2000), which provides the basis for preventing the introduction of harmful plant pests into the EU, or their spread within the EU, with the aim of contributing to the protection of public and private green spaces, forests, and natural landscapes, as well as to food security.

From an analysis of the various regulations and directives promulgated, at least at a European level, in recent years, there appears to be no existing unified framework for tackling all IAS in a comprehensive manner. Often, actions are undertaken only at a national level, resulting in inadequate efforts to counteract the introduction, establishment, and spread of IAS within the EU. In addition, little international coordination and great variability in the countermeasures adopted by countries to prevent IAS spread within the EU (Keller and Perrings 2011) end up promoting pest spread, showing that unilateral action cannot prevent the pest from continuously spreading (e.g. through trade) (Touza and Perrings 2011). Improved coordination of efforts at the international level represents a key factor in the success of strategies against IAS. In this context, EU Regulation no. 1143/2014 of the European Parliament and of the Council, published on October 22, 2014, supports achievement of the objectives of previous directives (e.g. 2000/60/EC, 2008/56/EC and 2009/147/EC) of the European Parliament and of the Council, and of Council Directive 92/43/EEC setting out rules to "prevent, minimise and mitigate the adverse effects of invasive IAS on biodiversity and related ecosystem services, and on human health and safety as well as to reduce their social and economic impact within the Union." Three distinct types of measures are considered in the Regulation: (1) prevention, comprising all measures foreseen to prevent the entry of new IAS into the EU, (2) early warning and rapid response (i.e. the adoption in each Member State of an early warning system to detect the presence of IAS, and to take, as early as possible, rapid measures to prevent their establishment), and (3) management of already well-established IAS that includes the actions needed to manage the IAS in the EU territory, to prevent their further spread and to minimize the harm they cause.

13.3 Threats and Risks presented by IAS: The case of RPW and PBM

The harmful impact of IAS on the natural environment, biodiversity, and ecosystem services may have direct and indirect adverse effects on human well-being. In the case of both the RPW and PBM, the detrimental effects of their infestations on economies, societies, and ecosystems are widely known (see Chapter 3, this volume). They have caused direct losses of millions of euros (i.e. costs of containment and control as well as annual losses in production and market access), in addition to the indirect costs of environmental damage, trade disruption, and disease risk (Pimentel *et al.* 2000; Lodge *et al.* 2006). For example, the threatening effects of the recent invasion of RPW on date fruit production, which has provided a staple carbohydrate food for many people for nearly 5000 years (Purseglove 1972; Jones 1995), have included an estimated yield decrease from 10 t to 0.7 t/ha (Gush 1997). To date, the adoption of several traditional farming practices (e.g. flooding rather than drip irrigation and the removal of leaves during harvesting or pruning of offshoots) further promotes RPW infestation in date plantations (Aldryhim and Khalil 2003).

In European countries, where the most susceptible palm species to RPW infestation is the Canary palm (*Phoenix canariensis* Hort. ex Chabaud), the major economic impact of the pest is damage to and death of these palms which represent an important aesthetic component of the local landscape. In fact, Canary palms are extensively planted in private, public, and historical gardens, main squares, and promenades, often enhancing the facades of important historical monuments, as also shown by ancient paintings and illustrations. In addition, severe damage and plant mortality due to PBM infestation have been reported in Italy, France, and Spain (Aguilar, Miller, and Sarto i Monteys 2001; Drescher and Dufay 2001; Sarto i Monteys and Aguilar 2005; Riolo *et al*. 2004), wherein some nurseries' damage led to a 90% loss of palm production (Riolo, Isidoro, and Nardi 2005). In fact, the palm nursery industry has been seriously negatively impacted by both borers. Native palm species such as *P. canariensis* in the Canary Islands and *Chamaerops humilis* L., and to some extent *Phoenix theophrasti* Greuter in the Mediterranean and associated ecosystems, are being damaged and endangered.

Troubling is the presence of unidentified heavily infested palms in urban areas, a public danger due to the possible sudden collapse of large palms. Such an incident was documented in southern Italy in October 2014, when a large date palm, planted in a public garden, suddenly collapsed due to RPW infestation, killing a young woman seated on a bench just below the tree (Suma, personal communication); before that, two other cases of casualties from falling palms had been reported, one in the Canary Islands and one in India.

13.4 The Action Plan as Part of a Global Strategy for the Containment of RPW and PBM Infestations

The development of an action plan usually starts with the identification of the key pathways through which an IAS enters and spreads through a country; the subsequent construction of a clear picture provides opportunities for immediate and longer-term effective actions to minimize and ideally eliminate both the introduction of new IAS and the spread and impact of those already present in a country. Bacon, Bacher, and Aebi (2012) indicated that the high levels of insect invasions in Europe are significantly correlated with the gaps between the trade pathways that should be inspected and the actual number of interceptions. These gaps in border control can be explained by the massive volumes of goods traded and the difficulty in physically inspecting commodities within the available timeframe. As a result, relatively few insect interceptions have been reported, taking into account global trade volumes, even when the most likely introduction pathways are targeted for inspection checks. The identification of an optimal inspection strategy based on the underlying risks of trade could lead authorities to implement, globally, more effective and consistent border controls (Bacon, Bacher, and Aebi 2012). In the case of both palm pests, RPW and PBM, the key pathways through which they entered into the EU are now well defined (see Chapters 4 and 6, this volume), and these achievements have been recently used in the revision and upgrading of the Community legislation (regulation (EU) no. 1143/2014 of the European Parliament and of the Council).

An action plan requires a long-term approach that considers the relationship between a healthy environment and a sustainable economy, and it should therefore be based on specific principles: (1) a strategy has to be developed that works within existing domestic and international legislation and agreements; (2) it has to be implemented in a cooperative manner with all relevant governmental authorities, industry, and other stakeholders locally and internationally; and (3) development of a control strategy has to be science-based, utilizing the best available knowledge and considering as many factors as possible (environmental, social, economic, cultural, and human health) to recognize regional interests and priorities. The suggested steps to follow in the management of both RPW and PBM are presented in Fig. 13.1.

13.5 Analysis of Pest Status and Distribution of RPW and PBM as a Strategy for Detecting Change and Emerging Impacts

The present distribution of RPW and PBM is reported in Chapters 4 and 6, this volume. Comparing such information with the distribution of their main host plants, and analyzing the geographic areas in terms of advantageous climatic conditions for the pests, it is possible to anticipate where the pests could still spread and where impacts might be expected (Baker *et al.* 2000). Such a comparison fits into the process of pest risk analysis (MacLeod 2015) and this approach can also identify where current control methods might need to be strengthened. Then, factors such as the degree of potential damage to the ecosystem, the value of potential harm caused to the economy, and the costs of control measures could be used as criteria for assessing and prioritizing the allocation of resources to inhibit pest spread and impacts. In fact, for both pest species, the problem is

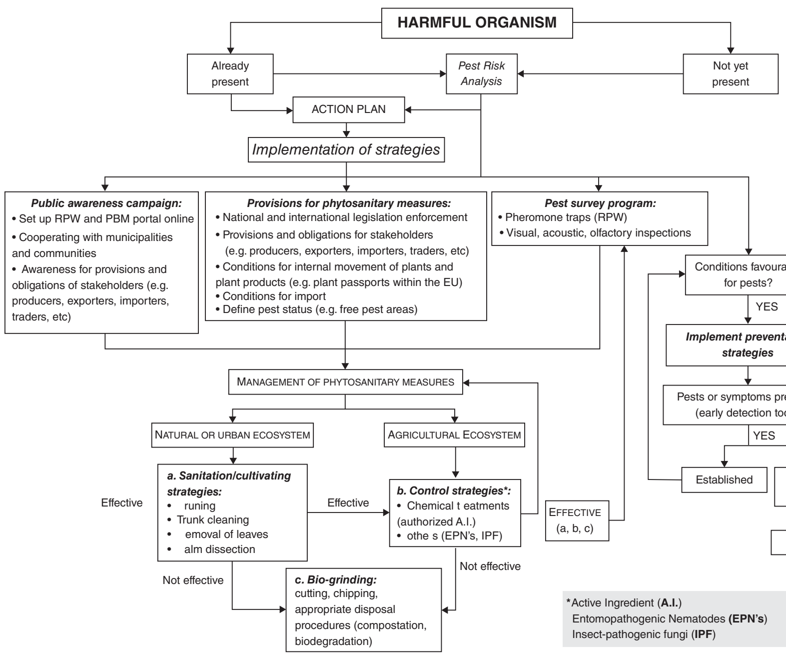

Figure 13.1 Flow chart of measures to be taken against both the RPW and the PBM.

not only of significant economic importance for date-producing farmers (e.g. countries in the Middle East and North Africa) and nurseries (El-Juhany 2010) but also with a relevant social aspect, as the palm tree is known to have been significant in the cultures of several religions, including Christianity, Islam, and Judaism, since antiquity. Ornamental resources are often severely threatened, with a devastating impact in places of special importance (e.g. Palmeral of Elche in Spain, recognized by the UNESCO as a World Heritage Centre in 2000) (see Chapter 3, this volume). The increase in the populations of these pests has changed the landscape aspect of the Mediterranean area, because in destroying the palms they are affecting the dominant plant species in these landscapes (André and Tixier-Malicorne 2013).

13.6 Establishing Effective Systems to Assess Risk and Prioritize Management

Prevention is the most cost-effective way of dealing with any potential threats. In the case of RPW and PBM, the most efficient control measure is elimination of the infested plants. This should be done as quickly as possible in a way that ensures destruction of all pests and their developmental stages. Elimination by shredding is the preferred method as it guarantees the destruction of any part of the plant on which even the smallest larvae could complete their cycle. If it is not feasible to destroy the entire palm, the infested part should be cut and shredded and, to limit pest attraction to and oviposition in the cut, the remaining stems should be thoroughly treated and painted with pruning paint, with or without insecticide.

In several countries (e.g. France and Italy), Canary palm trees attacked by RPW have been replaced by other palm species that are considered less attractive to this pest. However, this cannot be considered a complete solution. In fact, according to the definition of host-range expansion (Agosta 2006), whereby a population colonizes a new host plant but continues to use previous host plants, the pest could adapt to the less attractive palm species when the preferred ones are no longer available or are limited. A crucial point in the prevention of RPW and PBM spread is the quarantine procedures, which should be well defined at national and international levels. In general, mass quarantine can inflict significant social, environmental, and economic costs with no guarantee of its efficacy in solving the problem. Hence, to justify the adoption of plant quarantine restrictions, some specific principles are essential. First, the quarantine should represent a measure for which there is no other substitute that involves less interference with normal activities, and its application must be reasonable of expectation; second, it should be based solely on biological grounds and should not be adopted as a means of limiting trade for economic reasons, placing no more restrictions on normal trade than is necessary to afford the needed protection. Lastly, quarantine restrictions should be kept under continuous review and should be modified promptly when necessary (FAO 2006). Quarantine measures taken against a new alien pest in a new country are strongly influenced by knowledge about its bio-ethology. However, despite the large amount of literature on the behavior of a specific pest in its area of origin, in the new environment, an IAS can meet a new host that can allow it to express its full fitness potential and, consequently, accelerate its spread, as in the cases between RPW and *P. canariensis* and PBM and *C. humilis*. Two biological parameters in particular should be taken into account to evaluate the approach to the new invasion of a pest: its biotic potential (i.e. the maximum reproductive capacity of a population under optimum environmental conditions) and its ability to disperse (e.g. by flying). In the case of the RPW, both parameters are promotive of its spread in new environments. *R. ferrugineus* was declared a quarantine pest, but its flight potential was difficult to assess in the field. Today, it is clear that its displacement capacity is beyond 10 km (see Chapter 4, this volume). Knowledge of its flight potential is important for improving the preventive and more efficient quarantine measures to manage a pest. Moreover, today, with this information, it is possible to better forecast the dispersal of RPW, and to define a safety perimeter that must be applied in a new area that has just been invaded by the insect, thereby avoiding or limiting the dispersion capacity of the pest.

13.7 Definition of an Early Warning and Monitoring System

The development of an effective global warning system is crucial for mitigating the impacts of biological invasions (Wittenberg and Cock 2001). Such a system must be designed to provide information that is as up-to-date as possible on the spread of pests within countries in order to warn neighboring countries and identify emerging threats at an early stage. In this way, it would be possible to determine where targeted monitoring efforts should focus a particular pest, and better define impacts of measures taken to prevent or contain the pest. This system would have to include several components: surveillance and monitoring functions; risk-assessment modules, such as CPLAS (see Chapter 11, this volume); supported communication between the relevant authorities, procedures and resources for eradication; and, finally, a pest-management component to support the selection of pest-management strategies.

In 2003, the Council of Europe adopted the European Strategy on IAS with the aim of organizing the establishment of effective systems to share IAS information between neighboring countries, trading partners, and regions with similar ecosystems to facilitate the identification, early warning and coordination of prevention, mitigation and restoration measures (Genovesi and Shine 2004). For the successful management of IAS as it is underlined in the Commission's Communication, there is an urgent need for the Commission and the Member States to develop an appropriate early warning and information system ("Towards an EU Strategy on Invasive Species"; COM (2008) 789 final). Although EU regulations include an obligation to report new findings of IAS and to rapidly perform appropriate eradication or containment measures, most sectors lack such provisions.

13.8 Citizen Involvement in Undertaking Voluntary Measures to Counteract the Spread of RPW and PBM

The establishment of extensive communication and publicity efforts coupled with official surveys for the presence of RPW and PBM represents another important aspect to be considered. The engagement of citizens in volunteer actions can increase general awareness of the problem, improving early detection and also restricting pest spread. In this view, a large-scale mass-trapping experiment was performed in the city of Palermo (Italy), within a 2-year project funded by the Sicily region (2009, 2010).

After involving public administrations and citizens via an advertising campaign about the risks resulting from weevil infestation, an action called “Adopt a trap” was applied in which 500 pheromone- and kairomone-baited traps were distributed in public and private gardens from May to September 2009. In total, these traps caught about 140,000 adult RPW (Peri *et al.* 2013).

13.9 Setup of an RPW and PBM Portal Online

The availability of web-based information-gathering systems allows information supplied by citizens, authorities, etc., concerning sightings of both pests and their natural phenomena to be collected in one location, making as much information as possible available to support decision-making and representing an intermediate step in any decision-making process. The information-gathering system could be a portal that provides a notification and reporting tool linked to dedicated websites managed by other organizations, so that all observations by people and bodies representing different interests and areas of activity can be gathered together in a user-friendly manner. The Secretariat of the European and Mediterranean Plant Protection Organization (EPPO) developed the EPPO Global Database (EPPO 2015), which was intended, over time, to house all of the information on plant pests relevant to the EPPO. The information includes all data related to distribution, host species, and pest categorization, as well as articles from the monthly news summary EPPO Reporting Service, pictures, and other associated documents. Information on PBM and RPW is available at https://gd.eppo.int/taxon/PAYSAR and at https://gd.eppo.int/taxon/RHYCFE, respectively. Other valuable tools, available online, are the “global portal for the red palm weevil” (www.redpalmweevil.com), which is rich in content and information related to the weevil, and a more generalist website, the DAISIE database, which provides information on biological invasions in Europe (http://www.europe-aliens.org/default.do).

13.10 Development of Funding Mechanisms to Manage RPW and PBM Infestations

One of the main aspects in the management of RPW and PBM infestations is the availability of sufficient resources to prevent the entry of these pests, and other IAS, and to manage those outbreaks that are already present. Unfortunately, there was a very low level of interest when RPW was first reported to be spreading internationally from its endemic area. Thus, its further spread was not prevented and the pest moved rapidly in several countries. Indeed, in most of the European countries where the weevil initially appeared (i.e. Spain and Italy), there was a delay between awareness of the pest’s incursion and the first available funds for control and research purposes. In the meantime, the weevil continued to spread freely all over the country. For example, in Italy, the first project proposals submitted to local entities with the aim of deeply investigating the bio-ecological traits of the “new” pest were judged too costly for the presumed threat associated with “a small insect.” By contrast, today, after gaining awareness of the danger of this pest, many hundreds of thousands of euros have been invested in repairing the problem but with very few successes, emphasizing that prevention is undoubtedly the most cost-effective way of dealing with this kind of potential threat.

13.11 Case Studies

13.11.1 *R. ferrugineus* in Israel

The weevil invasion in Israel dates back to 1999 (Soroker *et al.* 2005), following the occurrence of RPW and its spread in neighboring countries. In Israel, as in many other Mediterranean countries, palms are very popular as ornamental trees. The main ornamental palm species are *Phoenix dactylifera*, *P. canariensis*, *Washingtonia robusta*, and *Syagrus romanzoffiana*, in addition a diversity of palm species are grown. Palms are also intensively propagated for both local markets and export to European countries. However, the most significant palm species in Israel is the date palm *P. dactylifera*, one of the most economically valuable crops for both local date consumption and export. The date palms are generally vegetatively propagated, mostly by offshoots. In addition, date palms are common in desert oases and ancient farms throughout the country, as "wild" or "feral." First detection of RPW occurred via surveillance traps. These traps were buckets baited with an aggregation pheromone and plant kairomone mixture (Soroker *et al.* 2005). Shortly after initial trapping of adults, an intensive integrated pest management (IPM) program was initiated and a contention strategy developed. Three governmental agricultural agencies joined forces to cope with the weevil threat: the Israeli Plant Protection and Inspection Services (PPIS), Agriculture Extension Services, and Agricultural Research Organization (ARO), along with the help of Peres Center for Peace that facilitated the collaboration with neighboring countries' authorities: Palestinian and Jordanian Plant Protection Inspection and Extension services. The infested area (approximately 1130 ha) was declared under quarantine with a strict restriction on the export of any palm material from it. A general management policy was developed, starting with the accurate monitoring and mass trapping of adult weevils using pheromone traps (Table 13.1) that were GIS-mapped and regularly (every 2 weeks) operated and inspected by PPIS. Date plantations were examined by experts for infestation symptoms such as drying offshoots, drying crowns, or oozing from the trunk. Assisted by monitoring traps, about 35 infested date palms were detected in 1999. Following chemical treatment by a variety of means, most palms were cured and survived. Only the heavily infested trees (about 10) were uprooted and burned. A prophylactic approach was taken in the entire infested agricultural area by means of three soil applications of an imidacloprid-based insecticide, while broad-spectrum organophosphate insecticides (azinphos-methyl, diazinon, chlorpyrifos) were sprayed, once a month, on the offshoots and palm trunks (Soroker *et al.* 2005). Moreover, to prevent RPW infestation following offshoot removal, the cutting wounds were treated as above. Over the next 3 years (1999–2001), approximately 60 moderately infested palms were found. Once identified, they were immediately treated by means of trunk infusion with organophosphate insecticides and/or soil application with imidacloprid-based insecticide. The trunks of

Table 13.1 RPW trap numbers and density during 1999–2012.

Year	Total number of traps	Trap density	Total monitored area
1999–2001	5000	1/ha–10/ha	(1800 ha)
2001–2008	~1250	1/3 ha–7/ha	(4100 ha)
2009–2012	1250–2500	1/50 ha–1/ha	>8000 ha

those trees were then wrapped in plastic nets to prevent possible escape of surviving adults. Quarantine was imposed on the area. This intensive approach proved successful between 2002 and 2009. No additional infested trees were detected and weevil catches by traps almost ceased. However, a continuous trickle of weevils in the monitoring traps and a sudden increase in weevil trapping in a residential area in the south of the country indicated that the RPW danger remains in the area.

In any case, the area of the former infestation remained under the quarantine regime and offshoots were not allowed to be transported out of it. However, large date palms not carrying offshoots were occasionally allowed to be sold for landscaping in the central part of the country following intensive chemical treatment and inspection.

In 2009, the status of RPW infestation changed with the report of a dead typical umbrella-shaped Canary palm in a private house in the city of Nahariya in the northwest of the country. Inspection of the surrounding area revealed several additional Canary palms showing different degrees of damage. PPIS set up surveillance traps in the area to determine the focal point of the infestation. As the traps were distributed and palms inspected visually, the infested area appeared to be extensive, suggesting that a weevil population had been established in the area for quite some time. The source of weevils in Nahariya is still unclear. Molecular analysis of the different weevil populations collected in Israel showed no clear differences (examined by Prof. Jean-Francois Silvain the Laboratoire Evolution, Genomes et Speciation in France), and thus a common origin cannot be refuted.

Whatever the source, the PPIS's attempts to eliminate the new RPW infestation in urban areas, using the chemical treatments that were so successful in the date plantations, failed. Most of the weevil infestation reported in the last few years has been in Canary palms in parks and gardens. However, other infested palm species (i.e. *P. dactylifera*, *Washingtonia* spp., *Syagrus*, and *Ravenea* spp.) have also been reported in private and public areas and, in the case of date palms, in date plantations. As time passes, the infestations are spreading to other regions of Israel.

A comparison of the different infestation phases is presented in Table 13.2. The main difference between the outcome of former infestations (in 1999 and 2004) and the current one (starting in 2009) seems to be mainly a result of timing, area of the outbreak, and management scheme. In 1999 and 2004, the outbreak was detected in its very early

Table 13.2 A comparison of weevil detection and management in 1999 and 2009 in Israel.

Parameters	1999	2009
Time of detection	Before establishment	After establishment
Infested area	Restricted to agricultural area	Diffused and spread mostly in parks and gardens
Hosts	Limited to *P. dactylifera*	Variable: *P. dactylifera*, *P. canariensis*, *Washingtonia*, *Syagrus*
Tree management	Commercial date plantations or hotels (2004)	Private or public management, many owners and managers
Pest management	Systematic and well organized, area-wide	Variable, not organized, local, and limited/no access to all infected trees
Palm irrigation	Systematic irrigation	Variable/no irrigation

stages, prior to the pest's establishment in the area. In contrast, in 2009, the pest was detected too late. Moreover, in 1999–2002, eradication was performed over a wide area in large orchards, managed by a few cooperative farmers, with tools for efficient treatments. Similarly, in 2004, cooperation of the municipality and hotels enabled the rapid treatment of thousands of trees (practically all of the palm trees in the municipality). The fact that in these cases the area surrounding the infested palms was mostly desert also contributed to the eradication success. In contrast, since 2009, infestation has occurred on numerous private properties, primarily on the very susceptible Canary palms, allowing rapid development of a high pest population. Many of the affected palms are not accessible to inspection or treatment. The municipalities do not usually take responsibility for organized treatments or elimination of infested trees, leaving dead palms behind for further proliferation of the pest. The same treatment that was so efficient in the case of date palms (i.e. chemical treatments with soil drench) does not seem to control RPW in Canary palms. One possible explanation is that the active ingredients are not transported efficiently to the palm crown, especially in the absence of a dedicated irrigation system. In Canary palms, the treatment has now shifted to crown applications. Although providing good results (see Chapter 12, this volume), these applications require special equipment that is not always available. Considering the thousands of palms cultivated in the infested area, efficient and rapid treatment of all suspected trees is very problematic to achieve, mainly due to a lack of compulsory regulations and full cooperation from local authorities, as well as economic issues.

13.11.2 *R. ferrugineus* in Italy

In October 2004, the first occurrence of RPW in Italy was reported in a nursery near Pistoia, Tuscany (Sacchetti *et al.* 2005). It remained confined there until 2005, when it was detected in southern Italy (Sicily) (Longo and Tamburino 2005), probably introduced through a shipment of palms imported from Egypt. From that point, RPW continued to spread fairly quickly into other Italian regions (EPPO Reporting Service 2006, 2007, 2008, 2010). Currently, infestations are recorded in almost all Italian regions where palms, especially Canary palms, are present. More recently, in Sicily, RPW infestation was recorded on other ornamental palms (Longo *et al.* 2011; Giovino *et al.* 2012; Raciti *et al.* 2013) as shown in Table 13.3.

The Regional Phytosanitary Services of the most interested regions started to adopt regional decrees (RD) for the control of RPW (e.g. Campania RD 31/1/2006 and 18/1/2008; Sicily RD 23/3/2007; Latium RD 5/6/2007), providing for management measures to be taken in infested areas, and including penalties for non-compliance. Measures were taken in Campania and Sicily before Commission Decision 2007/365/EC was issued, which was intended to prevent the introduction and spread of *R. ferrugineus* into and within the EU.

At the time of the insect's discovery, the Sicilian Plant Protection Services, in collaboration with the Section of Applied Entomology of the University of Catania, instituted a technical committee to combat the weevil's spread, through educational campaigns to raise awareness and explain the importance of adopting a timely and effective strategy. From the actuation of these directives in infested areas, all people (public functionary or private) who suspected or found a new RPW-infested palm had to notify the Regional Plant Protection Services to assess the most appropriate phytosanitary measures and inform the relevant municipal administration. The compulsory control measures were

Table 13.3 Different palm species infested by the RPW in Sicily (from Raciti *et al*. 2013; Longo *et al*. 2011).

Palm host species	RPW-infested palms (no.)
P. canariensis	19,722[a)]
P. dactylifera	25[b)]
Sabal spp.	20
Washingtonia spp.	16
Brahea spp.	6
C. humilis	5
Howea forsteriana	5
Jubaea chilensis	3
Butia capitata	1
Trachycarpus fortunei	1
Total	19,804

a) Data from Sicilian Regional Phytosanitary Service, 2012
b) Suma 2015, personal observation in Catania municipality

taken immediately, enabling the recognition of around 20,000 palms, mostly Canary palms, that were infested by RPW, in the period 2006–2011 in the entire region, of which 16,000 were cut and destroyed in the context of a specific program of the Sicilian region applied by the Forestry Department; however, the control measures were hindered by several factors (Table 13.4) and the pest continued to spread.

Five years after the first infestations, the Italian Phytosanitary Services reported approximately 40,000 infested palms (Griffo 2010), although the exact number still remains undefined. More recently, efforts against the RPW problem have decreased due to the initial poor results, although the situation is still serious, especially given that

Table 13.4 Main constraints to the efficacy of the control measures adopted in Italy at the beginning of RPW infestations.

Subject area	Constraint
Detection of infested trees (e.g. urban areas)	Diffuse distribution of susceptible hosts (i.e. over a wide area)
	Location of hosts and problems with access (e.g. in private gardens)
	Size of infested palms (i.e. very tall, difficult to inspect)
	Difficulty detecting early symptoms
Management of the infestations	Interventions could not all be implemented at the correct time due to the large number of infested palms
	Ineffective monitoring procedure due to cryptic insect behavior
	Difficulty in correct early detection (see above)
	Inability/reluctance of private owners to pay the costs for felling and destruction
Insecticide treatments	Lack of authorized treatments
Administrative elements	Delayed transposition of Commission Decision 2007/365/EC into domestic legislation

the insect has found new "alternative" hosts, such as *W. filifera*, adding to the difficulty of detecting infested palms.

Nevertheless, encouraging results were obtained when, immediately after the first outbreak of RPW in 2007 in the Marche region (central eastern Italy), Commission Decision 2007/365/EC was implemented in the regional legislation (DGR 1183/2007), prompting the application of official phytosanitary measures in a timely fashion (Table 13.5). Nardi *et al.* (2011) reported that in that region the spread of the RPW infestation could be limited by means of accurate monitoring activity, accurate regulation of the movement of susceptible plants, and the implementation of compulsory measures.

13.11.3 *R. ferrugineus* in the Canary Islands

In 2005, RPW was first detected in two resorts in the Canary Islands of Gran Canaria and Fuerteventura, Spain. As a consequence, in 2006, strict actions were established for the whole Autonomous Community of the Canary Islands to protect native forests of *P. canariensis* palms, including a rigorous eradication program and the prohibition on the importation of any palms from outside the Islands (BOC 2007). This Community had their own phytosanitary regulations, apart from those employed in the rest of Spain. Up until 2008, new foci appeared, including an outbreak on the previously non-infested island of Tenerife in 2007. However, no additional foci have been identified since 2008, and the islands of La Gomera, El Hierro, Lanzarote, and La Palma have remained pest-free. Until now, eradication has been successful only in the Canary Islands, with the first pest-free foci being declared in 2010 after almost 5 years of

Table 13.5 Phytosanitary emergency measures applied against the RPW invasion in the Marche region (Italy) (from Nardi *et al*. 2011).

Policy	Emergency measures
Regulation of import and internal movement of plants susceptible to the pest	Rapid implementation of measures in accordance with European Commission decision 2007/365/EC
Survey and monitoring	Periodic visual inspections and use of pheromone traps
Establishment of demarcated areas	Rapid identification of the boundaries of the infested zones (zone within a radius of 1 km around the infested palm) and buffer zones (zone with a boundary of 10 km beyond the boundary of the infested ones) according to the Italian Ministerial Decrees of 09/11/2007 and 07/02/2011
Implementation of "cut-and-destroy" measures	Compulsory cutting and destruction of infested palms via bio-grinding (grinding of infested plant material into 2–3 cm pieces with special equipment)
Implementation of sanitation measures	Mechanical sanitation (i.e. spherical pruning)
	Bio-grinding of the pruned plant material
	Washing of the crown with water at high pressure to remove specimens from galleries
	Insecticide treatments on the crown with entomopathogenic nematodes or other authorized products
Integrated approach	Spherical pruning plus treatment application (e.g. entomopathogenic nematodes, chlorpyrifos, deltamethrin, azadirachtin)

non-detection of infested palms and no collection of adults in pheromone-baited traps in the demarcated areas.

13.11.4 *P. archon* in the Marche Region (Italy)

In November 2002, *P. archon* was reported for the first time in Italy, when three adults were observed along the seafront of Salerno (Campania) (Espinosa, Di Muccio, and Russo 2003). In the fall of 2003, in the province of Ascoli Piceno (Marche region), workers in a palm nursery reported damage on palms due to 'big white' larvae. Investigations revealed the presence of *P. archon* in some nurseries of this province (Riolo *et al.* 2004). At the moment, *P. archon* is known to be present in both palm nurseries and the urban environment. The first introduction into the region was probably due to the importation of infested trees from both Argentina and Spain (Riolo *et al.* 2004). The moth has since spread fairly quickly through other Italian regions (see Chapter 6, this volume for more details).

In the Marche region, a high PBM infestation rate has been reported for *C. humilis*, *T. fortunei* , *W. filifera*, and *P. canariensis*, although other palm species native to South America (e.g. *Trithrinax campestris*) have been also found infested by PBM (Riolo and Nardi, personal communication). In some nurseries, damage has led to a 90% loss of palm production (Riolo, Isidoro, and Nardi 2005).

The moth is currently listed in the EPPO A2 List (no. 338) of "Pests recommended for regulation as quarantine pests" (OEPP/EPPO 2008) and in the European Phytosanitary Legislation in Annex II/Part A/Section II (Commission Directive 2009/7/EC of February 10, 2009, amending Annexes I, II, IV, and V of Council Directive 2000/29/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). This Directive defines the phytosanitary requirements for the importation and internal movements of the *P. archon* palm host in Europe (see Chapter 6, this volume).

In 2010, the Plant Phytosanitary Organization (PPO) of the Marche region carried out a wide survey and, according to the data obtained, the pest status of the PBM in the region was established (DD ASSAM no. 259/2010). An awareness campaign to prevent the further spread of this harmful organism was carried out, and the phytosanitary actions were addressed in particular to the nurseries located in the area delimited by the presence of PBM (DD ASSAM no. 259/2010, and following).

The palm producers located in the demarcated area must submit to 2 years of official inspections, carried out three times per year, before they can be authorized to use plant passports. Official controls consist of visual observations for *P. archon* symptoms on all susceptible palm species grown in the nursery. After the 2 years of official controls, the regional PPO continues to carry out official controls with the same frequency. The results of the phytosanitary actions referring to 2012, 2013, and 2014 are reported in Table 13.6.

Compulsory measures were not included in the phytosanitary regulation according to Commission Directive 2009/7/EC, and phytosanitary measures were applied only at the plant-production sites. The control measures adopted in the nurseries have limited the spread of PBM-infested palms for planting (see Fig. 13.2). Studies and experimental activities have demonstrated the efficacy of the entomopathogenic nematode *Steinernema carpocapsae* in killing PBM larvae (Nardi *et al.* 2009) and the poor effectiveness of chemical insecticides under conditions in the nursery (Nardi *et al.* 2009).

Table 13.6 Phytosanitary emergency measures applied against PBM invasion in the Marche region (central eastern Italy).

Regulation of importation and internal movements of plants susceptible to the pest	In accordance with European Commission Directive 2009/7/EC
Survey and monitoring	Periodic visual inspections
Establishment of demarcated areas	Definition of the boundaries of the infested zones (demarcated area) according to the Plant Protection Organization disposition in the Marche region (DD ASSAM no. 259/ 2010)
Implementation of "cut-and-destroy" measures	Compulsory measures applied only to palms intended for planting (i.e. in the nurseries) in accordance with Directive 2009/7/EC
Implementation of control measures	Insecticide treatments on the crown with entomopathogenic nematodes or other authorized products. Entomopathogenic nematodes provided free of charge to municipalities. Teaching activities for municipality gardeners on PBM symptoms recognition, its life cycle, and pest management

The combined action of both phytosanitary measures in the nurseries and entomopathogenic nematode treatments in urban and private areas can be considered an efficient strategy for controlling PBM infestation in the region.

13.12 Action Programs for Agricultural and Non-Agricultural Areas

Agricultural regions are very different from non-agricultural ones in terms of treatment priorities and constraints. In the agricultural sector, the order of priorities for the control strategy is usually pest elimination, fruit free of residues, low treatment cost, low labor investment, and least important, environmental safety. As has already been stated, the palms are intensively managed and can be efficiently treated from crown to base. We believe, based on our previous success (Soroker *et al.* 2005), that via intensive and area-wide organized management, including mass trapping and chemical treatments based on monitoring, RPW control in conventional date farms is possible and will be required for many years. However, the possibility of controlling the pest in organic orchards is questionable, unless biological control means prove successful. On the other hand, intensive management, mostly based on synthetic insecticides, is problematic in the long run and sustainable means will have to be developed.

In contrast, non-agricultural areas are characterized by a stronger emphasis on environmental safety. Thus, recourse to broad-spectrum synthetic insecticides to control RPW in urban environments or landscapes is highly undesirable. On the other hand, individual palms are often highly valuable for patrimonial or other reasons and a rapid control of the infestation will require intensive control measures. For these cases, palm spherical crown pruning combined with chemical treatment, as suggested by Ferry *et al.* (2009), seems to be a good method not only for limiting disposable material but also for improving pesticide delivery. However, this method is very time-consuming and demands dedicated trained personnel that are not always available. In fact, sanitation is

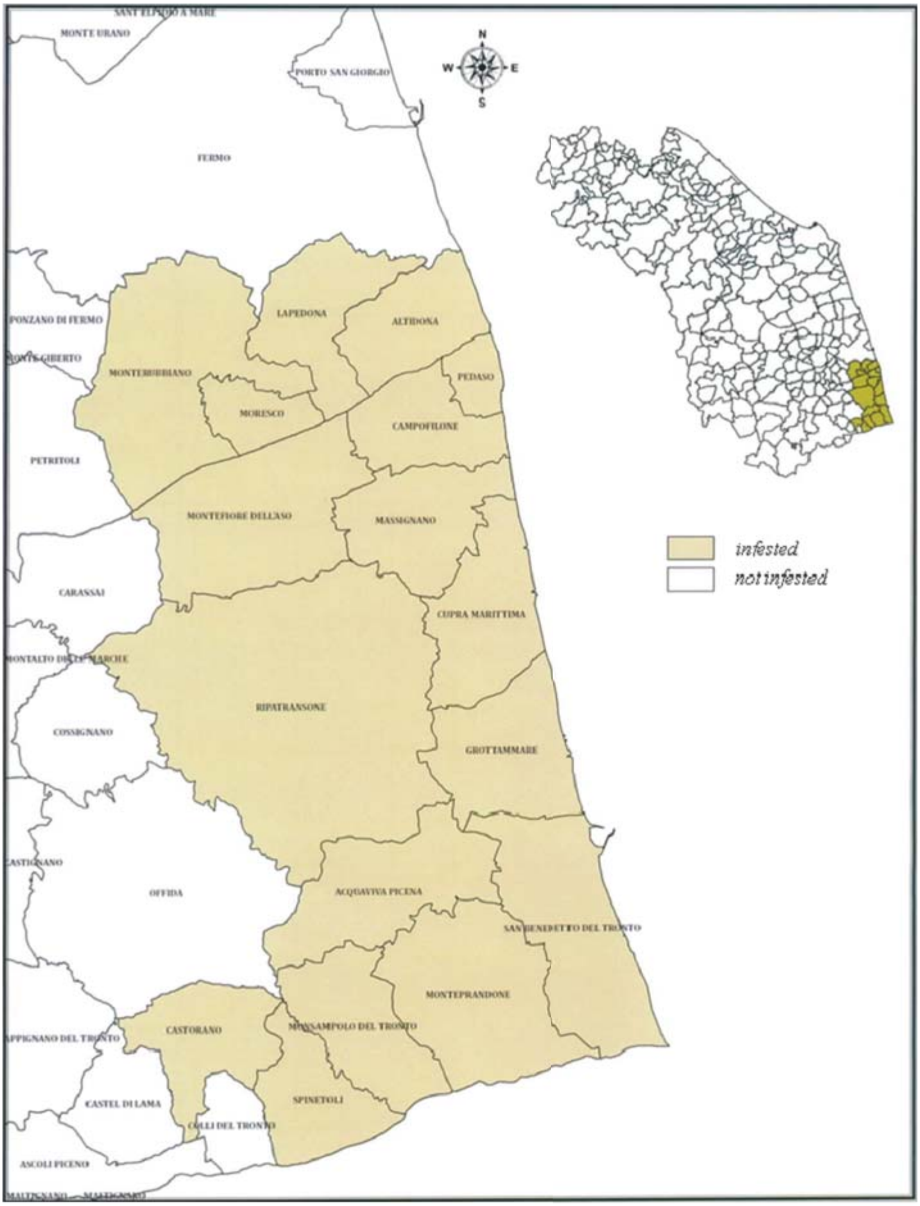

Figure 13.2 Official demarcated area for the presence of the PBM in the Marche region, for the years 2010, 2011, 2012, and 2013.

a critical common aspect for both agricultural and non-agricultural systems—especially with large Canary palms, as dead palms, even when cut down, are often neglected and left untreated, each serving as a source of hundreds of weevils. Compulsory measures need to be imposed not only for control but also for safe transportation and disposal of the dead palms; the best method of palm disposal is probably shredding followed by composting.

13.13 Conclusion and Future Outlook

To date, the best method for preventing the introduction and further spread of RPW and PBM is to prohibit the importation of all host species or to reduce the movement of susceptible plants from infested areas for planting, unless they comply with the conditions of Decision 2007/365/EC. In fact, to prevent or minimize the spread of both pests, the different responsible official bodies (e.g. National Phytosanitary Service, Regional Phytosanitary Service, Food and Veterinary Office, etc.) have determined that, in some cases, the importation of these plants from countries where the pests are already established should no longer be allowed. The first time a country realizes it has an outbreak of either pest, the initial objective should be to seek eradication. Although the problems associated with these insects have been recognized for several years, and extensive control measures have been put in place, the pests have continued to spread, due to factors hindering the implementation of control measures (e.g. difficulties in identifying and destroying infested trees, particularly in urban environments, lack of scientific data on the pests, etc.). Efficient control measures developed to date still need to be evaluated on a large scale. More effort needs to be aimed at increasing public awareness and governmental involvement, in the hopes that the arsenal of means and application schemes that already exist will be further developed in the future and will be later adopted in a centralized fashion area-wide, enabling palms to continue to be the major component of the Mediterranean landscape as they were before the RPW and PBM invasion.

There is still a need for better coordination at the EU level in encouraging Member States to apply the provisions of legislation, at least in terms of general measures, and better enforcement of the current legislation on intra-community trade and on the improvement of control activities with respect to imports from third countries. Most of these points are addressed in Regulation (EU) no. 1143/2014 of the European Parliament and of the Council published in October 2014, and, presumably, the correct adoption of all of the reported measures can lead to restoration of the two pests' status to the state of well-managed and non-hazardous organisms.

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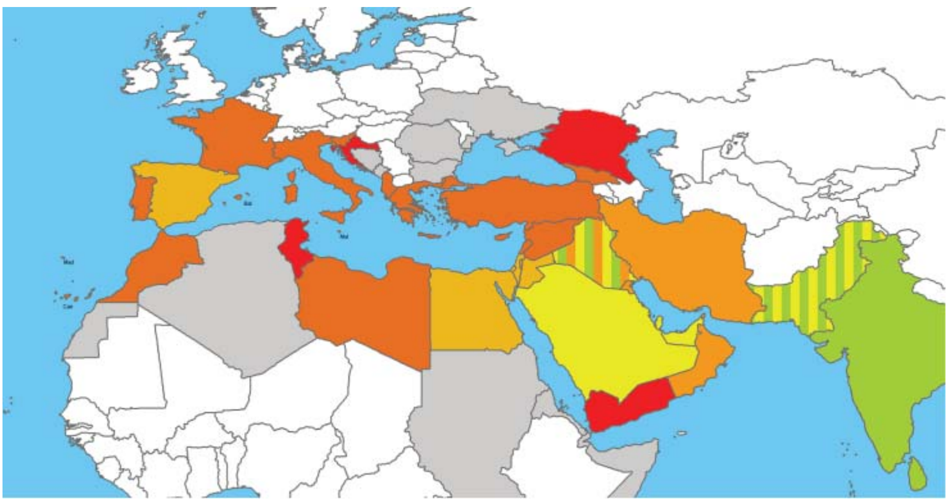

Figure 4.2 Western distribution area of the RPW, with chronology of invasion from 1985. Caribbean and Far Eastern areas are not illustrated. The entire concerned countries are colored according to the date of first report irrespective of the actual zones where outbreaks occurred. Green: native area, established before 1980. First reports from: 1980–89 (yellow), 1990–99 (pale orange), 2000–2009 (bright orange), and 2010–2015 (red). Striped coloring with same coding as above indicates an uncertain situation: Pakistan: RPW should be a native species originally growing on local *Phoenix dactylifera* and *Phoenix sylvestris*. Iraq: an ancient dubious report suggests RPW possibly native on date palm. Current presence has been reported but without precise dating for first outbreak. Russia: only a portion of Russia is colored with an arbitrary northern limit. Gray: areas under high threat due to proximity of infested countries and reports of palm movements.

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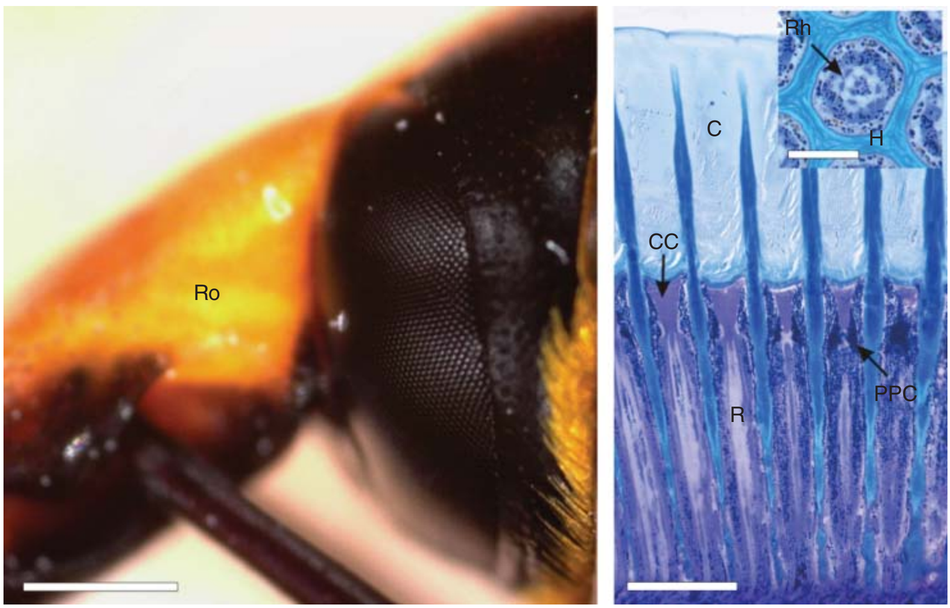
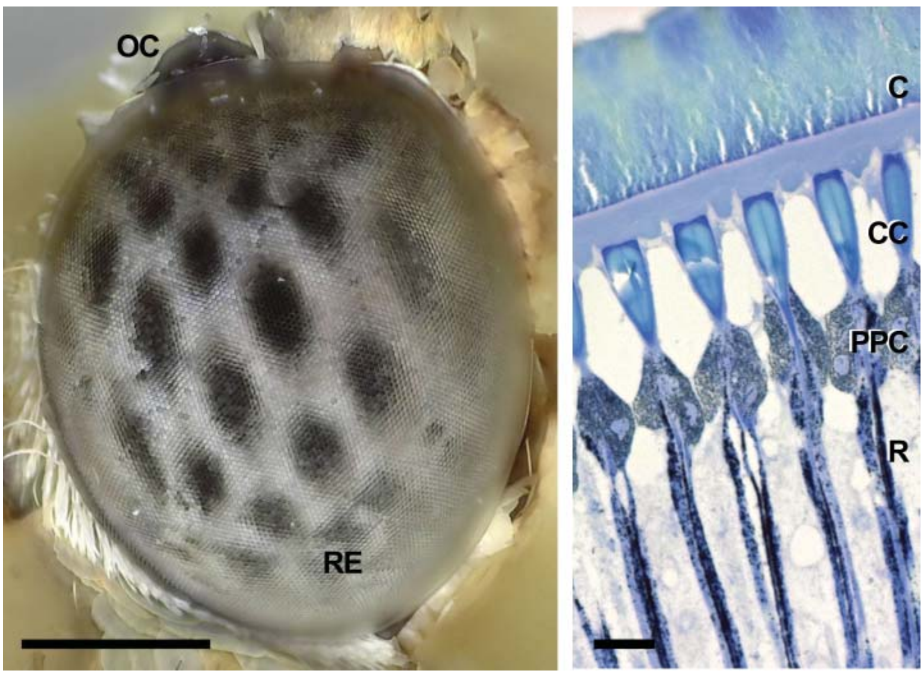


Figure 5.2 Visual system of *R. ferrugineus*. A. compound eye at the base of the rostrum (Ro). B., semi-thin sections of the retina; longitudinal section showing the cornea (C), crystalline cones (CC), primary pigment cells (PPC), photoreceptors (R). Inset, cross-section showing rhabdom (Rh) composed of six rhabdomeres at the periphery of the ommatidium and one rhabdomere at the center of the ommatidium, embedded in chitin (H). The macro photo was obtained with a USB microscope; the semi-thin sections were fixed with 3.5% glutaraldehyde and 4% paraformaldehyde, embedded in Spurr's resin, cut with a glass knife (1.5 µm) and stained with Azur II. Scale bars: A. 0.5 mm, B. main picture, 50 µm, inset, 20 µm.



(a) (b)

Figure 7.7 Visual system of *P. archon*. (a) The compound eye (RE, retina) and ocellus (OC) of a female moth, immobilized with beeswax (yellow mass). The compound eye has multiple pronounced pseudopupils (dark spots). (b) Semi-thin cross-section of the distal part of the retina, with (distal to proximal): cornea (C), crystalline cones (CC), primary pigment cells (PPC) and photoreceptor cells (R) showing dark stripes of perirhabdomal pigment granules. The rhabdoms of the photoreceptor cells (adjacent to the perirhabdomal pigments) connect to the tip of the CC. Scale bar: 1 μm (a), 20 μm (b).

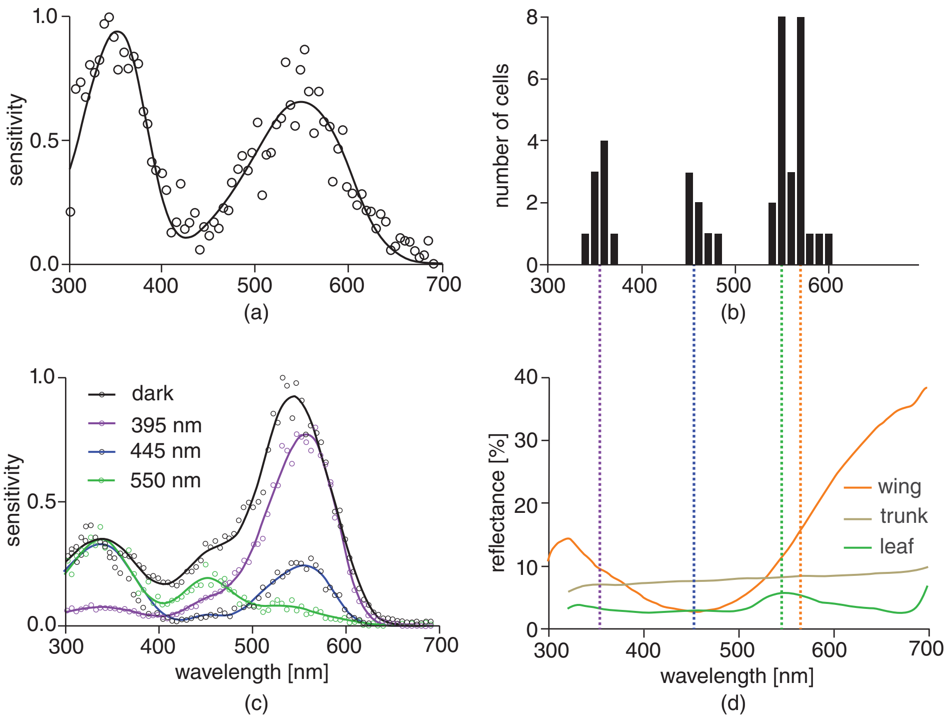


Figure 7.8 Spectral sensitivity of *P. archon* ocelli (a) and compound eyes (b, c) and representative spectra of the relevant environmental cues. (a) Spectral sensitivity of ocellus, measured by ERG. Data are fitted with double nomogram function with peak sensitivities at 350 and 550 nm. (b) Distribution of spectral sensitivity peaks of impaled photoreceptors, grouped in 10 nm bins. The 40 cells comprise three clearly distinguishable classes (UV peaking at 355 nm, blue peaking at 454 nm, long wavelength, LW). The peaks of the LW photoreceptors are widely dispersed across a 50 nm interval (550–600 nm) with bimodal distribution, forming two distinct classes (green-sensitive peaking at 550 nm, orange-sensitive peaking at 570 nm). (c) Spectral sensitivity of a compound eye obtained with ERG. Data are smoothed by adjacent averaging. Black curve shows sensitivity of dark-adapted retina. Pink, blue, and green curves correspond to retina adapted with UV, blue, and green light at 395, 445, and 550 nm, respectively. Chromatic adaptation reveals selective suppression of sensitivity in the three parts of the spectrum, corresponding to at least three classes of photoreceptors with peak sensitivities at 350, 450, and 550 nm. (d) Reflectance spectra of relevant visual cues. Dotted bars show average sensitivities of four classes of retinal photoreceptors. Orange curve shows the reflectance spectrum of orange scales on the inner wings. Reflectance rises monotonically above 500 nm with the steepest slope between 550 and 600 nm, coinciding with the peaks of the two LW photoreceptor classes. In addition, there is a smaller reflectance peak in the UV. The green curve shows reflectance of the host-plant leaves (*Washingtonia filifera*). The leaves have a reflectance peak in the green part (550 nm) and in the near infrared part of the spectrum (>700 nm). The gray curve shows that the reflectance spectrum of the trunk, which appears silvery-brown to us, has a flat reflectance spectrum that rises slightly toward the LW part.

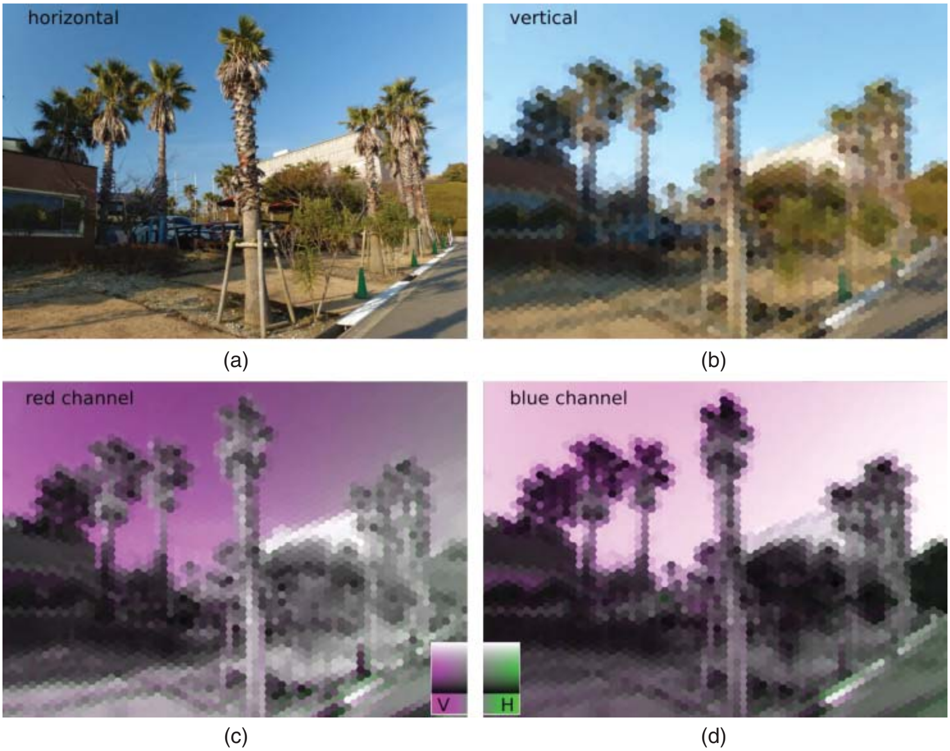


Figure 7.9 Simulation of an urban visual scene containing palm trees using the visual acuity of *P. archon*. The scene extends about 90° × 60°. (a) RGB picture taken with the polarizer set horizontally to minimize sky irradiance. (b) RGB picture taken with the polarizer set vertically and down-sampled to match the optical acuity of *P. archon*. (c) Polarization and intensity contrast in the red channel. (d) Polarization and intensity contrast in the blue channel. Non-polarized pixels are shown in gray; magenta and green tints indicate vertical and horizontal polarizations, respectively. Down-sampled facets span approximately 1.5°.

Figure 9.1 Flattened crown of a Canary palm (*P. canariensis*).

Figure 9.2 Gap in the crown of Canary palm.

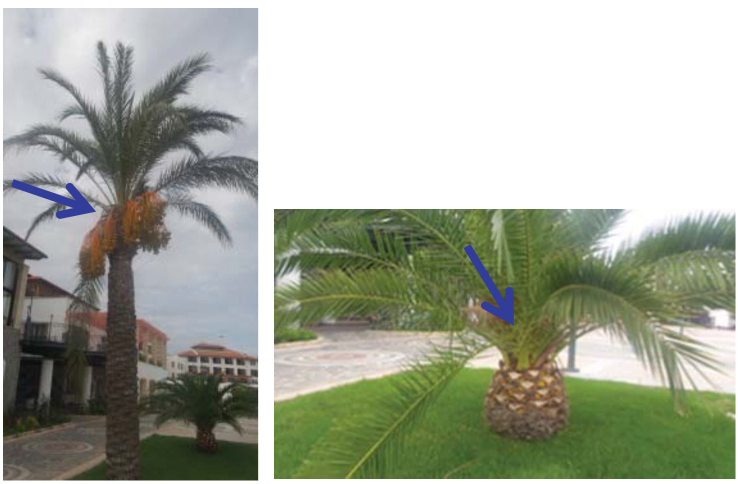


Figure 9.3 Canary palms with broken leaves (arrows).

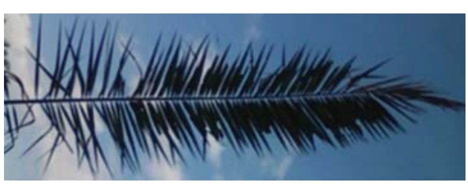


Figure 9.4 Leaf of Canary palm with damaged leaflets.

Figure 9.5 Dry outer leaves on date palm (*P. dactylifera*).

Figure 9.6 Canary palm.

Figure 9.7 Date palm.

Figure 9.9 Holes in Canary palm leaves.

Figure 9.10 Damaged leaves of Canary palm.

Figure 9.11 Damaged leaf of *Trachycarpus fortunei* showing a series of consecutive perforations in a circular pattern.

Figure 9.12 Collapsed leaves on Canary palm.

Figure 9.13 Asymmetric inner leaf growth on Canary palm.

Figure 9.14 Partially collapsed crown of Canary palm.

Figure 9.15 Absence of new young leaves in Canary palm.

Figure 9.16 Canary palms with the typical "umbrella" shape crown.

(a) (b)

Figure 9.17 Collapsed infested crowns of (a) *Washingtonia* sp. and (b) *P. dactylifera* (infested palm marked with an arrow).

Figure 9.18 Wilted inner leaves in date palm.

(a) (b)

Figure 9.19 Dry offshoots in (a) Cretan date palm (*P. theophrasti*) and (b) *P. dactylifera.*

Figure 9.20 Dry sawdust emitted from infested date palm.

Figure 9.21 Dry or fresh emission of sawdust from *Washingtonia* sp. stipe.

Figure 9.22 Fresh sawdust extruding from larval galleries in *Howea forsteriana* stipe.

Figure 9.23 Abundant sawdust extruding from larval galleries in the crown of *T. fortunei*.

Figure 9.24 Liquid oozing from the stipe of *Washingtonia* sp.

Figure 9.25 Liquid oozing from the stipe of *H. forsteriana*.

Figure 9.26 Dry or wet material oozing from the stipe of *P. dactylifera*. At this stage, the crown usually remains green with no obvious symptoms.

(a) (b)

Figure 9.27 *Washingtonia* sp. palm tree infested (a) at the top and (b) at the bottom of the stipe.

(a) (b) (c)

Figure 9.28 Infested by RPW: (a) *Brahea* (= *Erythaea*) sp. (b) *Ravenea* broken below the crown. (c) *Syagrus* stipe with marks of oozing, cocoons, and larvae. Reproduced with permission from Yaakov Nakach.

Figure 9.29 Distinctive oval gallery holes caused by the activity of PBM larvae in the leaf petiole of Canary palm.

Figure 9.30 *P. archon*: small egg cluster and egg chorion on the stipe (indicated by arrow).

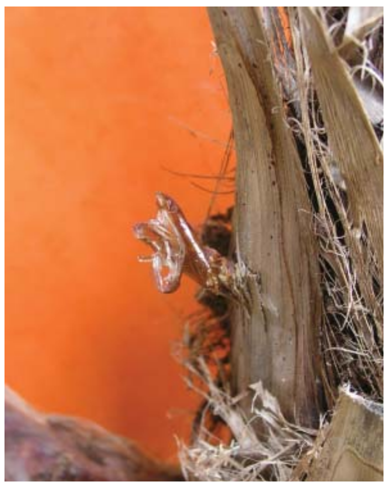


Figure 9.31 *P. archon*: pupal exuviae protruding from the stipe.

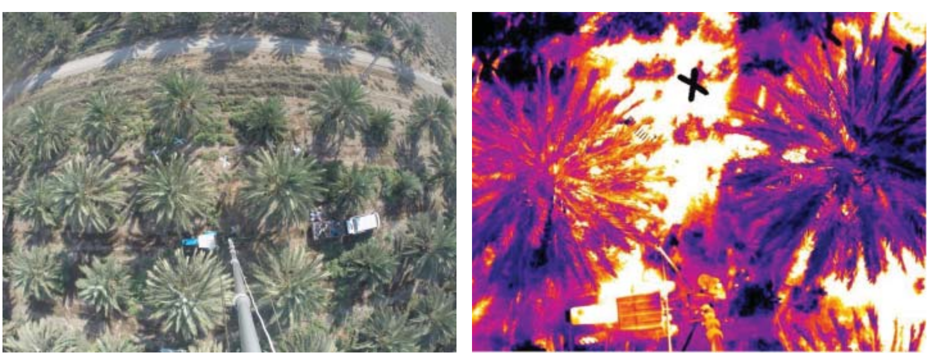


Figure 10.7 RGB (left) and thermal (right) images of date palm trees in a commercial plantation using a specially designed mast. In the thermal image, higher temperatures are observed (yellowish color) in part of the canopy of an infected tree (on the left) compared with lower temperatures (bluish colors) in the canopy of a healthy tree. The images were captured from cameras attached to a 20 m high pole.

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Note: illustrations are indicated by *italic page number*; tables by **emboldened numbers**. Acronyms used: PBM = *Paysandisia archon* (palm borer moth); RPW = *Rhynchophorus ferrugineus* (red palm weevil)

Handbook of Major Palm Pests: Biology and Management, First Edition.
Edited by Victoria Soroker and Stefano Colazza.