AperTO - Archivio Istituzionale Open Access dell'Università di Torino

Devices to detect red palm weevil infestation on palm species

This is a pre print version of the following article:

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/1693676> since 2020-04-03T18:48:30Z

Published version:

DOI:10.1007/s11119-018-9573-6

Terms of use:

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 0

Pugliese Massimo*, Rettori Andrea Alberto*** Martinis Roberto***, Al-Rohily Khalid***, Al-Maashi Ali***

* AgriNewTech srl, Via Livorno 60, 10144 Turin, Italy;

** Studio Associato Planta, Via Chiesa 19, 10090 Rosta (TO), Italy;

*** Saudi Basic Industries Corporation, Riyadh, Kingdom of Saudi Arabia

Abstract

The date palm (*Phoenix dactylifera* L.) and other palm species have recently been threatened by the red palm weevil (RPW) *Rhynchophorus ferrugineus* Olivier, which is very difficult to be detected at early stage. This research tested non invasive approaches to detecting RPW including: a TreeRadarUnit™ (TRU); a densitometer, a penetrometer used for evaluation of the standing trees stability; a thermal camera and a digital camera. The technologies were applied in Italy on 715 palms (173 *P. dactylifera*, 453 *Phoenix canariensis* Chabaud and 311 of other palm species), and on 86 adult date palms in Saudi Arabia. In Italy, the thermal camera showed a high accuracy (96.29%) compared to close visual observation over the following nine months. The digital camera did almost as well (92.57%). Tree Radar Unit and densitometer also showed good accuracy (83.33 and 88.89% respectively). In the Kingdom of Saudi Arabia, the thermal camera showed a good accuracy (77.73%) when compared to invasive diagnosis (i.e. cutting down and opening up palm trunks). The digital camera showed a lower accuracy of 66.67% due to the fact that the red weevil mainly attacks the base of the stem and therefore there are no visible symptoms on the crown shape that would be picked up in image analysis. TRU gave good results (74.73% compared to invasive diagnosis), with the best accuracy at ground level (80.65%). The densitometer results were similar to the TRU case, with higher accuracy (82.26% compared to invasive diagnosis) and the highest at ground level (87.10%).

Keywords: *Rhynchophorus ferrugineus*; precision farming; Tree Radar Unit; densitometer; thermal camera.

Introduction

31 The date palm (*Phoenix dactylifera* L.) is an important economic resource for many countries,
32 especially the Kingdom of Saudi Arabia (KSA), and countries in the Middle East and North Africa.
33 In those areas, date palms are a major agricultural crop, with production of high quality dates and at
34 the same time cultural relevance. The number of date palm trees is about 100 million worldwide of
35 which 62 million palms can be found in the Arab Gulf countries (FAO, <http://www.fao.org>). In
36 Southern Europe, although less widespread than the *Phoenix canariensis*, date palm represents an
37 important element of the landscape in seaside areas. In Italy, they are present along boulevards or in
38 public parks and private gardens, especially in the coastal areas of the southern regions. In urban
39 areas decay inside the stem, at different levels (base and/or top), could also represent a safety
40 problem for the public (EPPO, 2007)

41 Date palms (and other palm species) are being severely damaged in all these countries by
42 *Rhynchophorus ferrugineus* Olivier (Red Palm Weevil - RPW), a native pest of South and South
43 East Asia. It causes serious and important crop and landscape damage (EPPO, 2007). The Red Palm
44 Weevil is an economically important tissue-boring pest of date palm trees widespread in many parts
45 of the world. RPW is a member of *Coleoptera: Curculionidae*. The male and female adults are large
46 reddish brown beetles about 3 cm long and with a characteristic long curved rostrum; with strong
47 wings, they are capable of undertaking long flights (Salama et al., 2009). RPW damage to palms is
48 produced mainly by the larvae. Adult females lay about 200 eggs at the base of young leaves or in
49 wounds to the leaves and trunks; the grubs feed on the soft fibers and terminal bud tissues. They
50 reach a size of more than 5 cm before pupation. Just before pupating they move towards inner
51 tissues of the palm tree making tunnels and large cavities. They can be found in any place within
52 the palm (Alkhalil et al., 2009) from the base of the trunk where the roots emerge up to the apical
53 bud. About 70% of infestations along the trunks of date palm trees occurred from the ground up to
54 1 -1.5 m. On other palm trees (i.e. *P. canariensis*) the attacks occur principally near the apical bud
55 (80-90%) (Pugliese et al., 2017).

56 RPW comes from southern Asia and Melanesia, where it is a severe pest of coconuts (*Cocos*
57 *nucifera*). This weevil has been spreading westwards very rapidly since the mid 1980s. RPW
58 reached the eastern region of the Kingdom of Saudi Arabia, the northern United Arab Emirates,
59 and then it spread to almost the entire U.A.E. and Oman by 1985. In Iran, it was reported in 1990
60 and it was discovered in Egypt at the end of 1992. In 1994, it had been captured in the south of
61 Spain. It was observed in Italy in 2004. During August 2010, RPW adult and weevil larvae were
62 reported in the city of Laguna Beach, Orange County, California (USA): this was the first record of
63 this pest in the USA (Vacante, 2013). The spread of this pest occurs due to transporting infested

64 young or adult date palm trees and offshoots from contaminated areas (Vacante, 2013). The external
65 symptoms on infested palm trees are a progressive yellowing of the leaf area, destruction of the
66 rising leaf and also necrosis in the flowers as a result of the destruction of internal tissues of the
67 palm tree by the larvae and the reduced flow of sap. Leaves begin to dry in ascending order in the
68 crown. Eventually the apical leaf bends and eventually drops. However, external symptoms on date
69 palm trees are not clear enough for an identification because damage primarily occurs at the bottom
70 level of the trunk, and consequently, compared to other palm species, they are more difficult to
71 diagnose and never present at an early stage of the attack. Internally, the galleries and damage to
72 leaf-stems produced by the larvae are easily detected in seriously infested plants. Pupae and old
73 larvae are frequently found by inspecting the crown of infested plants. Affected plant tissue turns
74 foul, producing strong characteristic odors (EPPO, 2007). For these reasons it is very important to
75 study a feasible method to detect the infected palm tree at an early stage, particularly on date palms.

76 Several methods are applied to detect palm trees infestation with the use of pheromone baited traps
77 being one of the most common (Al-Saoud et al., 2010; Vidyasagar et al., 2000). RPW is highly
78 attracted to two different types of odours:

- 79   ○ volatiles emanating from unhealthy or damaged palm trees, or pineapple and sugar cane.
- 80   ○ aggregation pheromones (commercially available) which male weevils release to attract
81   other male and female weevils (ex. rhynchopherol, rhynchopherol and ethyl acetate).

82 Neither the stressed palm “odors” or the weevil aggregation pheromone are very effective on their
83 own. However, in combination they can be powerful in attracting weevils to traps. Another method
84 applied is the visual survey. It is difficult to apply it because it is not easy to detect in big palms,
85 unless access to the actively growing portions can be observed. It is important that arborists,
86 working in palm canopies, to pay attention for signs of larval mines and/or excrement in leaf bases
87 in the central growing point of the palm. These are signs of early infestation. On date palm trees it is
88 very important to also observe each tree near the ground.

89 Other techniques under study are:

- 90   - bioacoustic detection (Gutiérrez et al., 2010; Mankin, 2011) with tool capable of amplifying
91   the noise made by *R. ferrugineus* larvae;
- 92   - use of thermal detection with portable thermal camera to detect local increase of temperature
93   within the trunk - due to an increase of leaf transpiration - that extends up enough to surface

to be analyzed overtime (at different solar radiation conditions during the day). Diseases induce some changes of both transpiration processes and crown shape, because of damages of vascular tissues (Lhomme and Monteny, 2000; Catena, 2003; Chaerle et al., 2007; Guilioni et al., 2008);

- the use of X-Ray techniques, that is an experimental method that uses a specially designed radiography system. In this way it is possible detect clearly the larvae in the radiographs. Specifically, the different tunnels made inside the tree trunk are clearly visible along with the larvae inside each tunnel. The system is useful to inspect the trade of unplanted palm trees of different sizes exported for landscaping. It is difficult to use this system in open fields (Tofaillia, 2010; Ma et al., 2012).

A variety of devices and techniques have been developed to evaluate tree stability in the last 20 years. There are many legal issues concerning tree care standards, and the owners' liability in case of tree fall. Consequently, scientists have developed a broad literature about tree biomechanics (Rust and van Wassenaeer, 2017). Arborists have described trees as engineered structures, using equations and terms such as modulus of rupture, applied bending moment, and lever arm. Tree stability assessment is based on identifying and assessing structural conditions to evaluate potential failure. There are many methods and all of them have similar logical operations. In all tree inspection protocols, the arborists have to systematically view the tree from top to bottom and move all around it. Sometimes visual assessment is not enough to understand inner trunk conditions. Several internal defect detection technologies have been developed and tested on urban trees: sound velocity measurement, density analysis, tomography, Tree Radar Unit inspections (Trunk and Roots), Pressler borer (drilling technique) and measurement of the wood strength (Fractometer).

Considering the widespread presence of RPW and the difficulties in detecting infected tissues at an early stage, a new approach was applied to study internal palm tissue health by applying technologies adopted on urban trees. This included: thermal imaging to measure trunk temperature and comparing it with temperatures measured from neighboring trees; a tree radar unit (TRU) to detect internal state of wood plants; a digital camera to assess the shape and condition of the palm crown; and a densitometer to measure the resistance of the tree tissues to drilling. As part of a wider project on date palms, funded by Saudi Basic Industries Corporation, the devices were tested for palm inner tissue evaluation. The objective of this work is to compare the efficacy of different non-invasive systems to detect the red palm weevil and to create a methodology for diagnosis. The main hypothesis is that it is possible to detect the pest early in the infestation with a high accuracy

126 without damaging the palms. Because the TRU and the densitometer can identify anomalies in the
127 plant tissues, the hypothesis is that they will have the highest efficacy in detection.

128

129 **Materials and methods**

130 Devices

131 To detect the RPW presence the following tree assessment devices were used:

132 1. Thermal camera: it is a tool used for years in agriculture science to detect plant stress and at
133 experimental level to find hidden cavities inside trunks of woody plants (Brown et. al., 1984;
134 Catena, 2003; Sepulcre-Canto et al., 2006; Chaerle et al., 2007);

135 2. Tree Radar Unit (TRU): Ground Probing Radar used with dedicated software for the analysis of
136 the internal state of wood plants and already used in USA and Europe for decay detection on
137 deciduous trees (Godio et al., 2000; Nicolotti et al., 2003; Sambuelli et al., 2003). Two type of
138 antennas were used: 900 MHz and 2000 MHz. The 2000 MHz antenna was specifically set to be
139 used on palm tissues, because never applied before on plants;

140 3. Digital camera: standard digital camera used to aid the visual analysis and processing digital
141 images (Al-Saqer and Hassan, 2011);

142 4. Densitometer: it is a penetrometer used for evaluation of the standing trees stability (Mattheck et
143 al., 1997; Kersten and Schwarze, 2005). It consists of a drilling needle inserted in the trunk which
144 moves horizontal to the ground and records wood decays. The device applied was the IML RESI
145 PD500 (IML North America, LLC, USA).

146 These four devices were chosen because they are not at all or minimally (densitometer) invasive.
147 The RPW is attracted by wounds to the plants, and consequently these methods avoid attracting the
148 pest and can be applied without providing negative effects for the palms. At the same time they are
149 devices that can be used on a large number of plants per day, they are easily available on the market
150 and all of them are user-friendly and require a very short training period for users.

151

152 Data analysis

153 The digital images of selected palm trees were taken with the thermal measurements in order to
154 obtain pictures of the same palm tree at the same time and with the same view angle through two
155 different techniques. This is important because different weather conditions, the reduction of
156 sunlight, sun reflections and glitters may alter the results, which rely on plant tissues transpiration.
157 The digital images were analysed with a Computer-Aided Drafting (CAD) software for significant
158 differences in shape (slope of leaves, angles) between healthy and infested palm trees. The thermal
159 camera was used to compare internal temperatures of neighbouring palm trees: only a comparison
160 between nearby palm trees shows if a palm is warmer than the others. If a palm is warmer than the
161 others, at the same climate and solar conditions, it is probably infested. Statistical analysis was
162 carried out using an ANOVA Tukey test between pixels of thermal images selected on the health
163 palms compared to those infested.

164 TRU measurements were carried out along the entire trunk of living trees at multiple levels. The
165 results are a kind of cross-section in which it is possible to detect tissue discontinuities, such as the
166 presence of larvae and galleries, without creating damaging the palm trunk. It is also possible to
167 calculate the percentage of residual healthy tissue. The densitometer was used to confirm the TRU
168 results. As with the TRU, the Densitometer can detect inner structural anomalies, even of small
169 size, such as the single tunnel of RPW larva or the wide cavity due to a high infestation. However,
170 the Densitometer always provides a measure depending on the direction of the needle, consequently
171 one or more measurements are necessary to detect the presence of RPW in the trunk. The drilling
172 needle must intercept a gallery that, in the early stage of infestation, is about 1 cm in diameter and
173 horizontal to the ground.

174

175 Experimental sites in Italy and methods adopted

176 The choice of localities in Italy was done in August 2012 in the Regions of Sicily and Lazio,
177 according to the reports of high infestations by RPW. Indeed, the red palm weevil in the selected
178 locations was first reported in the province of Catania in 2005 and in Lazio in 2006 (Eppo, 2007;
179 Vacante, 2013). Four experimental sites were selected in Sicily, all in the Province of Catania near
180 Mount Etna. This is a palm growing area with volcanic soil used by the nursery industry and
181 gardens. Palm trees, healthy and infested, were present on each site. These selected sites were
182 located on private and public land. The attention is focused on nurseries and other places where
183 palm trees of different species and age were present. The same selection was done in Lazio (Central
184 Italy). Five experimental sites were chosen near the cities of Rome and Viterbo, on private and

185 public land. In these areas palm trees of different species and age are present. In both regions (Sicily
186 and Lazio) in all experimental sites healthy adult palm trees were used as controls. The presence (in
187 all sites) of palm trees of different age was verified. All palm trees chosen in nursery had a pot size
188 diameter more than 28 cm wide and palm tree diameter always more than 5 cm large. Different
189 phases of RPW attacks on palm trees were present in all sites.

190 The analyses were done on young palm trees in pots, from a minimum diameter of 5-6 cm
191 (minimum size attacked by RPW), to adult palm trees in open field (from 3 to 8 m of height).
192 Infested and healthy palm trees were analyzed and for each palm the following parameters were
193 recorded:

- 194 • ID: number for identifying the single palm tree;
- 195 • geographical position, in order to recognize all palm trees in each monitoring periods;
- 196 • species;
- 197 • height;
- 198 • diameter at 1.30 m;
- 199 • compass orientation of the analysis (for all devices).

200 Images of each palm tree were captured with thermal and digital cameras. Some palm trees were
201 tested with Densitometer and TRU. In the case of TRU, measurements were carried out on adult
202 palms with both 900 and 2000 MHz antenna at the same level of the trunk. If possible,
203 measurements were carried out on a sector or on entire section of the trunk. In some cases a one-
204 point analysis, corresponding to a single drill in the trunk, was done. On potted palms, due to their
205 small dimensions, only the 2000 MHz antenna was used, with an horizontal to the ground
206 measurement. The measurements with thermal camera were repeated during four monitoring
207 periods in Lazio (October, January, March and May) and three times in Sicily (December, February
208 and May) always on the same palm trees. In this way it was possible to track palm trees infestations
209 and to verify the efficacy and precision of the diagnostic method. During each monitoring period,
210 palms warmer or those with an abnormal crown shape were identified. All palms were observed
211 each monitoring period for symptoms of the RPW presence. The thermal camera files for each palm
212 in different periods of monitoring were compared in order to detect any significant thermal delta.
213 Images analysis was carried out also for the digital camera in the monitoring periods to detect the

214 variation of the crown shape. To verify the effectiveness of the measures, a careful visual inspection
215 was carried out during a period of 9 months on the palms for the presence of RPW (galleries, larvae,
216 cocoons, adults) and of clearly visible symptoms. The visual inspection over the nine month period
217 was considered as the reference point for accuracy calculation.

218

219 Experimental sites in KSA and methods adopted

220 The research was carried out in April 2013 in Riyadh and at the Bin Slama and Al-Matrodi date
221 palm orchards, Al Mahdia valley and Wadi Hanifah, to evaluate the effectiveness of the proposed
222 methodology. The aim of the field activities was to test the efficacy of the devices used in Italy to
223 early detect the presence of Red Palm Weevil on *P. dactylifera*. Infested farms were identified by
224 experts from the Ministry of Agriculture and King Saud University. On these sites 89 date palm
225 trees were selected randomly and tagged.

226 The methodology applied was similar to that used in Italy, with some variations, as shown below:

- 227 1. Thermal camera analysis: shots on 89 date palm trees (53 in the first site, 22 in the second
228 site and 14 in the third one);
- 229 2. Digital camera analysis (crown shape analysis): shots on 89 palm date trees;
- 230 3. Tree Radar activities (on 31 out of 89 palms selected for invasive diagnosis):
- 231   ○ 3 scans at different levels with 2000 MHz antenna (0.2 – 1.0 and 1.5 m) on each
232 palm tree (on plants shorter than 1.5 m one or two measurements were carried out);
- 233   ○ 3 scans at different levels with 900 MHz antenna (0.2 – 1.0 and 1.5 m) on each palm
234 tree (on plants shorter than 1.5 m one or two measures were carried out).

235 Tree radar analysis were repeated twice on the same tree: the first time without clean the
236 bark and the second time on smooth surface without petioles and shoots. This operation
237 was done to assess the effectiveness of penetration of the radar signal.

- 238 4. Densitometer tissue density measurements were carried out on each of the three horizontal
239 to the ground levels analyzed with the tree radar to better interpret and to validate TreeRadar
240 results (2000 MHz and 900 MHz) (on the 31 out of 89 palms selected for invasive
241 diagnosis).

242 All four types of measurement were carried out at the same levels and with the same direction on
243 each date palm tree. For Densitometer the following scale of values were used: (-) Healthy; (+) Low
244 infestation; (++) Medium infestation; (+++) Heavy infestation.

245 Thirty one palm trees were selected among those with clear signs of infestation or suspected to be
246 infested, according to results obtained with the 2 cameras, and analyzed with radar and
247 Densitometer. At the end of the measurements, the 31 palm trees were felled, and the TRU and
248 Densitometer analysis (20, 100 and 150 cm from the ground) conducted to verify the effectiveness
249 of these devices. To verify the effectiveness of the thermal and digital cameras, a careful
250 observation for the presence of RPW was carried out on the trunks of the 31 plants analyzed and cut
251 open. An accuracy percentage was calculated considering the results from cut tree as the reference
252 point.

253

254 **Results**

255 Diagnosis in Italy

256 In total 937 palm trees were analyzed in Italy, including young and adult, infested and healthy
257 palms. The RPW presence was very abundant and infestations were everywhere. Using the thermal
258 camera 25 palm trees of the 937 were initially identified as infested and 12 palms were classified as
259 suspected. The term "suspected" means palm trees with the crown hotter than the surrounding ones,
260 but without any symptoms visible from the outside (sawdust, anomalies in the shape of the crown,
261 decay, etc. ....). After 9 months of monitoring with thermal camera, the final condition of the
262 monitored plants was quite different: 38 were identified as infested and 19 suspected (Tab. 1).
263 Overall, 4% of the palms analyzed were infested and 2% suspected. *P. canariensis*, the most
264 representative (453 palms, 350 of them adults), was the most infested (8,16%). In addition to
265 Canary palm, also some *P. dactylifera* and *Washingtonia robusta* were found suspected and one *W.*
266 *robusta* attacked. Considering only the 350 adults *P. canariensis*, 13 palm trees, defined as
267 suspected during the project, were really infested at the end of the observation period (May 2013)
268 (Tab. 2). A statistically significant difference was found between pixels of thermal images selected
269 on the health palms compared to those infested, with a higher temperatures for the second ones
270 (Tab. 3). With the TRU it was possible to detect discontinuities, such as galleries and holes, even on
271 apparently healthy palm trees. Due to the conformation of the trunk and the type of pruning,
272 sometimes it was not possible to measure the entire section, but it was necessary to analyze sectors

273 or to do horizontal to the ground measurements. Based on careful visual observation of the same
274 plants during 9 months, the accuracy calculated on *P. canariensis* was high: 96.29% for thermal
275 camera and 92.57% for digital camera (Tab. 4). This type of analysis was performed also on the
276 data of TRU and Densitometer on 18 *P. canariensis* trees randomly selected and analyzed with both
277 tools, reaching 88.89% accuracy for Densitometer and 83.33% for TRU (Tab. 5).

278

279 Diagnosis in the Kingdom of Saudi Arabia

280 The aim of this part of activities was to test the efficacy of all devices on date palm trees in the
281 environment of the Arabian Peninsula. Analysis with thermal camera and digital camera were carried
282 out simultaneously on the same palms and it took few hours to be carried out on all 89 date palms,
283 identifying 19 palms infested and 1 dead (Table 6). According to the applied protocol, Densitometer
284 and TRU measurements were carried out on palm trees identified as infested by digital and thermal
285 cameras (19 infested and 1 dead) afterwards. These measurements were carried out on three levels
286 on the trunk (20, 100 and 150 cm to the ground). Subsequently 11 date palm trees showing differing
287 diagnoses with the two cameras (i.e.: infested for thermal and healthy for digital camera, or the
288 opposite), suspected to be infected or with unclear results were analyzed in the same way. At the
289 end of measurements all these 31 (20+11) palms were cut at the three levels of analysis to compare
290 TRU and Densitometer results with cross sections (observed visually). The remaining 58 palms,
291 considered healthy by the two cameras, were carefully inspected for the presence of RPW (galleries,
292 larvae, cocoons, adults) and of clearly visible symptoms and the visual inspection confirmed they
293 were healthy.

294 The Densitometer and TRU had a high percentage of correct diagnoses (Red Palm Weevil presence
295 or not: galleries, larvae, cocoons, adults), particularly at 20 and 150 cm. The Densitometer showed
296 an 87% accuracy and the TRU 80% at 20 cm. In the case of thermal and digital camera, the
297 percentage of accuracy is equal to 77.4% and to 66.6% for thermal and digital cameras respectively
298 (Tab. 7). In Table 7 it is possible to observe that 24 out of 31 plants surveyed (22 infested and
299 healthy 2) have been correctly assessed with an accuracy equivalent to 77.42 %. Considering that
300 26 plants were really infested and 22 of them have been correctly identified by the thermal camera
301 with a percentage of success equal to 84.6%. False positive cases were 3 out of 26, corresponding to
302 9.7%, and false negative cases were 4, corresponding to 12.9% (Tab. 7). There were no significant
303 differences in diagnostic accuracy between the devices used, except for the digital camera (Tab. 8).

304

305 **Discussion**

306 Devices and techniques, applied to evaluate tree stability in the last 20 years in other environments,
307 were tested for the early detection of RPW infestations in Italy and Saudi Arabia. All instruments
308 have long been used in agriculture and in arboriculture, but it is the first time they are used all
309 together and at the same time to make a RPW diagnosis. Regarding the TRU in particular the 2000
310 MHz antenna was used for the first time in this field.

311 In both countries all four selected methodologies have shown a diagnostic capacity, the digital
312 camera was less accurate on date palm in KSA than the other technologies. In Italy thermal camera
313 had a very high accuracy (96.29%). compared to the reference point which was visual inspection for
314 the presence of RPW and symptoms. The digital camera also was highly accurate (92.57%). Tree
315 Radar Unit and Densitometer were used to verify the diagnoses and to test the instruments. They
316 also showed a high accuracy (83.33 and 88.89% respectively) compared to the reference point. The
317 high accuracy of thermal camera in Italy is due to the fact that many plants are constantly treated
318 against the RPW making it easy to verify the diagnosis on the relatively few infested palms (8.16%
319 *P. canariensis* was infested). This data should not suggest that there are no infestations in Italy; in
320 reality there are many palms dead in investigated sites. The high accuracy of the digital camera in
321 Italy is also due to high number of palms treated with pesticides, making easier to identify those
322 infested. Moreover, the different type of attack on *P. canariensis*, which is located on the apical bud
323 and causes an opening of the top leaves in a relatively short time, is easier to be identified in
324 comparison to *P. dactylifera*. With regard to early detection, the thermal camera allows the
325 detection of an attack up to 5 months before visible symptoms. The digital camera diagnosis is
326 usually made when the attack is already quite advanced, but this tool can detect the attack in time to
327 treat (and save) the palm. It can therefore be concluded that the use of digital camera corresponds to
328 a careful visual analysis of the crown and this technique could be spread to people with no
329 experience of red palm weevil infestations and thus no knowledge of crown shape symptoms.

330 In the Kingdom of Saudi Arabia, the tests were carried out on 89 palms, chosen from very infested
331 farms. In this case the protocol, developed for an early diagnosis, was affected by the high RPW
332 infestation level. A group of 31 palms were diagnosed as infested or suspected to be infested using
333 the thermal and digital cameras. Those palm trunks were cut down to clarified their status. The
334 digital camera showed an accuracy equal to 66.67% compared to the reference point (31 cut palm
335 trunks). This may be explained because the red weevil mainly attacks the base of the stem on the

336 date palm and therefore there are often no visible symptoms on crown shape. Thermal camera
337 showed a good accuracy (77.73% out of 31 cut palm trunks) and it detected correctly 84.6% of
338 attacked palms out of the 89 palms tested in the KSA. In any case it is necessary to emphasize that
339 the thermal camera identifies plant stress due to many causes, such as water stress, nutritional
340 deficiencies, fungal diseases, etc. TRU gave good results in the analyzed sections (74.73% out of 31
341 cut palm trunks), with the best accuracy at ground level (20 cm), equal to 80.65%. The
342 Densitometer performed similarly with higher total accuracy (82.26% out of 31 cut palm trunks)
343 and the highest at 20 cm, equal to 87.10%. This high accuracy when the attack is near the ground it
344 is probably due to the presence of high, widespread and repetitive infestation in that portion of the
345 trunk. The results with the TRU and Densitometer were slightly below expectations in the KSA, but
346 it should be noted that these are two tools created and modified to identify all anomalies and
347 alterations in the plant tissues. During field activities these instruments identified several types of
348 structural decay including RPW galleries, but also old infestations or other alterations (e.g. fungal
349 decays).

350 Regarding the use of the TRU, it is also necessary to point out that it is a very sensitive tool and
351 subject to the signal attenuation. In particular, on the unprofessionally pruned palm trees analyzed
352 in Riyadh, , there were problems of coupling between the antenna and the trunk because the area on
353 the trunk was not easily accessible because of the presence of shoots and petioles. In many cases,
354 the analysis with the 900 MHz antenna was impossible and only horizontal to the ground
355 measurements by 2000 MHz were performed. After the cleaning, the situation was improved for the
356 900 MHz antenna, while with the antenna 2000 MHz it remained the same. TRU provides good
357 results, but it needs the intervention of well trained operators due to the difficulty of image
358 interpretation. The Densitometer is the most accurate (although there are no statistically significant
359 differences with others) and it is easier to use and to interpret than the TRU. The presence of
360 petioles and shoots was not been an issue with the Densitometer. However the Densitometer always
361 provides a horizontal to the ground measure, while the TRU, even in the case of “horizontal”
362 measurements (virtual drill), gives information on a sector (3-5 cm wide) of the stem. The use of the
363 900 MHz antenna is not easily practicable on the date palms with long petiole residues, but it would
364 be possible on other species with smooth trunk surfaces (e.g. *Washingtonia* sp.).

365 Conclusions

366 In conclusion, this manuscript shows with concrete results a non-invasive approach to study internal
367 palm tissue health and to detect RPW. The technologies tested allow for early detection of
368 infestations in palms with a good accuracy level. Thermal cameras and densitometers are suggested

and encouraged to be adopted in order to obtain the correct information and to detect RPW. Digital cameras are not shown to be reliable enough, especially on date palms. Tree radar units (TRUs) are effective, but more difficult to work with. The satisfactory results obtained both in Italy and in KSA are a good “starting point” to develop a protocol for the eradication of RPW, combining an early detection protocol of red palm weevil with control strategies.

Acknowledgments

We would like to thank Prof. Maria Lodovica Gullino and Dr. Ernesto Occhiello for the critical review of the manuscript and Saudi Basic Industries Corporation for the financial support.

REFERENCES

- Alkhalazal, M. H., Youssef, L. A., Abdel-Wahaed, M. S., Kassab, A. S., & Saleh, M. M. E. (2009). Factors affecting infestation pattern of the red palm weevil, *Rhynchophorus ferrugineus* Oliv. In date palm farm in Qatif, Saudi Arabia. *Arab Universities Journal of Agricultural Sciences*, 17(1), 177-183.
- Al-Saoud, A. H., Al-Deeb, M. A., & Murchie, A. K. (2010). Effect of color on the trapping effectiveness of red palm weevil pheromone traps. *Journal of Entomology*, 7(1), 54-59.
- Al-Saqer, S. M., & Hassan, G. M. (2011). Red palm weevil (*Rhynchophorus ferrugineus*, Olivier) recognition by image processing techniques. *American Journal of Agricultural and Biological Sciences*, 6(3), 365-376.
- Brown, G. K., Burton, C. L., & Schulte, N. L. (1984). Progress in detecting hidden bark damage. *American Society of Agricultural Engineers*, Paper No. 84-1570.
- Catena, A. (2003). Thermography reveals hidden tree decay. *Arboricultural Journal*, 27(1), 27-42.
- Chaerle, L., Hagenbeek, D., Vanrobaeys, X., & Van Der Straeten D. (2007). Early detection of nutrient and biotic stress in *Phaseolus vulgaris*. *International Journal of Remote Sensing*, 28(16), 3479-3492.
- EPPO (2007). *Rhynchophorus ferrugineus* and *Rhynchophorus palmarum*. *Bulletin OEPP/EPPO Bulletin*, 37(3), 571-579.
- Godio, A., Guo, T., Martinis, R., Nicolotti, G., & Sambuelli, L. (2000). Radar investigation on wood decay and roots. In G. F. Backaus, H. Balder, & E. Idczak (Eds.), *Proceedings of the*

401 *International Symposium on Plant Health in Urban Horticulture*, (p. 285). Braunschweig,
 402 Germany.

403 Guillioni, L., Jones, H. G., Leinonen, I., & Lhomme, J. P. (2008). On the relationships between
 404 stomatal resistance and leaf temperatures in thermography. *Agricultural and Forest Meteorology*,
 405 148(11), 1908-1912.

406 Gutiérrez, A., Ruiz, V., Moltó, E., Tapia, G., & del Mar Téllez, M. (2010). Development of a
 407 bioacoustic sensor for the early detection of Red Palm Weevil (*Rhynchophorus ferrugineus*
 408 Olivier). *Crop Protection*, 29(7), 671-676.

409 Kersten, W., & Schwarze, F. W. M. R. (2005). Development of decay in the sapwood of trees
 410 wounded by the use of decay detecting devices. *Arboricultural Journal*, 28(3), 165-181.

411 Lhomme, J. P., & Monteny, B. (2000). Theoretical relationship between stomatal resistance and
 412 surface temperatures in sparse vegetation. *Agricultural and Forest Meteorology*, 104(2), 119-131.

413 Ma, A. K. W., Alghamdi, A. A., Tofailli, K., & Spyrou, N. M. (2012). X-ray CT in the detection of
 414 palm weevils. *Journal of Radioanalytical and Nuclear Chemistry*, 291(2), 353-357.

415 Mankin, R. W. (2011). Recent developments in the use of acoustic sensors and signal processing
 416 tools to target early infestations of red palm weevil in agricultural environments. *Florida*
 417 *Entomologist*, 94(4), 761-765.

418 Mattheck, C., Bethge, K. A., & Albrecht, W. (1997). How to read the results of Resistograph M.
 419 *Arboricultural Journal*, 21(4), 331-336.

420 Mucciardi, A., Luley, C. J., & Gormally, K. H. (2011). Preliminary evidence for using statistical
 421 classification of vibration waveforms as an initial decay detection tool. *Arboriculture and Urban*
 422 *Forestry*, 37(5), 191-199.

423 Nicolotti, G., Socco, L. V., Martinis, R., Godio, A., & Sambuelli, L. (2003). Application and
 424 comparison of three tomographic techniques for detection of decay in trees. *Journal of*
 425 *Arboriculture*, 29(2), 66-78.

426 Pugliese, M., Rettori, A. A., Martinis, R., Al-Rohily, K., Velate, S., Moideen M. A., & Al-Maashi,
 427 A. (2017). Evaluation of the efficacy of insecticidal coatings based on teflutrin and chlorpyrifos
 428 against *Rhynchophorus ferrugineus*. *Pest Management Science*, 73(8), 1737-1742.

429 Rust, S., & van Wassenae, P. (2017). Tools for tree risk assessment. In F. Ferrini, C. C.
 430 Konijnendijk van den Bosch & A. Fini (Eds.), *Routledge Handbook of Urban Forestry* (pp. 489-
 431 499). Abingdon, UK: Routledge Handbooks Online.

432 Salama, H. S., Zaki, F. N., & Abdel-Razek, A. S. (2009). Ecological and biological studies on the
 433 red palm weevil *Rhynchophorus ferrugineus* (Olivier). *Archives of Phytopathology and Plant*
 434 *Protection*, 42(4), 392-399.

435 Sambuelli, L., Socco, L. V., Godio, A., Nicolotti, G., & Martinis, R. (2003). Ultrasonic, electric and
 436 radar measurements for living trees assessment. *Bollettino di Geofisica teorica ed applicata*, 44(3-
 437 4), 253-279.
 438 Sepulcre-Canto G., Zarco-Tejada, P. J., Jimenez-Munoz, J. C., Sobrino, J. A., De Miguel, E., &
 439 Villalobos, F. J. (2006). Detection of water stress in an olive orchard with thermal remote sensing
 440 imagery. *Agricultural and Forest Meteorology*, 136(1-2), 31-44.
 441 Tofaillia, K. (2010). The Early Detection of Red Palm Weevil: a New Method. *Acta Horticulturae*,
 442 882, 441-449.
 443 Vacante, V. (2013). Punteruolo rosso delle palme: aggiornamenti sulle tecniche di lotta. *Protezione*
 444 *delle Colture*, 6(5), 38-51.
 445 Vidyasagar, P. S. P. V., Ohammed, H., Abozuhairah, R. A., Al-Mohanna, O. E., & Al-Saihati, A.
 446 A. (2000). Impact of mass pheromone trapping on red palm weevil: adult population and infestation
 447 level in date palm gardens of Saudi Arabia. *Planter*, 76(89), 347-355.
 448 Table 1 – Final conditions (after 9 months) of monitored palms (young and adult) in Italy according
 449 to thermal camera results.

Species	healthy	suspected	infested
<i>Phoenix canariensis</i>	403	13	37
<i>Phoenix dactylifera</i>	168	5	0
<i>Washingtonia robusta</i>	28	1	1
<i>Chamaerops humilis</i>	162	0	0
Other species (<i>Washingtonia filifera</i> , <i>Brahea edulis</i> , <i>Phoenix robellinii</i> , <i>Arecastrum romanzoffianum</i> , <i>Trachycarpus fortunei</i>)	119	0	0
TOTAL	880	19	38

450
 451
 452 Table 2 – Health state of monitored adult *Phoenix canariensis* according to thermal camera results
 453 in Italy.

October 2012		May 2013	
Adult palm trees	%	Adult palm trees	%
healthy	90.0%	healthy	86.0%
suspected	3.1%	suspected	3.7%

infested	6.9%	infested	10.3%
	100.0% (350)		100.0% (350)

454

455

456 Table 3 – Temperature values (°C) between 2 groups of healthy and 1 of infested palm trees in
457 Italy.

	Temperature values (Mean °C)	Healthy group n. 1	Healthy group n. 2	Infested group n. 3
			F value	
Healthy group n. 1*	16.96a	----	1.093	1.375**
Healthy group n. 2	17.17a	1.093	----	1.446**
Infested group n. 3	19.66b	1.375**	1.446**	----

458

459 *Group 1 is represented by 3 healthy plants nearby 3 infested palms (group n. 3) and the group n. 2
460 is made by three healthy plants far from groups n. 1 and 3.

461 ** Significantly different

462

463

464

465 Table 4 – Accuracy assessment (% , based on visual inspection on the presence of *Rhynchophorus*
466 *ferrugineus* and symptoms) for detection of RPW with thermal camera and digital camera on adults
467 of *Phoenix canariensis* in Italy.

	Thermal camera	Digital camera
Valid cases	350	350
Mean (%)	96.29	92.57
Std. error of mean	1.01	1.40
Variance	358.66	689.64
Std. Deviation	18.94	26.26

468

469

470
471
472

473
474
475

476
477
478
479

480

481
482
483
484
485
486

Table 5 – Accuracy assessment (% , based on visual inspection on the presence of *Rhynchophorus ferrugineus* and symptoms) for detection of RPW with Densitometer and TRU on adults of *Phoenix canariensis* in Italy.

	Densitometer	TRU
Valid cases	18	18
Mean (%)	88.89	83.33
Std. error of mean	7.62	9.04
Variance	1045.75	1470.59
Std. Deviation	32.34	38.35

Table 6 – Correspondence between thermal and digital cameras results in KSA.

Thermal camera diagnosis		Digital camera diagnosis	
Dead	2	Dead	2
Healthy	41	Healthy	35
		Infested	1
		N.C.*	2
		Suspected**	3
Infested	37	Healthy	13
		Infested	19
		N.C.	3
		Suspected	2
Suspected	9	Healthy	8
		Suspected	1
Total	89	Total	89

* The term "n.c." means not classifiable.
**The term "suspected" means that the diagnosis is not sure, because the probable presence of infested palm trees nearby the subject under observation. So “suspected” because in field the Thermal camera monitor was not possible detect a large temperature difference with the palms nearby the subject under observation.

487

488 Table 7 – Results with Thermal camera on 31 date palm trees in KSA.
489

Results by thermal camera (after post processing)	N. of palms	Real situation (after sectioning) integrated by in field direct observations	N. of palms	%
infested	26	Correct (infested)	22	70.9% (22/31) 84.6% (22/26)
		False positive (healthy)	3	9.7%
healthy	5	Correct (healthy)	2	6.5%
		False negative (infested)	4	12.9%
TOTAL			31	100.0%

490

491 Table 8 – Accuracy assessment (%) for detection of *Rhynchophorus ferrugineus* infestation with all
492 devices on date palm trees in KSA (ANOVA, Tukey test, $p \leq 0.05$, accuracy refers to the evidence
493 of infestation in the cut palm trunks).

	DENSITOMETER	TRU	THERMAL CAMERA	DIGITAL CAMERA
Valid cases	31	31	31	30
average	82.26 ± 4.44a	74.73 ± 5.83a	77.42 ± 7.63a	66.67 ± 8.75a

494