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## Devices to detect red palm weevil infestation on palm species

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(Article begins on next page)



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

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

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

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

116 Considering the widespread presence of RPW and the difficulties in detecting infected tissues at an  
117 early stage, a new approach was applied to study internal palm tissue health by applying  
118 technologies adopted on urban trees. This included: thermal imaging to measure trunk temperature  
119 and comparing it with temperatures measured from neighboring trees; a tree radar unit (TRU) to  
120 detect internal state of wood plants; a digital camera to assess the shape and condition of the palm  
121 crown; and a densitometer to measure the resistance of the tree tissues to drilling. As part of a wider  
122 project on date palms, funded by Saudi Basic Industries Corporation, the devices were tested for  
123 palm inner tissue evaluation. The objective of this work is to compare the efficacy of different non-  
124 invasive systems to detect the red palm weevil and to create a methodology for diagnosis. The main  
125 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

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

374

## 375 **Acknowledgments**

376

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379

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 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
<b>TOTAL</b>	<b>880</b>	<b>19</b>	<b>38</b>

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)

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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

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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

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473 Table 5 – Accuracy assessment (% , based on visual inspection on the presence of *Rhynchophorus*  
474 *ferrugineus* and symptoms) for detection of RPW with Densitometer and TRU on adults of *Phoenix*  
475 *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

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480 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

481 \* The term "n.c." means not classifiable.

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

486

487

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

489

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

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).

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

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