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Preliminary Evaluation of Electrical Resistance Tomography for Imaging Palm Trunks

Monica L. Elliott, Timothy K. Broschat, and Lothar Göcke

Abstract. In a preliminary study, electrical resistance tomography (ERT) was used to obtain trunk images of *Syagrus romanzoffiana*, a common ornamental palm grown in southern Florida, U.S. Seven palms, four healthy and three diseased, were evaluated in the middle of the dry season, with four located in an irrigated site and three in a non-irrigated site. Two healthy and three diseased palms were felled and cross sections obtained to examine their internal structure and compare to the tomograms obtained. ERT was effective in illustrating the relative electrical resistance value of healthy palms, as the tomograms obtained for palms situated in the irrigated site (low electrical resistivity) were distinctly different from the tomograms of palms situated in the non-irrigated site (high electrical resistivity). ERT was also effective in visualizing internal palm trunk areas affected by the fungal pathogens *Ganoderma zonatum*, a wood decay pathogen, and *Fusarium oxysporum* f. sp. *palmarum*, a vascular wilt pathogen, as these areas had a low electrical resistivity.
Key Words. Electrical Resistance Tomography; Electrical Resistivity; Florida; *Fusarium oxysporum* f. sp. *palmarum*; *Ganoderma zonatum*; Palms; *Syagrus romanzoffiana*; Wood Decay.

Palms are important landscape elements in tropical, subtropical, and Mediterranean climates, and cold-hardy palms are often used in the landscape in southern temperate climates. As monocotyledonous trees, palms differ significantly from dicotyledonous and coniferous trees. Palms have no vascular cambium and, therefore, no sapwood, heartwood, or phloem rings. Instead, a palm trunk is composed of thousands of vascular bundles, with each bundle containing xylem vessels, phloem sieve tube cells, and fibers. The fibers are the primary tissues that provide mechanical support to the trunk as the amount of cellulose and lignin deposition increases over time. The lowest portion of the palm trunk is the oldest portion and, therefore, has the greatest amount of cellulose and lignin. While vascular bundles are dispersed throughout the palm trunk, their distribution within the trunk is species specific, with some palm species having more vascular bundles concentrated near the outside of the trunk and others having the bundles evenly dispersed throughout the trunk (Tomlinson 1990; Tomlinson et al. 2011).

As with dicotyledonous and coniferous trees, non-destructive methods that examine the internal structure of the palm trunk are highly desirable, especially to confirm internal trunk decay or damage due to pathogens or insects. One such method is electrical resistance tomography (ERT). As it applies to trees, this method uses pulsed electric current (DC) to examine tree properties that affect the resistivity of the wood. The primary properties are water content, cell structure, and ion concentration, which are properties that change if decay in the tree is detected. The resulting measurements are displayed on a two-dimensional map, showing the apparent electrical resistance of the wood, called an electrical resistance tomogram. In general, areas of low resistance to electrical current correspond to areas with high water content or high ion concentration, whereas areas of high resistance correspond to areas of low water content or low ion concentration (al Hagrey 2006; al Hagrey 2007). While the use of electrical resistance to evaluate wood decay (Tattar et al. 1972) or stem water potential (Nadler and Tyree 2008) is not new, using electrical resistance to develop a tomogram is relatively new. ERT has been used to evaluate trunk decay or the sapwood–heartwood interface in dicotyledonous and coniferous trees (Nicolotti et al. 2003; Brazee et al. 2011; Lin et al. 2012; Guyot et al. 2013). While one disadvantage of ERT is the difficulty in characterizing defects or cavities in dry heartwood (al Hagrey 2007), this is not an issue for palm trunks as they have no heartwood.

To date, tomography techniques reported for detection of wood decay or insect damage within palm trunks have used ultrasonic and stress waves (Lin et al. 2011; Najmie et al. 2011; Huang et al. 2013), gamma rays (Abdullah et al. 2013), sound (Mazliham et al. 2008; Al-Sulaiman and Hawwa 2012), X-rays (Ma et al. 2012), cone beam neutron (Alghamdi 2012), and infrared heat (Al-Sulaiman and Hawwa 2012), but not ERT. One of the current authors (Göcke) has used ERT on various palms in multiple locations worldwide but results have not been reported publicly.

For a tool to be useful, baseline data is required. A preliminary study was conducted in March 2014 in southeastern Florida, U.S., on *Syagrus romanzoffiana* (queen palm) to determine the usefulness of ERT in imaging palm trunks for assessment and comparison of healthy and diseased palms. Two distinctly different urban sites were selected, but at both sites, queen palms were dying from *Ganoderma* butt rot caused by *Ganoderma zonatum*, a typical white rot fungus (Elliott and Broschat 2001). One site was also affected by *Fusarium* wilt caused by *Fusarium oxysporum* f. sp. *palmarum*, a vascular wilt pathogen (Elliott et al. 2010).

MATERIALS AND METHODS

Study Sites and Palm Selection

The palms selected at the two urban landscape sites for ERT were evaluated 19–20 March 2014, in the middle of the six-month dry season for southeastern Florida. The first site was a residential community located in Palm Beach County. The landscape was intensively maintained and well-irrigated, and over one-third of the queen palms had died from either *Ganoderma* butt rot or *Fusarium* wilt. The four palms selected had trunks with approximately 5 m of gray wood and diameters of approximately 26 cm. The second site was a minimally maintained, non-irrigated site in Broward County at the University of Florida's Fort Lauderdale Research and Education Center. This site has a concentration of queen palms in one location on the property, and *Ganoderma* butt rot has affected some of these palms. The three palms selected had trunks with approximately 6 m of gray wood and diameters of approximately 30 cm.

At each location, a palm was selected that was severely wilted, with *G. zonatum* basidiocarps emerging from the trunk. At the Palm Beach County site, a queen palm with typical and severe *Fusarium* wilt symptoms was also selected. Two apparently healthy queen palms were selected at each site for comparison with the diseased palms.

Electrical Resistance Tomography

The instrument used to measure electrical conductivity within the palm trunks was a PiCUS Treetronic® (Argus Electronic GmbH, Rostock, Germany), a multichannel, multielectrode resistivity system. Electrical resistance of the wood was measured by inserting 12 zinc-galvanized nails (3 mm diameter) equidistant into the trunk at each cross section measured (three to five sections per palm). The nails were only tapped until firmly in place. Electrical cables were attached to each nail and to the base unit. Between two of the nails, an electric DC voltage (12 to 50 volts) with changing polarity was applied, which caused an electrical current of 0.003 to 0.01 amps to flow. The duration of the impulses was less than one second and was applied to all nails in sequence. Data was collected, processed, and analyzed using PiCUS software to obtain color tomographs, which illustrate the apparent electrical resistance of the wood.

After the tomographs were obtained, diseased queen palms at both sites were felled and cross sections cut at the height of sampling with the instrument. One healthy queen palm was felled at the Palm Beach County site for comparison of internal cross sections with diseased queen palm cross sections.

Fungal Isolation from Trunk Tissue

Cross sections from diseased queen palm trunks were brushed free of debris and transferred to the University of Florida plant pathology laboratory in Broward County, where they were placed in large plastic containers and covered loosely with plastic bags to encourage fungal growth. *Ganoderma*-like growth grew out of the trunk sections associated with the palm with *Ganoderma* butt rot. *Fusarium oxysporum* grew out of the trunk associated with *Fusarium* wilt. For both fungi, DNA was extracted and used for the polymerase chain reaction, using internal transcribed spacer region primers for *Ganoderma* and translation elongation factor primers for *Fusarium*. Sequencing of resulting amplicons identified the pathogens as *Ganoderma zonatum* and *Fusarium oxysporum* f. sp. *palmarum*.

RESULTS AND DISCUSSION

In this preliminary study using ERT to obtain images of queen palm trunks, it was apparent that the internal water content naturally varies for healthy palms of the same species. As shown in Figure 1, the healthy queen palms in the irrigated site in Palm Beach County (A and B) had a lower electrical resistance [average ER minimum/maximum (ohms) = 43/109], which indicates a higher water content than the non-irrigated site in Broward County (F and G) [average ER minimum/maximum (ohms) = 130/190]. Healthy queen palms in the non-irrigated site had lower water content overall, and this appears to be uniform across the lower trunk, up to about 130 cm, the highest measurement point on the trunks. Healthy queen palms in the irrigated sites during the dry season had higher water content overall but tended to have more water concentrated in the center of the palm near the soil line, and became more uniformly saturated up to about 130 cm or the highest measurement point on the trunks. This difference in the tomograms from each site would suggest the importance of determining the "standard" for the palm species at each location before using ERT for diagnostic purposes.

However, even with this natural variability in healthy palms, the palm tissue decay due to *G. zonatum* appeared essentially the same on the tomograms of the Palm Beach County site (Figure 1D) and Broward County site (Figure 1E). *Ganoderma zonatum* is a typical white rot fungus that degrades the cellulose and lignin associated with the fibers

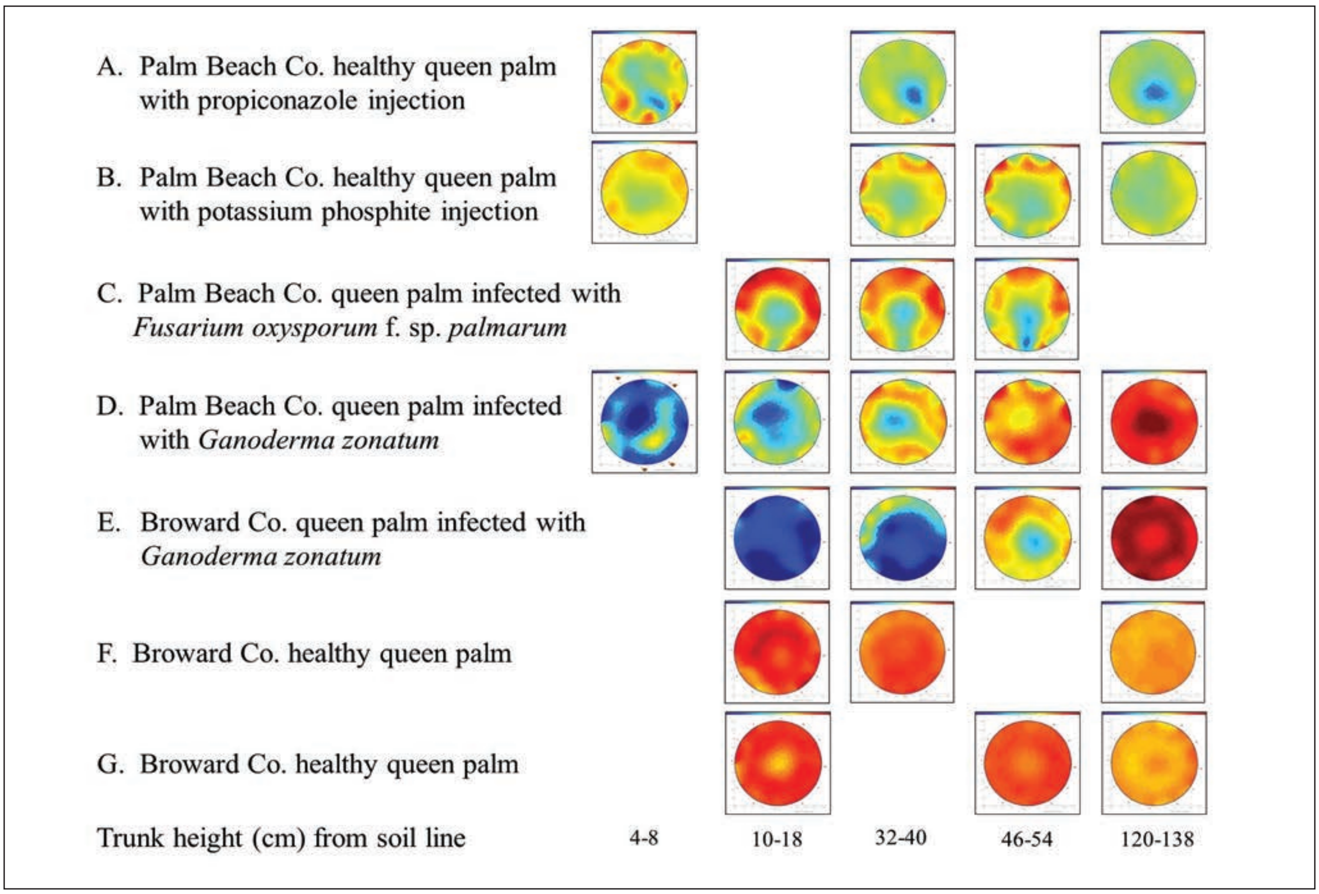

Figure 1. Comparison of electrical resistance tomograms for healthy and diseased *Syagrus romanzoffiana* (queen palm) at two different locations in southeastern Florida, in March 2014. The resistance range for all tomograms is 10 (min) to 350 (max) ohms. Blue indicates low resistance (high water content), and red indicates high resistance (low water content). Each row includes the tomograms from one palm at the height range listed in the figure legend. Each column includes tomograms from each palm within the height range shown, if the palm was evaluated at that height range.

in the vascular bundles within the palm trunk (Blanchette 1991; Elliott and Broschat 2001). Queen palms infected with *G. zonatum* had uniformly low electrical resistance (higher water content) at the soil line (Figure 1D; Figure 1E; Figure 2) up to about 35 cm trunk height. At about 50 cm, there was more electrical resistance, and at about 120–140 cm, the trunks had a uniformly high electrical resistance (low water content) (Figure 1D; Figure 1E). Low water content of infected palms above 40 cm trunk height at both sites suggests that the palms were under water stress, possibly due to fungal destruction or blockage of xylem vessels, which are part of the vascular bundle, along with phloem sieve tube cells and fibers (Tomlinson 1990). This pattern of electrical resistance corresponds with the normal observations of decay by *G. zonatum* within the palm trunk (Elliott and Broschat 2001), with a decrease in wood decay as one moves up the trunk from the soil line (Figure 3). The measurement obtained at 138 cm from the soil line shows uniform high electrical resistance, which corresponds to the lack of obvious wood decay in that section. What is not known is whether the high water content observed in the lower 50 cm of *G. zonatum*-infected queen palm trunks was due to the amount of fungus present or due to the cell content leakage of the palm tissue (and corresponding increase in ions) or both.

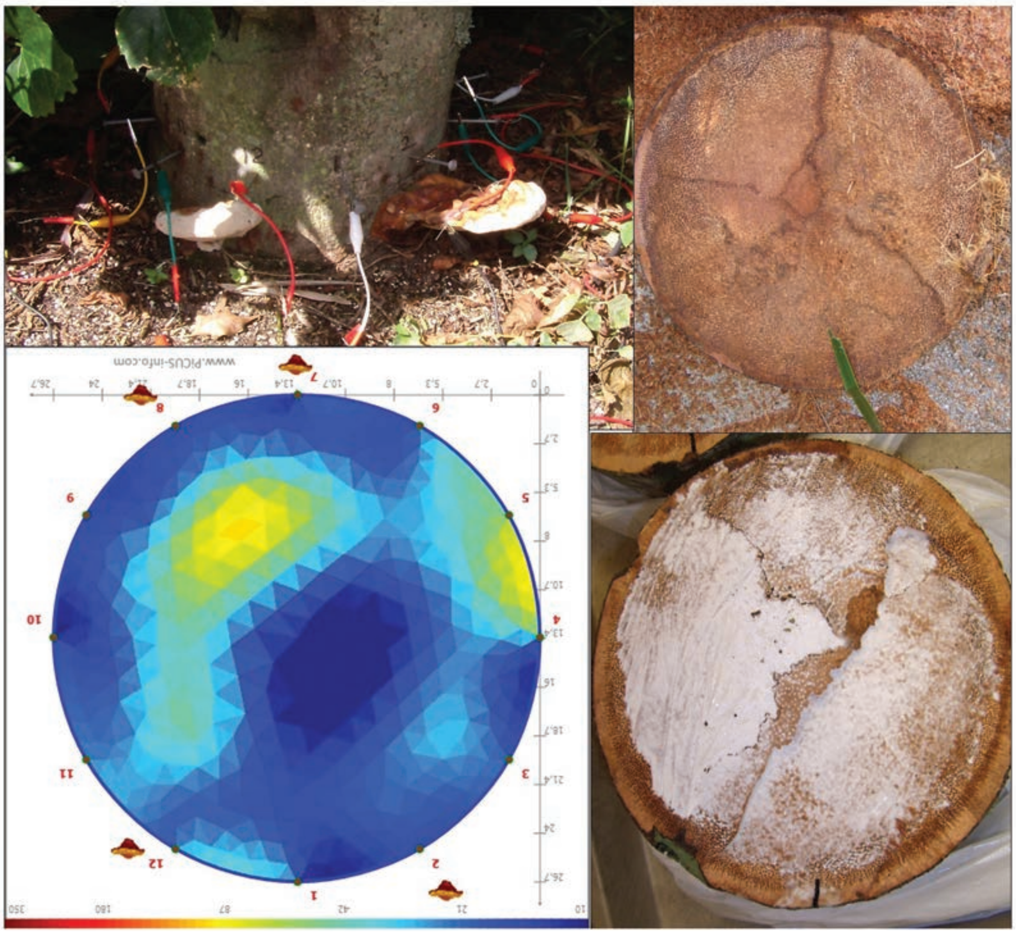

Figure 2. Illustrations of *Ganoderma zonatum*-infected *Syagrus romanzoffiana* in Palm Beach County Florida (irrigated site), in March 2014 (Palm D). All cross-sectional photographs or diagram are oriented the same, with nail number 1 located at the center bottom and corresponding to the halfway point between the two basidiocarps shown in the photograph in the upper left. The tomogram shown was obtained at 8 cm trunk height above the soil line. The upper right photograph is the cross section at the 8-cm location. The lower right photograph is the same cross section after incubation in the laboratory. The white growth is mycelia of *G. zonatum.* The blue color of the tomogram indicates low electrical resistance.

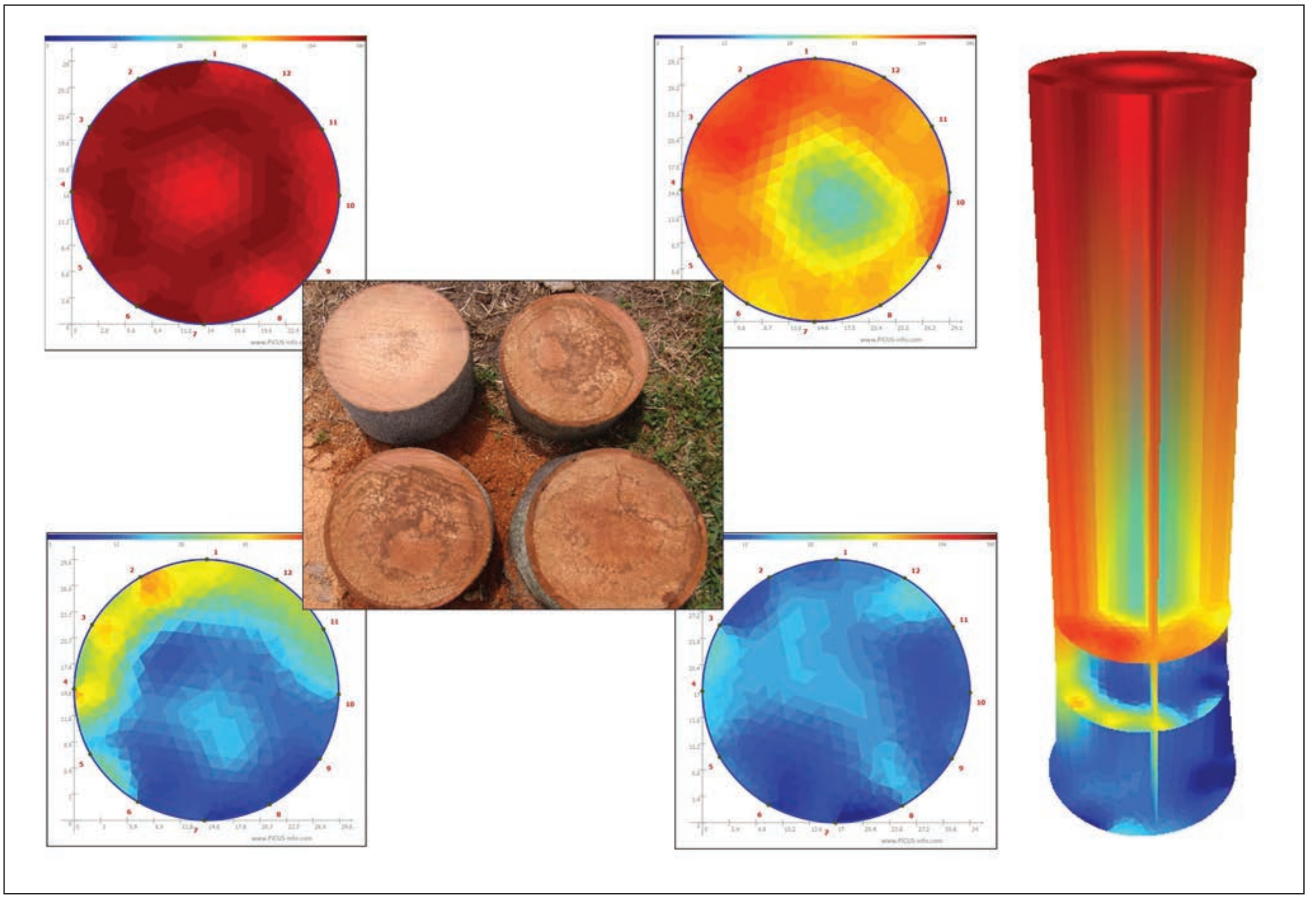

Figure 3. Illustrations of *Ganoderma zonatum*-infected *Syagrus romanzoffiana* in Broward County, Florida (non-irrigated site), in March 2014 (Palm E). All cross section photographs or diagrams are oriented the same, with nail number 1 located at the center top. Clockwise, starting in the upper left, the tomograms and cross sections were obtained at 138, 50, 12, and 35 cm trunk height above the soil line. The tomogram at the far right side is a 3D graphic of the four scans taken from 12 to 138 cm. The blue color of the tomogram indicates low electrical resistance and the red color indicates high electrical resistance.

This observed relationship between trunk decay and low electrical resistance corresponds to results obtained using ERT to detect decay in dicotyledonous trees (Nicolotti et al. 2003; Bieker et al. 2010; Brazee et al. 2011; Martin and Günther 2013). In palms, ERT would appear to be just as effective as ultrasonic waves, or sound or gamma-ray tomography for detecting decay in palms due to *Ganoderma* (Mazliham et al. 2008; Najmie et al. 2011; Abdullah et al. 2013). Approximately half of the time, a basidiocarp of *G. zonatum* emerges from the palm trunk prior to palm death, which confirms the cause of symptoms observed. However, without the growth of the basidiocarp, the cause of the decline is unknown until the palm is felled and trunk cross sections examined (Elliott and Broschat 2001).

Examination of the raw data for healthy and *G. zonatum*-infected queen palms suggest that the value obtained by dividing the maximum level of resistance detected (measured in ohms) by the minimum level of resistance detected across all trunk measurement heights may also provide information about wood decay in this palm species (Table 1). This value is distinctly greater in *G. zonatum*-infected queen palms than in healthy queens, by a factor of 7 to 9X in the irrigated site and 21 to 25X in the dry site. Likewise, the mean of the difference between the maximum and minimum levels of resistance at each measurement height may be useful. The healthy palms at both locations—irrigated (Palm A, Palm B) and non-irrigated (Palm F, Palm G)—had values between 50.3 and 70.3 ohms. The *G. zonatum*-infected queen palms had values of 107.5 ohms at the irrigated site (Palm D) and 101.3 ohms at the non-irrigated site (Palm E). The *Fusarium*-infected queen palm at the irrigated site (Palm C) had a mean

Table 1. Minimum and maximum levels of resistivity measured in healthy and diseased *Syagrus romanzoffiana* (queen palm) at two different locations in southeastern Florida, U.S., in March 2014.

Palm identity[z]	Measurement height (MH) on trunk (cm)[y]	Trunk diameter at MH (cm)	Maximum resistance (ohms)	Minimum resistance (ohms)	Difference in resistance (ohms)
Palm Beach County, irrigated site					
A (healthy)	5	24	**137**	40	97
	38	23	84	34	50
	130	23	77	**31**	46
				Max/Min = 4.4[x]	**64.3**[w]
B (healthy)	4	29	116	63	53
	32	25	127	52	75
	53	24	**150**	47	103
	124	24	74	**44**	30
				Max/Min = 3.4	**65.3**
C (*Fusarium*)	15	31	**261**	49	212
	35	27	194	47	147
	54	25	164	**32**	132
				Max/Min = 8.2	**163.7**
D (*Ganoderma*)	8	27	64	**11**	53
	17	27	96	19	77
	32	27	132	39	93
	51	26	199	95	104
	72	24	281	143	138
	120	24	**333**	153	180
				Max/Min = 30.3	**107.5**
Broward County, non-irrigated site					
E (*Ganoderma*)	12	34	20	**7**	13
	35	30	72	7	65
	50	29	157	44	113
	138	28	**339**	235	104
				Max/Min = 48.4	**101.3**
F (healthy)	10	38	**265**	133	132
	40	30	190	134	56
	130	26	140	**117**	23
				Max/Min = 2.3	**70.3**
G (healthy)	18	30	**211**	135	76
	46	26	189	150	39
	138	26	147	**111**	36
				Max/Min = 1.9	**50.3**

[z] Letters used for palm identity correspond to letters used for palm identity in Figure 1.
[y] Measurement height (MH) is from the soil line.
[x] For each palm, minimum resistance value across all MHs and maximum resistance value across all MHs were used to calculate quotient.
[w] For each palm, value is mean of the difference between maximum resistance and minimum resistance at each MH.

value of 163.7 ohms. Use of ERT may help with early diagnosis or in tracking the extent of decay in order to make a decision regarding palm removal.

The second diseased queen palm evaluated with ERT at the Palm Beach County site was dying from *F. oxysporum* f. sp. *palmarum*. This fungus is a systemic (xylem-limited) pathogen that appears to normally infect via the palm canopy (Elliott et al. 2010). However, at this study site, due to the high level of pathogen pressure, it was apparent that fungal spores have become incorporated into the soil as progression of the disease and examination of the trunk demonstrates the pathogen is infecting the palm trunk via the roots (M.L. Elliott, pers. obs.). The growth of *F. oxysporum* f. sp. *palmarum* in the trunk cross section after incubation corresponded with the trunk area with the lowest electrical resistance (highest water content) (Figure 4). Again, it was unknown whether this was due to the presence of the fungus or palm tissue cell leakage. It is noteworthy that the presence of a systemic or vascular pathogen was detected in this instance, as tomography has normally been used to detect wood decay pathogens rather than vascular wilt pathogens. Compared to the healthy palms at this site, the remaining trunk tissue had higher electrical resistance (lower water content).

The Palm Beach County site was being used to study the effect of fungicide injections for *Fusarium* wilt disease prevention in palms. Palm A (Figure 1A; Figure 5) had been injected with 200 ml Alamo (14.3% propiconazole, Syngenta Crop Protection, LLC), without the addition of water, 15 days prior to ERT. Since the propiconazole is not 100% soluble in water, this may explain why the propiconazole injection site was visible on the tomogram. The product may not have completely dispersed from the injection site when the tomogram was obtained, which would make this injection site appear to have a higher water content (lower electrical resistance) (Figure 5). Mazliham et al. (2008), using sound tomography, could also detect chemical injection sites in palm trunks, but it is not stated what chemical had been injected.

In conclusion, internal palm trunk images obtained using ERT provided useful information regarding water status and health of the queen palms examined in this preliminary study. As shown by comparing healthy palms at both locations, tomograms of healthy palms are necessary to obtain a standard tomogram for the site at the time of sampling. If the tomogram of the healthy palms at the non-irrigated site had been obtained using ERT in the middle of the rainy season, it is likely the tomogram would have looked more similar to the irrigated site. ERT would also appear to be useful for detecting internal palm trunk areas affected by fungal pathogens, as trunk tissue affected by both the wood decay pathogen *G. zonatum* and the vascular pathogen *F. oxysporum* f. sp. *palmarum* could be easily discerned in the tomogram and correlated with pathogen growth from the trunk tissue. This was a preliminary study, and as such, the diseased palms selected were near death, as researchers wanted to be certain they were dealing with fungal infections. Thus, how early in the disease process fungal growth or decay can be detected is not known. Neither do researchers know how many tomograms are required for each palm, as this will likely depend on the pathogen and the disease it causes. For example, the greatest amount of decayed wood due to *G. zonatum* is always closest to the soil line. One tomogram may be all that is necessary, although multiple tomograms do produce a very realistic 3D representation of the fungal damage.

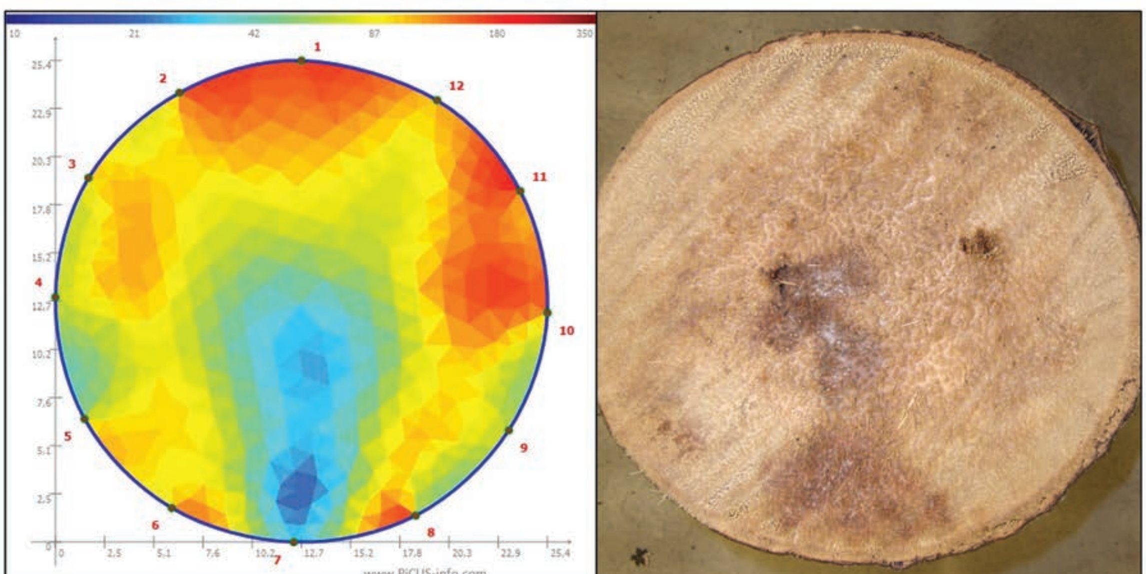

Figure 4. Illustrations of *Fusarium oxysporum* f. sp. *palmarum*-infected *Syagrus romanzoffiana* in Palm Beach County, Florida, in March 2014 (Palm C). The tomograph and cross section are oriented in the same direction and are at 54 cm trunk height above the soil line. The discoloration in the photograph is due to fungal growth after incubation in the laboratory. The blue color of the tomogram indicates low electrical resistance, and the red color indicates high electrical resistance.

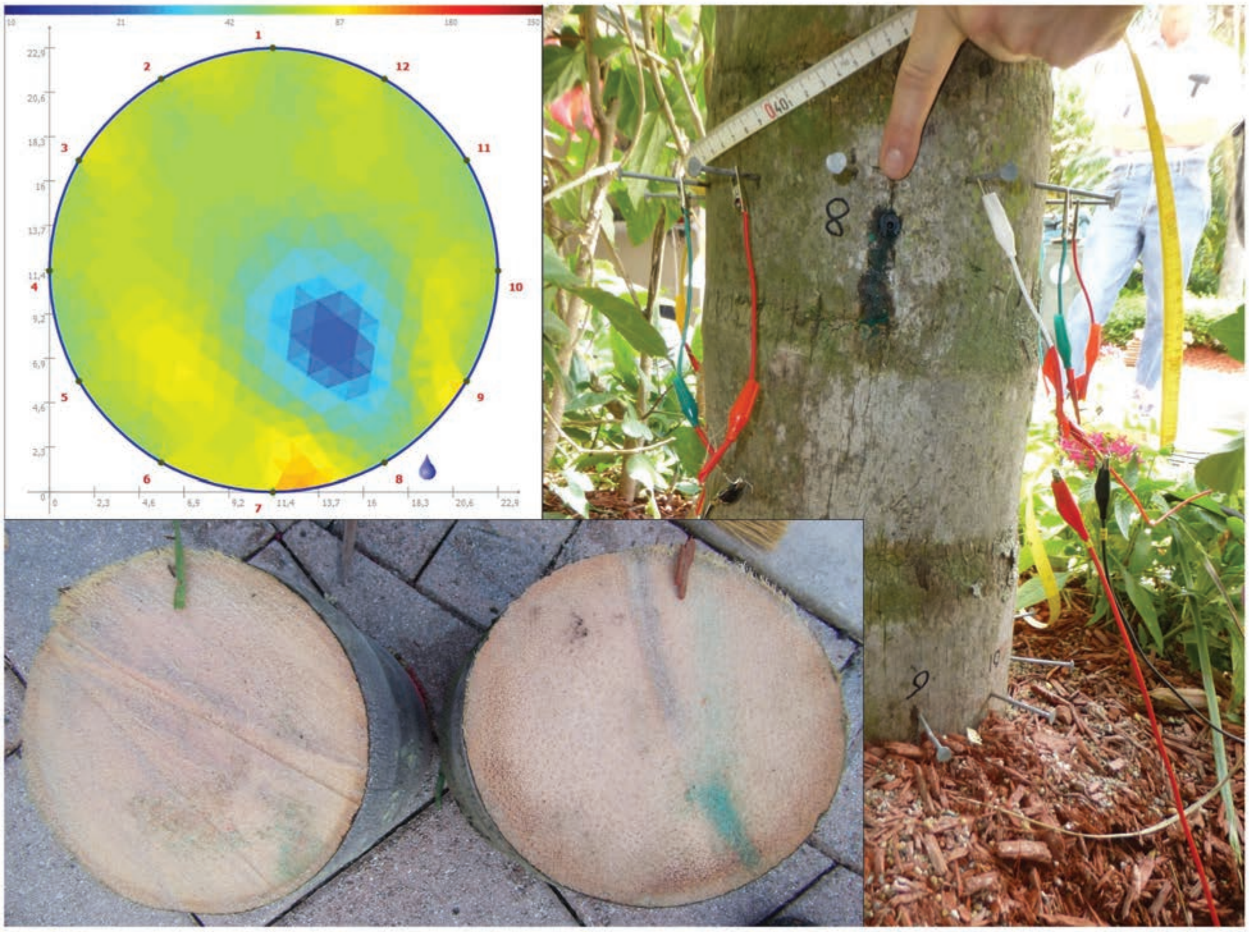

Figure 5. Illustrations of a healthy, propiconazole-injected *Syagrus romanzoffiana* in Palm Beach County, Florida, in March 2014 (Palm A). The tomograph and cross sections are oriented in the same direction with nail number 8 located at the bottom left (raindrop in tomogram; finger in photograph, which is pointing at the injection site). The tomogram was obtained at 38 cm trunk height above the soil line. The right and left cross sections were located 130 cm and 38 cm above the soil line, respectively. The blue color of the tomogram indicates low electrical resistance, and the red color indicates high electrical resistance.

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Résumé. Dans une étude préliminaire, la tomographie à résistance électrique a été utilisée afin d'obtenir des images du tronc du palmier de la reine (ou cocotier plumeux) (*Syagrus romanzoffiana*), un palmier ornemental commun poussant dans le sud de la Floride, États-Unis. Sept palmiers, soit quatre sains et trois malades, ont été évalués durant le milieu de la saison sèche, quatre étant situés dans un site irrigué et trois dans un site non irrigué. Deux palmiers sains et trois malades furent abattus et les découpes du tronc de ces arbres ont permis d'examiner leur structure interne et de comparer avec les images tomographiques obtenues. La tomographie à résistance électrique fut efficace en démontrant la valeur de la résistance électrique relative de palmiers sains, puisque les images tomographiques obtenues des palmiers situés sur le site irrigué (faible résistivité électrique) étaient nettement différentes des images obtenues avec les palmiers situés sur le site non irrigué (haute résistivité électrique). La tomographie à résistance électrique fut également efficace pour la visualisation interne des sections de troncs des palmiers affectées par le champignon pathogène *Ganoderma Zonatum*, un pathogène de carie du bois, et le *Fusarium oxysporum f. sp. palmarum,* un agent de dépérissement vasculaire, puisque ces zones des troncs montraient une faible résistivité électrique.

Zusammenfassung. In einer vorangegangenen Studie wurde ein Verfahren zur tomografischen Messung des Elektrischen Widerstands (ERT) verwendet, um Stammbilder von *Syagrus romanzoffiana*, einer gewöhnlichen ornamentalen Palme in Südflorida, USA, zu erhalten. Sieben Palmen, vier gesunde und drei kranke, wurden in der Mitte der Trockenperiode bewertet: vier an einem bewässerten Standort, drei an einem unbewässerten Standort. Zwei gesunde und drei erkrankte Palmen wurden gefällt und die Querschnitte erfasst, um deren interne Struktur zu untersuchen und die erhaltenen Tomogramme zu vergleichen. Das ERT war bei der Illustration des relativen elektrischen Widerstandwertes der gesunden Palmen sehr hilfreich, wobei sich die Tomogramme der Palmen an den bewässerten Standorten (niedriger elektrischer Widerstand) deutlich unterschieden von den Tomogrammen der Palmen an den unbewässerten Standorten (hoher elektrischer Widerstand). Das ERT war auch hilfreich bei der Visualisierung des internen Palmenstamms, der durch eine Infektion mit dem fungalen Pathogen *Ganoderma zonatum*, ein Fäulnis verursachender Pathogen und *Fusarium oxysporum* f. sp. *palmarum*, einem Welke-erzeugendem Pathogen beeinflusst war, da diese Bereiche eine niedrige elektrische Resistenz aufwiesen.

Resumen. En un estudio preliminar, se utilizó la tomografía por resistencia eléctrica (ERT) para obtener imágenes del tronco de *Syagrus romanzoffiana*, una palma ornamental común del sur de Florida, Estados Unidos. Se evaluaron siete palmas, cuatro sanas y tres enfermas, a la mitad de la estación seca, cuatro se encuentran en un sitio con riego y tres en un sitio de secano. Dos palmas sanas y tres enfermas fueron taladas y las secciones transversales obtenidas se examinaron en su estructura interna para comparar con las tomografías obtenidas. El ERT fue eficaz para ilustrar el valor de la resistencia eléctrica en las palmas sanas, así como las tomografías obtenidas para las palmeras situadas en el sitio de regadío (baja resistividad eléctrica) eran claramente diferentes de las tomografías de palmeras situadas en el sitio de secano (alta resistividad eléctrica). El ERT también fue eficaz en la visualización de zonas internas del tronco de la palma afectados por los hongos patógenos *Ganoderma zonatum*, un decaimiento patógeno madera, y *Fusarium oxysporum* f. sp. *palmarum*, un patógeno del marchitamiento vascular, ya que estas áreas tienen una resistividad eléctrica de baja.