This thesis would be incomplete without a mention of the support given by God.

I dedicate this master thesis to my dad Hassan who has never failed to give us financial and moral support, for giving all our need along my life and my mom Ehsan who you have given me so much, thanks for your faith in me, and for teaching me that I should never surrender. The two most special persons in my life, they, not only gave me life, but also fill it with all the love and affection one can wish for. Thank you.

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Amira Hassan

October 2010
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List of Abbreviations

%: percentage

CTV: Citrus Tristeza Virus

EC: European Commission

EPPO: European and Mediterranean Plant Protection Organization

Fig.: Figure

IPM: Integrated Pest Management

IR: Infrared

LAI: Leaf Area Index

Min: minutes

NIR: Near Infrared

nm: nanometer

R: Reflectance

REP: Red Edge Position

RGB: red, green and blue. RGB is a color model

RPW: Red Palm Weevil
Chapter 1

Introduction

*Phoenix canariensis* is a large, stately ornamental palm with orange-yellow clusters, date-like (Gilman and Watson, 1994). It is widely planted in warm temperate regions of the world; Canarian islands, the area of palm origin, and the Euro-Mediterranean region are well characterized by this species in landscape and historical sites, being the most planted ornamental palm in numerous touristic sites, public and private parks and gardens.

In the last years, these palms have been severely treated by a destructive pest, the red palm weevil (RPW), which was recently introduced in the Mediterranean from Saudi Arabia through Egypt, from where it was rapidly disseminated in the whole region by infested plants and shoots. *P. canariensis* has soon become the preferred pest host and a large number of individuals, of any age, have been destroyed in most of the countries, mainly in the European ones (Barranco et al., 2000). On the contrary of *P. dactylifera*, which is mainly infested at the base of the trunk, *canariensis* is attacked at the top by stripe boring and leaves chewing etc. Damages, which are characterized by a massive tissue rotting and boring with brown liquid oozing and chewed-up fibers discharge, are mainly caused by larvae. Unfortunately symptoms are visible only long time after pest infestation and, by the time the first signs of the infestation appear, the palm is just compromised (Giblin-Davis, 2001). This late detection of the presence of the weevil constitutes a serious problem in pest control and in any attempt to guarantee pest-free status in adult palms. Several control methods, such as wide area mass-trapping and chemical control, are effective against this pest where palms are cultivated as crop in production systems. Both mass-trapping and chemical control cannot be applied in urban areas where palms grow in boulevards, squares and gardens, which can be public and private; unfortunately biological control is not known, even in nature. In order to preserve palms safely for human health and environment, physical (microwave) and chemical (tree injection) applications have been developed, but several constraints have been encountered and few data are available on their efficacy in pest control. In this contest, preliminary successful results were achieved, after 4 years of treatments, by the use of tree injection method (9616PTIT dep.brev. BA2009A000014 int. code A 01 G 29 00) for the preventive control of the red palm weevil in *P. canariensis* in Italy and Malta.

Considering that this pest is still considered of quarantine even if largely distributed in EU, that no efficient control methods have been officially recognized, current EU regulations force to remove and destroy the whole palm when first signs of damage are detected in order to avoid the propagation of this pest (EU Decision 2007 / 365, 2007; Commission Decision of 25th May, 2007 on emergency measures to prevent the
introduction into and the spread within the Community of *Rhynchophorus ferrugineus* Olivier, OJ L139, 24). For this reason, periodic field visual inspections are currently conducted by experts, but they are unfortunately difficult to carry out, because of the heterogeneous palms distribution in the territory and the presence of many palms in private gardens, which are often difficult to perceive. Unfortunately, traditional methods for pest monitoring are not efficient, time consuming and highly expensive. Despite research carried out so far, few techniques have been developed for early pest detection sounds, smell, low energy X rays, IR.

Tacking into account these constraints, a technical support in the monitoring of the palms, which may be infested by the RPW, is highly needed for a sustainable pest control and management on a large scale. To this aim, technological advances in the field of remote sensing from aircraft or satellite platforms have greatly enhanced the ability to detect and quantify physical and biological stresses in several plant species. Reflected light in specific visible, near- and middle-infrared regions of the electromagnetic spectrum has proved useful in detection of nutrient deficiencies, disease, weed and insect infestations (Hatfield and Pinter, 1993). Very promising results have already been achieved in the monitoring of Citrus tristeza virus (CTV) by the use of proximal and remote sensing (Bouneb.M, 2009) by a spectral discrimination of CTV-infected and non-infected trees.

When satellite platform cannot be used, also aerial photo-interpretation by RGB images can provide a useful support in palm localization and for evaluating pest damages in space and time as number of removed or death palms.

Techniques need to be developed and implemented in the surveillance and control of the red palm weevil over large areas in order to provide Plant Protection Services and palm owners of relevant information in time for preventative action to be taken.
2.1. Canary Island Palm (*Phoenix canariensis*)

The Canary Island Palm has been a gift to landscapers throughout the world. Known for its immense green crown sitting on top of a beautifully carved nut, this palm has an appearance of a pineapple.

*Phoenix canariensis* is native to the Canary Islands which are located in the Atlantic Ocean of northeast Africa coast (Morici, 1998). It belongs to the botanical family *Arecaceae* and is widely planted as an ornamental plant in warm temperate regions of the world, particularly in the Mediterranean area.

This palm is a large, stately palm that often reaches a size too massive for most residential landscapes but is very slow-growing and will take a considerable amount of time to reach its 15 to 18 meter height. This palm can be identified by its single, upright, thick trunk topped with a crown of 2.5 to 4.5 meters long. It puts out stiff leaves with extremely sharp spines at their bases. The stalks of inconspicuous flowers are replaced with clusters of one-inch-diameter, orange-yellow, date-like, which ripen in early summer. The trunk can reach a diameter of 1.2 meters and is covered with an attractive, diamond-shaped pattern from old leaf scars (Gilman and Watson, 1994).

*Canariensis* palms can be attacked by many pests and diseases which cause serious damages to leaves, trunk and the whole palm. The most common and important pests and pathogens of palm trees are listed in Table 1.
Table 1: Main pests and diseases affecting *P. Canariensis* palm (casual agents are within brackets).

<table>
<thead>
<tr>
<th>Nematodes &amp; Insects</th>
<th>Fungal diseases</th>
<th>Bacterial &amp; Phytoplasma diseases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root knot nematodes <em>(Meloidogyne spp)</em></td>
<td>Bayoud</td>
<td>Lethal yellowing</td>
</tr>
<tr>
<td></td>
<td>Fusarium wilt <em>(Fusarium oxysporum forma specialis albedinis)</em></td>
<td></td>
</tr>
<tr>
<td>Bou Faroua <em>(Oligonychus afrasiaticus McGregor, and O. prate)</em></td>
<td>Bud rot Belâat <em>(Phytophtora sp Phytophthora palmivora)</em></td>
<td>Al Wijam</td>
</tr>
<tr>
<td>Caroub moth <em>(Ectomyelois ceratoniae. Zeller)</em></td>
<td>Black scorch disease <em>(Ceratoctis paradoxa)</em></td>
<td>Brittle leaves disease</td>
</tr>
<tr>
<td>Dubas bug <em>(Ommatissus lybicus, O. binotatus)</em></td>
<td>Brown leaf spot <em>(Mycosphaerella tassiana)</em></td>
<td></td>
</tr>
<tr>
<td>Giant Palm Borer Dinapate wrighti</td>
<td>Diplodia disease <em>(Diplodia phoenicium)</em></td>
<td></td>
</tr>
<tr>
<td>Mealy bug <em>(Meconellicoccus hirsutus, Planococcus citri, P. ficus)</em></td>
<td>Ganoderma butt rot <em>(Ganoderma zonatum)</em></td>
<td></td>
</tr>
<tr>
<td>Palm budworm Litoprosopus coachella</td>
<td>Graphiola leaf spot <em>(Graphiola phoenicis)</em></td>
<td></td>
</tr>
<tr>
<td>Palmetto Weevil <em>(Rhynchophorus cruentatus)</em></td>
<td>Khamedj disease <em>(Mauginiella scattae Cav.)</em></td>
<td></td>
</tr>
<tr>
<td>Red scale <em>(Phoenicococcus marlatti)</em></td>
<td>Omphalia root rot Omphalia <em>(O. tralucida Bliss and O. pigmentata Bliss)</em></td>
<td></td>
</tr>
<tr>
<td>Red palm weevil <em>(Rhynchophorus ferrugineus Oliv.)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Termites <em>(Microceroterms diversus)</em></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.2. Red Palm Weevil (*Rhynchophorus ferrugineus* Olivier, 1790)

2.2.1. Overview

The red palm weevil (RPW) is a Curculionidae (Table 2) and represents a main pest in different palm species. RPW has an extremely wide geographical distribution and is practically present wherever palms are grown.

Originating in southern Asia and Malesia, where it is a serious pest of coconuts, this weevil has been advancing westwards very rapidly since the mid 1980s. It had reached the eastern region of the Kingdom of Saudi Arabia in 1985 (pers. obs.) and afterwards spread too many other areas in the Kingdom (Abozuhairah *et al*., 1996). The pest was first recorded in the northern United Arab Emirates in 1985, and since then it has spread to almost the entire U.A.E. (El-Ezaby, 1998) and to Oman. In Iran, it was recorded in Savaran region in 1990 (Faghih, 1996). Then it was discovered in Egypt at the end of 1992 in El-Hussinia, Sharquiya region (Cox, 1993). In 1994, it had been found in the South of Spain (Barranco *et al*., 1996) and in 1999 had been reported in Israel, Jordan and the Palestinian Authority Territories (Kehat, 1999).

In Mediterranean countries, the two main attacked palm species are *P. dactylifera*, as a crop, and *P. canariensis*, as ornamental; nevertheless, other palm species can also be attacked (Barranco *et al*., 2000).

The RPW is currently spreading in Mediterranean European countries, endangering landscapes and public green areas which are very attractive (Ferry and Gómez, 1998; Khalid, 2007; Murphy and Briscoe, 1999; Soroker *et al*., 2006; 2005).

The primary mean of pest spread worldwide is by young palm trees or their offshoots (in the case of date palms), which are intensively traded and transported between and within countries (Giblin-Davis, 2001).

As RPW is a concealed borer, detecting infested palms becomes extremely difficult. If infestation is not detected early, attacked palms often die (Abraham *et al*., 1998).

The male and female adults are large reddish brown beetles about 3cm long and with a characteristic long curved rostrum; with strong wings, they are capable of undertaking long flights.

This weevil is predominantly active during the day and is capable of long distance flight (> 900 meters) to locate hosts or breeding sites. Marked and
released weevils migrated up to 7 km during a period of 3 to 5 days (Abbas et al., 2006).

Normally, the Red Palm Weevil prefers to infest palms below the age of 20 years, where the stem of the young palm is soft, juicy and easily penetrated. The larvae are responsible for damaging the palm, and once they have gained access, the death of the palm is generally ensue. The larva normally never comes to the surface, since it begins its life inside the palm. Therefore, neither the damage nor the larva can be seen. However, the trunk of the palm can be infested in any parts, including the crown. The damage caused by a few larvae of the weevil is astonishing. Even one larva may cause considerable damage, and, sometimes the death of the palm. It is difficult to assess the actual loss caused by this pest, but undoubtedly it affects the production of date palms.

Primary and secondary hosts of the RPW are reported in Table 3.

**Table 2:** Classification of RPW.

<table>
<thead>
<tr>
<th>Phylum</th>
<th>Arthropoda</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>Insecta</td>
</tr>
<tr>
<td>Order</td>
<td>Coleoptera</td>
</tr>
<tr>
<td>Family</td>
<td>Curculionidae</td>
</tr>
<tr>
<td>Genus</td>
<td><em>Rhynchophorus</em></td>
</tr>
<tr>
<td>Full Name</td>
<td><em>Rhynchophorus ferrugineus</em> (Olivier)</td>
</tr>
<tr>
<td>Preferred common name</td>
<td>Red palm weevil</td>
</tr>
<tr>
<td>Other common names</td>
<td>Asian palm weevil, Indian palm weevil, red stripe weevil, coconut weevil, Asiatic palm weevil, picudo asiático de la palma (Spanish), charançonasiatique du palmier (French), Indomalaiischer Palmen-Ruessler (German)</td>
</tr>
<tr>
<td>Cause similar damage</td>
<td>Palmetto weevil, <em>Rhynchophorus cruentatus</em> Fabricius</td>
</tr>
</tbody>
</table>
Table 3: Primary and secondary hosts of Red Palm Weevil.

<table>
<thead>
<tr>
<th>Common name</th>
<th>Scientific name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Betelnut palm</td>
<td>Areca catechu</td>
</tr>
<tr>
<td>Queen palm</td>
<td>Arecastrum romanzoffianum</td>
</tr>
<tr>
<td>Sugar palm</td>
<td>Arenga pinnata</td>
</tr>
<tr>
<td>Toddy palm</td>
<td>Borassus flabellifer</td>
</tr>
<tr>
<td>Palasan</td>
<td>Calamus merrillii</td>
</tr>
<tr>
<td>Fishtail palm</td>
<td>Caryota cumingii</td>
</tr>
<tr>
<td>Mountain fish tail palm</td>
<td>Caryota maxima</td>
</tr>
<tr>
<td>Coconut</td>
<td>Cocos nucifera</td>
</tr>
<tr>
<td>Gebang palm</td>
<td>Corypha utan</td>
</tr>
<tr>
<td>African oil palm</td>
<td>Elaeis guineensis</td>
</tr>
<tr>
<td>Ribbon fan palm</td>
<td>Livistona decipiens</td>
</tr>
<tr>
<td>Chinese fan palm</td>
<td>Livistona chinensis</td>
</tr>
<tr>
<td>Chinese fan palm</td>
<td>Livistona chinensis var. subglobosa</td>
</tr>
<tr>
<td>Sago palm</td>
<td>Metroxylon sagu</td>
</tr>
<tr>
<td>Thorny palm</td>
<td>Oncosperma horrida</td>
</tr>
<tr>
<td>Nibung palm</td>
<td>Oncosperma tigillarium</td>
</tr>
<tr>
<td>Cuban royal palm</td>
<td>Roystonea regia</td>
</tr>
<tr>
<td>Canary Island palm</td>
<td>Phoenix canariensis</td>
</tr>
<tr>
<td>Date palm</td>
<td>Phoenix dactylifera</td>
</tr>
<tr>
<td>East Indian wine palm</td>
<td>Phoenix sylvestris</td>
</tr>
<tr>
<td>Regal palm</td>
<td>Roystonea regia</td>
</tr>
<tr>
<td>Hispaniola palm</td>
<td>Sabal blackburniana</td>
</tr>
<tr>
<td>Chinese windmill palm</td>
<td>Trachycarpus fortunei</td>
</tr>
<tr>
<td>UWashington palms</td>
<td>Washingtonia sp.</td>
</tr>
<tr>
<td>American agave</td>
<td>Agave americana</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>Saccharum officinarum</td>
</tr>
</tbody>
</table>

EPPO 2008; (Murphy and Briscoe, 1999)

2.2.2. Life cycle and biology

The female RPW lays eggs in injuries in the trunks of established trees, at the base of the palm leaves, at tree crowns and adjacent to offshoots. The RPW larvae bore deep into palm crowns, trunks, and offshoots, generally concealed from visual inspection until the palms are nearly dead. Several weevil generations may develop within a single tree. Infested trees suffer from reduced productivity. Heavy infestations often result in collapsed trees and thus, total loss of crops (Blumberg et al., 2001).

Damage to palms is produced mainly by the larvae. Adult females lay about 200 eggs at the base of young leaves or in wounds on the leaves and trunks; larvae feed on the soft fibers and terminal bud tissues and move towards the interior of the palm making tunnels and large cavities. They can be found in any place within the palm, even in the very base of the trunk where the roots
emerge. They reach a size of more than 5cm before pupation (Martín and Cabello, 2005). The larva pupates in a cocoon made of brown dried palm fibers, generally outside the trunk, at the base of the leaves. Overlapping generations with all developing stages can be present within the same palm tree. Generally the adult weevils existing in one plant will not move to another one while they can feed on it (Cabello, 2006). RPW stages are represented in (Fig. 1).

**Figure 1:** Life cycle of *R. ferrugineus* (Olivier).

### 2.2.3. Behavior

Adult weevils are attracted to dying or damaged palms, but can also attack undamaged palms (Murphy and Briscoe, 1999). Male red palm weevils produce an aggregation pheromone, which attracts other adult weevils to their host; it is composed of ferrugineol (4-methyl-5-nonanol) and 4-methyl-5-nonanone (Murphy and Briscoe, 1999). The larvae can bore into soft tissue, such as the palm crown, the upper portion of the trunk, or the base of the petioles in mature palms, or into the trunk of young palms, or the decaying tissue of dying palms (Murphy and Briscoe, 1999). As palm trees mature, there is a reduction in areas suitable for infestation by the weevil larvae. In palms 5-years old or less, the bole, stem or crown may be infested, but in palms more than 15-years old the area is reduced to the crown, the stem 1 m
below the crown, and in the bases of leaf petioles (EPPO, 2008). Some of RPW damages in Canary palms are shown in (Fig. 2).

![Figure 2: Main damages in P. canariensis: chewed palm leaf (a); umbrella shape of the crown (b).](image)

2.2.4. Detection

Early signs of attack are distinctive but not easily visible: notches at the base of palm leaves, cocoons inserted into the base of the palm leaves, eccentric crown growth, holes at the base of the cut palms and symptoms resembling those of drought stress (wilting, yellowing). Larvae and adults may destroy the interior of the palm tree, without the palm tree showing distinctive signs of deterioration. When attacked, the trunk is structurally weakened, making the plant liable to collapse, thus the plant becomes a danger to the public. An attack on *Phoenix* leads, in the majority of the cases, to death of the palm trees whatever the size. Visual examination allows the detection of signs of attack such but will not detect larvae and adults inside the trunk stripe. Adult populations can be monitored by pheromone traps, acoustic detection or infra-red systems (Soroker *et al.*, 2004).

2.2.4.1. Visual inspection

Larvae, pupae, pupal cases, and adults, can be found in the dead or dying crown of the palm or infested fronds. In heavily infested palms fallen empty pupal cases and dead adults may be found around the base of the palm.

Early infestations or low numbers of the red palm weevil in plants are very difficult to detect. The older leaves of a palm begin to droop during the early stages of infestation but quickly collapse. Later stages or high infestations cause a decreased size and yellowing of the frond, particularly the new fronds as the larvae destroy the growing point of the palm. Eventually the frond canopy becomes very small relative to trunk and distorted.
Red palm weevil preferentially attacks young palm (under 20 years) trees (Falerio, 2006); however, in Europe and the Caribbean, old trees (30 to 50 years old) are also killed by the weevil. Researchers found that during the early invasion stage of the pest in Curacao and Aruba, date palms (*Phoenix canariensis*, *P. dactylifera* and *P. sylvestris*) were the first palms to display symptoms and die. The female lays eggs in wounds particularly those caused by pruning fronds, the base of frond petioles/axils near the crown of the plant.

Visual inspections should focus on the following symptoms. Popped neck - As the infestation progresses, the larval feeding damage and associated rot is so severe that the integrity of the crown is compromised and the top of the palm falls over. This condition is known as popped neck. If the palm is pulled apart at this stage, larvae, cocoons, and even adults may be found within the crown region. Tunnels with brown fluid - Highly infested trees may have tunnels in the trunk and base of the frond petiole and a thick brown fluid can be seen oozing from the tunnels. In date palms, infested offshoots become dry. Wilting and yellowing of fronds: When infestation is in the coconut crown, wilting or yellowing of the inner fronds may occur. Fronds with tunnels - The weevil is known to infest the base of fronds. Tunnels may be visible.

### 2.3. Occurrence of Red Palm Weevil in Italy

The red palm weevil is arrived in Sicily via Egypt two years ago - probably in a shipment of infected plants and is devouring the island's date palms by boring large networks of tiny tunnels into the trunks. *Rhynchophorus ferrugineus*, had already caused the destruction of over thirteen thousand date palms in Sicily by August 2009, and there’s no end to the massacre in sight. As shown in Table 4 and (fig.3), it has invaded mainland Italy, killing trees as far north as Genoa. RPW has had a strong spread in Apulia.

#### Table 4: RPW Infestations in Italian regions since 2004 (EPPO, 2008).

<table>
<thead>
<tr>
<th>Year</th>
<th>Species/ Cultivars</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td><em>P. canariensis</em></td>
<td>Toscana</td>
</tr>
<tr>
<td>2006</td>
<td><em>P. canariensis</em></td>
<td>Campania, Toscana, Sicilia</td>
</tr>
<tr>
<td>2006</td>
<td>Ornamental palms</td>
<td>Lazio</td>
</tr>
<tr>
<td>2007</td>
<td><em>Brahea armat, Butia capitata</em></td>
<td>Campania</td>
</tr>
<tr>
<td>2008</td>
<td><em>P. canariensis</em></td>
<td>Liguria, Imperia, Alassio, Savona, Genova</td>
</tr>
<tr>
<td>2009</td>
<td><em>P. canariensis</em></td>
<td>Apulia, Campania, Lazio, Liguria, Toscana, Sardegna, Sicilia</td>
</tr>
</tbody>
</table>
2.3.1. Measures to prevent its introduction and spread within the Community

EU Member States decided to take emergency measures to prevent the introduction and the spread of this pest within the Community and published the Decision 2007/365/EU on the 31st May, 2007 (L.139, pages 24 -27). The highest points of the Decision and the Ministerial Decree are:

• monitoring of the territory by the Plant Protection Services to identify areas of settlement, the infested zones, buffer zones and free zones;
• obligation for plants imported into Italy from a third country, a year of quarantine in the exporting country and importing country in a year with total chemical or physical protection;
• control measures on farms to the marketing of palm trees;
• palms can be moved for any reason unless accompanied by the plant passport;
• slaughter and destruction of infested plants by the owners;
• establishment of procedures by the municipal authorities for action as may be appropriate to safeguard public safety.
• Possible prosecution or administrative sanctions in case of defaults.

With the adoption of these emergency measures susceptible palms imported from Third countries into the Community must be accompanied by a
phytosanitary certificate with specific import requirements. Similarly, palm trees that are moved throughout the Community must be accompanied by a plant passport which is issued only when certain requirements are met.

Furthermore, countries where occurrence of this pest has been reported must take additional emergency measures to limit its spread and eradicate the specified organism with the establishment of demarcated areas which include marking infested zones and buffer zones and with the adoption of chemical and other measures.

2.4. Remote Sensing Technology

2.4.1. Overview

Remote sensing is the science and art of collecting information about an object without physical contact (Jensen, 2007). A remote sensor measures electromagnetic radiation emitted or reflected from an object or geographic area from distance. Valuable information can be subsequently extracted from the data with mathematical and statistical based algorithms. Waves of electric and magnetic energy move together through space to form electromagnetic radiation, and this energy can be categorized by its frequency and wavelength. The electromagnetic spectrum of waves is divided into sections based on wavelength. From the shortest wavelength to the longest, the electromagnetic spectrum consists of gamma rays, x-rays, ultraviolet light, visible light, infrared, and radio waves.

In general, the detection of crop stress by remote sensing is based on the assumption that stress factors interfere with photosynthesis or the physical structure of the plant, affecting the absorption of light energy leading to an alteration in the reflectance spectrum of the plant (Moran et al., 1997). Diseases may cause changes in pigment concentration and variation. A further challenge of disease detection using remote sensing technologies lies in the fact that diseases may have various physiological impacts on plants, such as stunting growth, causing leaf drop, interfering with nutrient uptake, or reducing seed viability (Burdon, 1987).

2.4.2. Imaging spectroscopy or hyperspectral remote sensing

Spectroscopy is the study of the interaction between radiation and matter. It studies light as a function of wavelength that has been absorbed, reflected or scattered from a solid, liquid or gas. As photons enter matter, some are reflected from the surfaces, some pass through, and some are absorbed. Photons reflected from the surface or refracted by molecules inside the matter are said to be scattered, and can be detected and measured. Above absolute zero, all natural surfaces discharge photons (Clark et al., 1990). At a molecular level, scattering or absorption of sunlight depends on the atomic bonds or molecular structure of the intercepting molecule, and these absorptions or scatterings are very specific to the atomic bonds or molecular
structure of the target. The properties that specify the response of the material at every wavelength are called spectral properties (Suits, 1983). In the 1970s, a group of scientists (Knipling, 1970; Hunt, 1977; Swain and Davis, 1978) studied the reflectance spectra of rocks, minerals and vegetation, and developed the concept of understanding the spectral properties in terms of the underlying quantum mechanical process in relation to the chemistry of the reflecting object. This directed scientists to the suggestion that, by measuring the amount of light that reflects from a surface, one can possibly distinguish the composition of chemical elements of that surface. When an image is constructed from imaging spectrometer data that measures spectra from contiguous image pixels, the term changes to imaging spectroscope. In the remote sensing community, the term imaging spectroscopy has many synonyms, such as imaging spectrometry and hyperspectral or ultraspectral imaging (Clark, 1999). The prefix “hyper” in the word “hyperspectral” refers to spectra consisting of large numbers of contiguous and narrow light sensors.

2.4.3. Remote sensing process

The solar beam must pass through the earth’s atmosphere to reach the target, some of this energy is absorbed and scattered before it reaches the target. Much scattering is selective by wavelength, for example the atmosphere scatters blue light much more than it scatters green or red light. Of the remaining energy, some will reach the target, of energy reaching the leaves; the infrared radiation (wavelength just longer than those of visible radiation) will be reflected. The green region of the spectrum will be reflected by a different portion of the leaf, while blue and red radiation will be absorbed for use in photosynthesis (Campbell, 2002). Energy that reaches the sensor must again pass the atmosphere, where it is again subject to attenuation. Thus, energy recorded by the sensor is much different than sunlight that entered the atmosphere. Some of the blue light was scattered by the atmosphere, and reaches the sensor without being reflected from the earth’s surface. Blue, red, green and infrared have been reflected from the canopy, but reach the sensor in proportions that differ from the proportions that were intercepted by the canopy. The image portrays these different kinds of the radiation they represent. Data with the image can be translated into information only through the process of image interpretation or image analysis (fig.4). The applications, in which the analyzed remote sensing data can be combined with other data to address a specific practical problem, such as disease spread, mineral deficiency, etc (Campbell, 2002).
Figure 4: The Remote sensing: (A) Energy Source or Illumination (sun-active, microwave-passive); (B) Radiation and the Atmosphere; (C) Target (Interaction with the Target); (D) Satellite (Recording of Energy by the Sensor); (E) Transmission, Reception, and Processing (digital or hard copy); (F) Interpretation and Analysis (image processing) and (G) Applications.
Man's long-term fascination with energy in many different regions of the electromagnetic spectrum (fig.5) has led to its use in a wide variety of applications. To an agriculturist, however, the human eye has always been the most important sensory organ because it permits qualitative information about crop growth and development to be obtained without physical sampling of the plants. A dark green canopy has generally been perceived as healthy whereas yellow is seen as stresses or unhealthy. However, the human eye is sensitive to scattered light in only a limited region of the spectrum. Furthermore, interpretation of the visual image is dependent upon training and previous experience and the processing and storage of the information is merely mental. Although (Knipling, 1970) suggested that physiological stresses would affect the reflectance properties of leaves more in the visible than in the near-infrared because of the sensitivity of chlorophyll to stress, there is also a significant amount of information contained within the near-, middle- and thermal-infrared wavebands that can be used in crop management schemes. To exploit to the full this information for repeatable, quantitative analysis it is necessary to use sensors that can detect small changes in surface properties over a wide range of spectral frequencies, and to understand how light interacts with agricultural targets.

2.4.4. Sensor systems

In remote sensing the acquisition of data is depending upon the sensor system used. Various remote sensing platforms (Aircraft, Satellite) are
equipped with different sensor systems. Sensor is a device that receives electromagnetic radiation, converts it into a signal and presents it in a form suitable of obtaining information about the land or earth resource as used by an information gathering system.

2.4.5. Remote sensing of vegetation

Vegetation has a unique spectral profile that is caused by variations in reflectance and absorbance at certain wavelengths of the electromagnetic spectrum. Energy that is intercepted by healthy green vegetation interacts with pigments, water and intercellular spaces (Jensen, 2007). Reflectance in the visible portion of the electromagnetic spectrum (400-700 nm) is controlled by leaf pigments located in the chloroplasts. Strong absorption of energy required for photosynthesis causes low reflectance and transmittance in this region (Kumar et al., 2001). Most chloroplasts in plants contain chlorophyll (65%), carotenes (6%), and xanthophylls (29%); however, the percentage and distribution of pigments is highly variable (Gates et al., 1965). Absorption peaks in the visible spectrum occur around 420, 490 and 660 nm, and these peaks are caused by strong absorption by chlorophyll (Kumar et al., 2001). For most green plants, absorbance in leaves is 80-95% in the blue region (400-500 nm), 60-80% in the green region (500-600 nm) and 80-90% in the red region (600-700 nm) (Loomis, 1965).

There is a dramatic increase in reflectance of vegetation between the visible and the near-infrared (NIR) region of the electromagnetic spectrum. This area of increasing reflectance, from 670 to 780 nm, is known as the red edge. The ‘red edge’ is a unique feature in the spectral profile of vegetation that results from chlorophyll absorption in the red region of the spectrum, causing low reflectance in the red region, and high internal leaf scattering in the spongy mesophyll, that causes high reflectance in the NIR region (Horler et al., 1983b). These characteristics cause a sharp linear increase in reflectance between the red and the NIR region.

2.4.6. Detecting Changes in Vegetation – Optical Responses to Plant Stress

Remote sensing of vegetation can be utilized for a wide variety of applications including differentiating between species and phenological stages. Remote sensing has been utilized to detect changes in plant response caused by various stresses such as those due to moisture, nutrients, pests, and pathogens (Jones and Schofield, 2008). Changes resulting from plant stress that may not be detected by sight or touch affect the amount and direction of radiation reflected and emitted from plants, and these changes can be detected through remote sensing (Jackson, 1986).
Reflectance values in the electromagnetic spectrum are heavily dependent on the relative composition of all the pigments in the leaf including chlorophylls, carotenoids and flavonoids. Because pigments are important to leaf function, variations in pigment content, especially chlorophyll, are good indicators of stress (Sims and Gamon, 2002, Jones and Schofield, 2008). Early detection of plant stress relies on identification of spectral regions of reflectance most responsive to adverse growth conditions (Carter and Miller, 1994). Stress sufficient to inhibit chlorophyll production can be detected first as increased reflectance at wavelengths of weak absorption, between 690 and 700 nm (Carter, 1993). Strong absorbing pigments must decrease dramatically in the violet-blue portion of the spectrum at 420 nm for reflectance to increase appreciably (Carter and Miller, 1994).

Reflectance in the visible spectrum, particularly the green region near 550 nm and the red region near 710 nm, increased in response to stress, regardless of the agent of stress or the species of plant; however, the differences near 710 nm were greater than those near 550 nm. Infrared reflectance was more variable, with stress causing no change or inconsistent change. The increased reflectance near 700 nm represents a shift towards shorter wavelengths, or a ‘blue-shift’ of the red edge. A blue shift of the red edge is caused by decreased absorption in the red region due to decreased absorption by pigments, and increased absorption in the NIR region due to changes in cell structure or leaf layers. The response to stress in the visible spectrum was not unique for particular stress agents and lends support to the idea that physiological responses to stress are similar across different types of stress.

2.4.7. Red edge of reflectance

Chlorophyll content in plants changes for a variety of reasons and these changes can be detected by observing wavelength shifts in the red edge of reflectance. Gates et al. (1965) were the first to note that changes in the red edge may be indicative of changes in chlorophyll content. It has been observed that as chlorophyll content increases, the red edge shifts to progressively longer wavelengths. Chlorophyll content generally increases as plants mature, and begins to decrease as plants undergo senescence (Baret et al., 1987).

The red edge shift is a unique phenomenon that can be observed independently of background variations and allows detection of subtle states of plant condition or stress (Collins, 1978). Vegetation stress varies by type and degree, and may cause biochemical changes at the cellular and leaf level that may influence pigment systems and canopy moisture content, or cause changes to the canopy structure, coverage or biomass (Clevers, 1994).
2.4.8. Vegetation indices
Vegetation indices are transformations of spectral bands utilized to reduce the dimensionality of data, enhance sensitivity to plant biophysical parameters, compensate for atmospheric effects, and normalize topography, canopy or soil variations (Jensen, 2007). Indices utilized to calculate the red edge of reflectance are based on the wavelength position of the transition between low reflectance in the red region of the spectrum and high reflectance in the NIR region (Horler et al., 1983a). (Guyot and Baret, 1988) developed a linear interpolation to determine the red edge wavelength by assuming the reflectance of the red edge could be simplified to a straight line centered on a midpoint between reflectance in the NIR region at 780 nm and the reflectance minimum of the chlorophyll absorption feature at 670 nm. This method of determining the red edge position (REP) uses only four wavelength bands. Theoretical studies using radioactive transfer models determined that the position of the red edge as calculated with the REP index moves toward longer wavelengths as chlorophyll content increases, and the largest effects occur at low levels of chlorophyll (Clevers and Jongsaap, 2001). The REP also moves towards longer wavelengths as LAI increases. When both chlorophyll content and LAI increase, the REP shifts towards longer wavelengths. The REP is fairly insensitive to soil background, and a small shift to longer wavelengths occurs with increasing soil reflectance. This shift is most pronounced at low LAI values, yet even at low LAI values, there is scarcely any influence on the position of the red edge. Simulation studies have also concluded that atmospheric conditions do not affect the position of the red edge. The red-edge index developed by (Guyot and Baret, 1988) offers a method to measure changes in chlorophyll content and LAI without interference from external factors such as soil brightness and atmospheric conditions.

2.4.9. Application of remote sensing technology in agriculture
Remote sensing has been used in agriculture for many decades. One of its earliest applications was on crop disease assessment. Reflectance data was found to be capable of detecting changes in the biophysical properties of plant leaf and canopy associated with pathogens and insect pests. Additionally, remote sensing may provide a better means to objectively quantify disease stress than visual assessment methods, and it can be used to repeatedly collect sample measurements non-destructively and non-invasively.

Studies on the use of remote sensing for crop disease assessment started long time ago. For example, in the late 1920s, aerial photography was used in detecting cotton root rot (Taubenhaus et al., 1929). The use of infrared photographs was first reported in determining the prevalence of certain cereal crop diseases (Colwell, 1956). In the early 1980s, (Toler et al., 1981) used aerial color infrared photography to detect root rot of cotton and wheat stem rust. In these studies, airborne cameras were used to record the
reflected electromagnetic energy on analogue films covering broad spectral bands. Since then, remote sensing technology has changed significantly. Satellite based imaging sensors, equipped with improved spatial, spectral and radiometric resolutions, offer enhanced capabilities over those of previous systems. Pathogens and pests can induce physiological stresses and physical changes in plants, such as chlorosis or yellowing (reduction in plant pigment), necrosis (damage on cells), abnormal growth, wilting, stunting, leaf curling, etc. (Nutter and Gaunt, 1996). Incidentally, these changes can alter the reflectance properties of plants. In the visible portion of the electromagnetic spectrum (approx. 400nm to 700nm), the reflectance of green healthy vegetation is relatively low due to strong absorption by pigments (e.g. chlorophyll) in plant leaves. If there is a reduction in pigments due to pests or diseases, the reflectance in this spectral region will increase. (Vigier et al., 2004) found that reflectance in the red wavelengths (e.g. 675–685nm) contributed the most in the detection of sclerotinia stem rot infection in soybeans.

2.4.10. Remote sensing for crop protection

Research and technological advances in the field of remote sensing have greatly enhanced our ability to detect and quantify physical and biological stresses that affect the productivity of agricultural crops. Reflected light in specific visible, near- and middle-infrared regions of the electromagnetic spectrum have proved useful in detection of nutrient deficiencies, disease, and weed and insect infestations. Multispectral vegetation indices derived from crop canopy reflectance in relatively wide wavebands can be used to monitor the growth response of plants in relation to measured or predicted climate variables. Any deviation from the expected seasonal pattern signals a potential problem and warrants further investigation by agricultural resource managers. The thermal infrared acquired from aircraft or satellite platforms can identify areas susceptible to frost damage, quantify crop water stress and provide some previsual disease detection capabilities. Continued research is needed to quantify the relationship between crop stress and remotely sensed parameters. Techniques need to be developed to implement surveillance over large areas and deliver relevant information to growers and consultants in time for preventative action to be taken.

2.4.11. Application of remote sensing in the monitoring of citrus tristeza virus (CTV)

A study was conducted in the application of remote sensing in the detection on a large scale of CTV in citrus species in order to early detect virus outbreaks. To this aim, high correlation of leaf-level indices with CTV infection, the suitability of ground-based sensors for early detection of CTV was evaluated. By these preliminary results of proximal sensing at leaf and
canopy level, aerial hyperspectral image could be used as a tool to support the monitoring of the virus (Buneb. M, 2009).
Objectives of the study

The main objective of this study was to investigate the possibility of discrimination of *P. canariensis* palms RPW infested and healthy by the use of proximal sensing as a preliminary phase for the application of remote sensing; this objective will be pursued by the acquisition of leaf and canopy spectrometer analyses.

Evaluation of the tree injection efficacy against RPW in protecting *P. canariensis* palms located in IAMB campus. This objective will be achieved by localizing *P. canariensis* palms in the area around the IAMB campus.

To realize this main objective, we subdivided it into sub objectives:

(1) To identify the potential spectral regions containing information regarding species discrimination. (Use of the spectral measures).

(2) Localization of *P. canariensis* palms by the:
   - Aerial photo-interpretation
   - Field visual inspection
   - Pest evolution in time and space
Chapter 3

Possible discrimination of *P. canariensis* palms RPW infested and healthy by proximal sensing as a preliminary phase for the application of remote sensing

3.1. Material and methods

3.1.1. Study site

This study was conducted in Bari (Southern Italy), at the ‘FIERA DEL LEVANTE’, which is a public area for exhibition (Fig.6).

![Figure 6: Location of the study site in Bari, Apulia.](image)

In this site, a total of 21 monumental *P. canariensis* palms are present and characterizing the beauty of this place (Fig.7). The recent RPW dissemination in Apulia has also interested these palms; the present situation after the infestation is that (i) N. 2 palms have been eliminated because induced to death by the infestation (N. 15, 21); (ii) 5 palms show clear cut RPW damages (N. 4, 9, 11, 13, 14); (iii) the remaining ones are apparently not infested yet (Fig.8).
Chapter 3  Possible discrimination of *P. canariensis* palms RPW infested and healthy by proximal sensing as a preliminary phase for the application of remote sensing

Figure 7: Localization of *P. canariensis* palms in ‘Fiera del Levante’.
Figure 8: Status of the *canariensis* palms in ‘Fiera del Levante’.

3.1.2. Choice of the palms
The choice of the palms was based on the type of damage induced by the RPW and on sex discrimination. The RPW infestation could be evaluated on the bases of the following types of damages: i) upper leaves are eaten as angle shape at the end of the leaf; ii) abnormal distribution of the canopy leaves; iii) appearance of one or two dry leaves from the centre of canopy; iv) loss spherical shape of the canopy; v) chewed tissue between the central leaves of canopy. Five asymptomatic palms (4 males and 1 female) and 5 damaged palms (3 males and 2 females) were selected in May 2010 for canopy reflectance measurements. One palm was also sampled for leaf analyses in laboratory.

3.1.3. Spectroradiometric measures

3.1.3.1. Canopy analyses

At clear sky conditions and nadir position (10.00-13.00 AM), canopy reflectance measurements were performed in all selected palms by the use of Field Spec (Analyical Spectral Devices, Inc., Boulder, CO, USA Handheld portable spectrometer) in the range between 325 and 1075 nm and with 512 bands, as described in ASD instructions. The spectrometer was connected to a notebook and to a fiber optic (10 mt of length); the latter was supported by a pistol grip for measurements. The spectrometer acquisition angle at about 1 mt on the top of the canopy was 25° and the corresponding acquisition area was 0.15 m². Calibration of the instrument was carried out by a reference panel (Labshere, Inc.) at 99% of reflectance. Reflectance signals were recorded from 14 different points along the canopy diameter. This operation has been done for each tree in a maximum of 5 minutes time (Fig.9).

The spectrometer was linked to a handheld computer; by the RS³ software (ASD, 1999) the visualization of the spectral signature of each measurement point as well as the reference panel was performed. After signal stabilization, the spectral signature was saved in the appropriate file for further processing and analyses in laboratory.
3.1.3.2. Leaf analyses

This analysis was performed on leaf in order to evaluate in detail the spectral signature of a palm with a moderate infestation level (palm N. 14). To this aim, 7 damaged leaves have been collected and analyzed in laboratory (Table 5).

**Table 5:** Leaf samples and number of leaf spectral measures of the RPW-infested palm N. 14.

<table>
<thead>
<tr>
<th>N. Leaf</th>
<th>N. Measure</th>
<th>Type of damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>Boring</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>Boring</td>
</tr>
</tbody>
</table>
### Chapter 3  Possible discrimination of *P. canariensis* palms RPW infested and healthy by proximal sensing as a preliminary phase for the application of remote sensing

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>34</td>
<td>Topped leaf, chewed leaf</td>
</tr>
<tr>
<td>4</td>
<td>29</td>
<td>Yellowing in the apical part</td>
</tr>
</tbody>
</table>
| 5 | 31 | Tunnel with larva  
Yellowing in the apical part |
| 6 | 30 | Tunnel  
Yellowing in the apical part |
| 7 | 34 | No damage |

Measurements were acquired in controlled conditions using a Plant Probe-Leaf Clip (ASD), linked to a spectrometer by a fiber optic 1 m long (fig.10).

The input interface Plant Probe-Leaf Clip ensures lighting conditions to portions of leaves to be analyzed, stable and repeatable (100 W halogen reflecting lamp); in this conditions spectral signatures can be acquired at any time of the day. The instrument calibration has been carried out by a
thermoplastic disc (Spectralon), which is inside the Leaf Clip system. Spectral signatures of each leaf was visualized and recorded through the RS³ software installed in a notebook connected to the spectroradiometer during measurements.

Figure 10: Acquisition instruments for spectral reflectance measurements in leaves.
3.2. Results and Discussion

3.2.1. Spectral analyses

The measured reflectance values (canopy and leaf) were elaborated and represented by ViewSpecPro® software of ASD Inc.

3.2.1.1. Canopy analyses

No discrimination was observed evaluating the spectral signatures of the measured canopies and marking in red color the infested palms and in green color the non-infested. This result was better shown by calculating the means of each group (infested and non-infested) and evaluating their spectral distance as indicated in (fig.11).

Figure 11: (a) spectral signatures of asymptomatic and symptomatic palms; (b) mean of hyperspectral reflectance of healthy (green color) and RPW-infested palms.
infested palms (red color); (c) spectral distance of the mean values of infested and healthy palms.

However, the previous evaluation did not consider the sexual palm differences, as male and female. The palm sex discrimination by spectral analyses is a consistent result as shown in (fig. 12), where female palms (marked in pink color) are well distinguished from the male individuals (marked in blue color).

**Figure 12:** (a) Spectral signatures of 7 male palms and 3 female palms; (b) mean reflectance spectra of male and female palms; (c) spectral distance of the mean of female and male groups.

The spectral distance of the means of the two groups shows a relevant discrimination; therefore an investigation was made on a larger sample. In particular, the difference shown in the visible range is mostly correlated to the orange clusters in the females; this color enhances the reflectance values at the green-yellow wavelengths (about 600 nm).
Based on these results, no discrimination between infested and healthy palms could be seen when spectral signatures were evaluated without a separation between male and female palms. On the contrary, a good discrimination was obtained when the evaluation was made only inside the male individuals. In this case, the spectral difference was increased by the severe symptoms occurring in palm N. 9. A figure shows the mean of canopy spectral signatures of RPW non-infested palms and RPW highly infested palms. In the case of the highly infested palm, which showed a necrotic apex (Fig.13), the spectral reflectance highlighted a great difference, mainly at the plateau, between this palm and the mean of healthy ones. This difference is well shown in (Fig. 14), where the spectral distance is represented.

Figure 13: *P. canariensis* palm showing necrotic apex.
Chapter 3  Possible discrimination of *P. canariensis* palms RPW infested and healthy by proximal sensing as a preliminary phase for the application of remote sensing

![Figure 14](image)

**Figure 14:** (a) mean of hyperspectral reflectance of healthy (green color) and RPW-infested palms (red color); (b) spectral distance of the mean values of infested and healthy palms.

These results we could better from the obtained results of the spectrometric measures we can conclude that it is possible to detect the highly RPW infested trees as the spectral reflectance reading of the highly infested palm trees is different than the spectral reflectance readings of the healthy palm trees, although the results were not so promising in comparison between the early infested palm tree and the healthy ones but the potential of the spectrometric measures in discriminating between healthy and infested palm trees is still possible as by doing the measures in each sex in separate the measures show variations between healthy and infected palm trees. In the case of spectral signatures referred to palm sex, data in Fig.13 show a difference among female (pink) and male (blue) colors. This clear
discrimination was assessed in the representation of the mean values of females and males in all acquisition range.

### 3.2.1.2. Leaf analyses

(Fig.15) shows the reflectance values obtained from the elaboration of the spectral signatures of the leaves collected from the infested palm N. 14. The means of the spectral curves acquired from each leaves have been graphically represented in red color with respect to the remaining. Certain reflectance variability was noticed in the visible range (close to the green wavelength) and a typical reflectance curve of a leaf not showing any type of stress. This spectral condition could be related to a nutrient deficiency of the palm after being infested by the RPW; in fact, tunnels inside the apical stripe of an infested palm induced by the weevil during its life cycle can influence the nutritional status of the palms in relation to their quantity. Nevertheless, a more consistent sample is needed to clarify this aspect either in infested that in non-infested palms.

![Figure 15: Leaf spectral signatures in palm N.14.](image-url)
Chapter 4

Evaluation of the efficacy of tree injection against RPW in protecting *P. canariensis* palms located in IAMB campus

4.1. Material and methods

4.1.1. Study site

The research work was conducted in the area surrounding the campus of the Mediterranean Agronomic Institute (IAMB), which is located in Valenzano (province of Bari), Apulia region (Southern Italy) (Fig. 16); the geographical references of Valenzano are: 72 meter above the sea level, latitude 41°03’16” North and longitude 16° 52’ 45” East Greenwich. The campus of IAMB is the place where pesticide trunk injection trials in symptomless palms of *P. canariensis* were conducted since 2006, as a preventive measure against infestations and damages by the red palm weevil. Being these palms still symptomless, the efficacy of trunk injections were evaluated by (i) estimating the number of palms in the area close to the campus; (ii) assessing their RPW-infestation status. The applied techniques were the photogrammetric recognition of aerial images (photointerpretation) and visual inspection of the palms.

![Figure 16: Location of the study site in Valenzano, Apulia.](image)

4.1.2. Verification of tree injection treatment

Trunk injections (patent 9616PTIT dep.brev. BA2009A000014 int. code A 01
Chapter 4

Evaluation of the efficacy of tree injection against RPW in protecting *P. canariensis* palms located in IAMB campus

G 29 00 - Metodo e dispositivo per iniettare fitofarmaci in piante) using Imidacloprid, Dimethoate and Fenthion, were conducted in the IAMB campus, since 2006, on 15 *Phoenix canariensis* palms (6 females and 9 males), 15-25 years old and 3-6 meters tall.

The treatment consists in injecting the pesticides into the trunk. This treatment has been done by making holes in the palm stripe; two holes were made for each palm on 160 cm height from the ground. Electrical drill and drill tip auger (40 cm length, 16 mm diameter) have been used to bore these holes in 45° angle to downward, inside the trunk where the injectors were placed. The pesticides were added directly into the injectors without dilution, dose was 20 ml (commercial insecticide) per injector per time. The pesticide was gently (0.2-0.4 bar) pushed into the palm by a 1 liter water filled tourniquet.

Water influx was controlled by a ball valve that was opened in approximately at the same time. After the water was absorbed, the tourniquet were removed and replaced by stoppers.

Electric generator 1.5 KVA was used to provide the electricity power for the drill and the apparatus (Hasanein et al, 2008)

![Image](image1.png)

**Figure 17:** Pesticide trunk injection: (a) injector with 1 liter water filled tourniquet for pesticide pressure.

**4.1.3. Aerial photo-interpretation**

An ortho-image RGB with resolution of 15 cm, which was dated 2006, was chosen being 2006 the year of the treatment trial in palms at IAMB campus (Fig. 18).
Figure 18: RGB ortho-photo of 2006 showing part of IAMB campus.

Aerial photo-interpretation, as described by (Brivio et al., 2006), was used in order to extract all the information relatively to elements which are represented in the (Fig. 19). The technique of photo-interpretation includes all the operations which make easier the use and interpretation of aerial photos, either qualitatively either quantitatively. In this interpretation process, the analyses of some parameters, which characterize the image such as shape, size, color, texture and structure, are considered. In this study a model including all the previous parameters correlated to the *P. canariensis* palms was set up following the scheme reported in (Fig. 19).
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4.1.4. Visual inspection for palm localization and symptom observation

Visual inspections were conducted in the area of Valenzano in order to gain information about ground truth data with respect to the data acquired by aerial photo-interpretation. All the palms, which could be possible to inspect, were mapped on the RGB image, by marking their position and numbering all the individuals. Information was also acquired on the status of *P. canariensis* palms relatively to RPW infestation, distinguishing severe damages (umbrella shape of the canopy) from early stages damages as: i) angle shape at the end of the upper leaves; ii) abnormal distribution of the canopy leaves iii) one or two dry leaves from the centre of canopy; iv) loss of spherical shape of the canopy; v) chewed tissue between the central leaves.
4.2. Result and Discussion

4.2.1. Photo-interpretation process

After importing in GIS (software ArcView 9.3 of Esri) RGB image of 2006 referring to the area surrounding IAMB in Valenzano, the image was orthorettified in the geographic coordinate system UTM WGS84 33N, in order to assure the exact geographic localization of the area. On this image, a photo-interpretation of the dataset RGB was made by generating a layer of points; this shape file was containing the geographic and descriptive information (Data Base) of the recognized palms (interpretation key). Results of this process are shown in (Fig. 20), where *P. canariensis* are marked by green color circles.

![Photo-interpretation process](image)

**Figure 20:** Layer and attributes of photo-interpreted *P. canariensis*.

The number of palms which were identified as *canariensis* was 225; they were distributed in an area of 1.28 km$^2$ (north-west of the Valenzano administrative area) which corresponds to 8 % of the total Valenzano administrative area (15.82 Km$^2$). With reference to the urban area of Valenzano, the investigated area is a representative sample, being the 47 % (Fig. 21).
4.2.2. Visual inspection

Results of visual inspections, which were carried out in spring-summer period 2010, were reported on a paper map at 1:1000 (geographical palm position) and on a model of paper sheet (palm infestation status). These results were implemented in GIS and a new layer was generated (shape file) with both collected data (Fig. 22).

**Figure 21**: Status of the art of *P. canariensis* palms identified in the study area.
Inspections data, which are reported in Table 6 and represented in (Fig. 23), show the rate of symptomatic and dead palms in relation to the 230 investigated palms; moreover, palms which were difficult to visually inspect were also reported.

Table 6: Rate of dead, symptomatic and asymptomatic inspected P. canariensis palms.

<table>
<thead>
<tr>
<th>Asymptomatic</th>
<th>Treated</th>
<th>Symptomatic</th>
<th>Dead</th>
<th>Undetectable</th>
</tr>
</thead>
<tbody>
<tr>
<td>192</td>
<td>15</td>
<td>16</td>
<td>1</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 23: The rate of symptomatic and dead palms in relation to the 230 investigated palms.
Figure 24: Map of the infestation status of *P. canariensis* inspected palms.

### 4.2.3. Infestation evolution in time and space

(Fig. 24) highlights the spatial distribution of the infestation grade in the study area and the asymptomatic status of the 15 *P. canariensis* palms in IAMB, which were treated by tree injection since 2006. It is evident that these palms are still not attacked by the red palm weevil, whereas in the nearby area 14 are damaged and 1 is dead. In true, the number of dead palms from 2006 up today is much more severe because many dead individuals have been already removed.

Temporal analysis on the number of dead *canariensis* palms was made by overlapping the layers previously obtained by photo-interpretation and visual
inspections (Fig.26). These data on the presence-absence of *P. canariensis* palms in the study area highlighted the absence of 51 additional palms, which could be most probably attributed to red palm weevil attacks, considering the high infestation rate which is about 24%.

**Figure 25**: Map of the status of the palms in the period 2006-2010.

As reported in (Fig. 25), the overlapping of the layers shows close red-green points, single red and green points. The case of close red-green points underlines the presence of the palms either in 2006 (photo-interpretation) either in 2010 (inspection), whereas the other 2 cases underline the palm localization by both procedures. This situation can be explained by the fact that:
• palms were present in 2006 and 2010 (identification by both techniques);

• palms were hided by another tree of bigger size (mutual exclusion by both techniques);

• new palms were planted after the image acquisition time (identification only by visual inspection);

• palms died most probably because severely infested by the RPW, after the acquisition time (identification by photo-interpretation);

• error can be made by the operator in applying both techniques;

• others.

In order to quantify the dead palms number, which were most probably infested by the RPW in the period 2006-2010, the following criteria was adopted:

1. palms, which were detected by both techniques, were excluded using an algorithm in ArcVieW, which identified as 7 mt the minimum nearby distance between two palms;

2. with reference to the layer 2006, dead palms were considered all palms which were not identified (no colour marked) in layer 2010 (using an algorithm similar to the previous one);

3. visual inspections in the sites and assessment of the dead palm.

Even if underestimated, 51 is the number of palms identified by this procedure. *P. canariensis*, which have died by weevil attacks, were not detected by visual inspection in 2010. Palms, which were found by the temporal analysis, were also added in the layer corresponding to the 2010 palm status (Table 7); this layer shows a new temporal and spatial distribution of the infestation in the area around IAMB (fig. 26).

**Table 7**: RPW infestation status in the study area of *P. canariensis* in the period 2006 - 2010.

<table>
<thead>
<tr>
<th>Asymptomatic</th>
<th>Treated</th>
<th>Symptomatic</th>
<th>Dead</th>
<th>Undetectable</th>
</tr>
</thead>
<tbody>
<tr>
<td>192</td>
<td>15</td>
<td>16</td>
<td>52</td>
<td>6</td>
</tr>
</tbody>
</table>
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Figure 26: Infestation status in space and time of *P. canariensis* in the study site.

(Fig. 26) reports the distribution in space and time of the infestation status of the surrounding area of IAMB in Valenzano. It is clear that the 15 palms in IAMB which have been treated by pesticide trunk injections since 2006 are still undamaged by RPW attacks; on the contrary, the weevil induced in the
surrounding area damages in 14 palms and the dead of about 52 palms; the latter were removed.
Chapter 5

Conclusion

GIS (Geographic Information System), photogrammetry, spectral analyses and satellite images offers potential investigation tools to support and improve integrated pest management programmes on a large scale. By the application of these techniques is possible to monitor plants and to set up planning programmes at site and territorial levels for precision intervention in pest/pathogen control and management. These techniques, in combination with the knowledge of climatic data, may be most efficiently used to predict conditions in which a particular disease or pest damage may occur and forecast the occurrence, rather than monitoring possible infestations.

This work was intended to preliminary explore the use of spectrometry for a possible discrimination of leaf and canopy stresses in *P. canariensis*, which are related to damages induced by *R. ferrugineus*. Despite the limited number of palm individuals (due to the difficulties to acquire spectral signatures on the top of the canopy), preliminary results were obtained in terms of: (i) discrimination between male and female individuals; (ii) inside the same sex, discrimination between severely damaged and non damaged canopy; (iii) leaf nutritional disorders related to the RPW damages. Being infested palms only discriminated when damages are severe, any type of intervention become unfortunately useless at this stage. These results are not in accordance with spectral discrimination in CTV-infected citrus trees which was observed at different symptomatic stages (different leaf chlorosis grades and canopy decline) as well as in asymptomatic trees; specific vegetation indices were set up in citrus strictly correlated to CTV infection (Ikhrichi, 2008; Bounéb, 2009). Therefore, it will be advisable to continue spectral investigations on a more consistent number of palm samples in order to identify specific vegetation indices (set of spectral parameters) able to better describe the stress condition associated to damage evolution in infested palms. Based on preliminary spectral measures and on spot territorial palm localization, satellite images could not be applied in this study. The minimum geometric resolution by satellite images is 0,5 mt (0,4 mt for military use) and represents a limit for a precise geographical localization of palms.

The combination of high resolution RGB images (0,15 mt) with GIS and the knowledge of the infestation status in 2010 allowed to reliably identify and map *P. canariensis* palms in the study area and approximately calculate the number of palm individuals which have been removed in the period 2006-2010, apparently due to RPW infestation. By an accurate analysis in space and time, a severe level of RPW infestation in Valenzano area was assessed in order to prove the success of preventive protection trials by pesticide injections of IAMB *P. canariensis* palms during the same period. A new
scenario was developed in preventive pest control by palm injections thanks to the accurate knowledge of the area (maps); this approach can be fundamental for a sustainable management of Canary palms in RPW-infested areas as well as in areas which are apparently pest free; it can also be extended to the pest control of other palm crop species (e.g. *P. dactylifera*), which are of great economical importance in Mediterranean rural areas.

Based on spectral data, the identification of severely infested palms by satellite images could already provide useful information on palm pest infestation, in terms of presence and distribution, in order to evaluate and plan the removal of severe damaged palms and analyze pest infestation evolution.

The combination of GIS, proximal and remote sensing can efficiently support intervention planning and epidemiological analyses on large scale. The overlap of a multispectral analyses (based on satellite image) on a geographical localization of the target palm (based on RGB image) can only improve pest control in time and identify palms in space by an automatic and consistent procedure (recognition algorithms). The implementation in citrus of a procedure for the rapid identification of suspected CTV-infected sites is now at the validation phase (Bouneb, 2009) and represents a concrete example on the use of these disciplines in precision plant protection.


References


