Devices to detect red palm weevil infestation on palm species

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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

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

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

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

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

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

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

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

Other techniques under study are:

- bioacoustic detection (Gutiérrez et al., 2010; Mankin, 2011) with tool capable of amplifying the noise made by *R. ferrugineus* larvae;
- use of thermal detection with portable thermal camera to detect local increase of temperature 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 Wassenaer, 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

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

Materials and methods

Devices

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

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

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

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

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

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

Data analysis

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

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

Experimental sites in Italy and methods adopted

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

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

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

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

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

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

Experimental sites in KSA and methods adopted

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

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

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

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

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

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

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

Results

Diagnosis in Italy

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

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

Diagnosis in the Kingdom of Saudi Arabia

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

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

Discussion

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

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

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

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

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

Conclusions

In conclusion, this manuscript shows with concrete results a non-invasive approach to study internal palm tissue health and to detect RPW. The technologies tested allow for early detection of 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.

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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
Phoenix canariensis	403	13	37
Phoenix dactylifera	168	5	0
Washingtonia robusta	28	1	1
Chamaerops humilis	162	0	0
Other species (*Washingtonia filifera, Brahea edulis, Phoenix robellinii, Arecastrum romanzoffianum, Trachycarpus fortunei*)	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)

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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

462
463

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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

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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.

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

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%**

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