DETECTING DETERIORATION IN ROYAL PALM (*ROYSTONEA REGIA*) USING ULTRASONIC TOMOGRAPHIC AND RESISTANCE MICRODRILLING TECHNIQUES

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LIN CJ, CHANG TT, JUAN MY & LIN TT. 2011. Detecting deterioration in royal palm (*Roystonea regia*) using ultrasonic tomographic and resistance microdrilling techniques. The objective of this study was to evaluate deterioration and defects in royal palm (*Roystonea regia*) using a combination of ultrasonic tomographic and resistance microdrilling techniques. High correlation (r^2 = 0.99) existed between the amount of decay detected by ultrasonic tomography and the amount actually present in cross-sections of discs and living palms according to the drill-resistance profile. However, ultrasonic tomograms underestimated the internal deterioration of royal palms. When defects occurred in the periphery of the trunk, ultrasonic tomography overestimated the area of deterioration. Therefore, detection of the location and determination of area of deterioration need to be improved. A combination of ultrasonic tomography and resistance microdrilling could accurately detect the general location and area of deterioration.

Keywords: Ultrasonic wave, tree risk assessment, visual tree assessment, non-destructive technique

LIN CJ, CHANG TT, JUAN MY & LIN TT. 2011. Pengesanan kemerosotan dalam pinang raja (*Roystonea regia*) menggunakan teknik tomografi ultrasonik dan teknik gerudi mikro rintang. Objektif kajian ini adalah untuk menilai kemerosotan dan kecacatan dalam pinang raja (*Roystonea regia*) menggunakan gabungan teknik tomografi ultrasonik dan teknik kerintangan gerudi mikro. Korelasi tinggi (r^2 = 0.99) wujud antara jumlah pereputan yang dikesan menggunakan tomografi ultrasonik dengan jumlah pereputan sebenar yang kelihatan pada keratan rentas cakera dan dalam palma hidup yang dikesan menggunakan teknik gerudi mikro rintang. Namun, pereputan yang dianggar oleh tomografi ultrasonik adalah kurang daripada jumlah sebenar dalam pinang rajah. Apabila kecacatan terdapat pada pinggir batang palma, teknik tomografi ultrasonik menganggar luas kawasan reput yang lebih besar daripada sebenarnya. Jadi, pengesanan lokasi dan penilaian luas reput perlu ditambah baik. Gabungan teknik tomografi ultrasonik dengan kerintangan gerudi mikro boleh mengesan lokasi dan luas kawasan pereputan dengan tepat.

INTRODUCTION

The royal palm (*Roystonea regia*) is a common palm planted along the streets in Taiwan. During a typhoon in June 2009, a royal palm was blown down causing the death of a man. This accident caused concerns among the people with regard to tree risk evaluation and protection. Standing trees must be evaluated in order to maintain *in situ* structural safety. Non-destructive evaluation (NDE) techniques are of special interest because they do not affect the present structural integrity and safety of a tree. Various NDE techniques are used to detect deterioration in trees in order to identify hazardous trees. Stress and ultrasonic wave proven to be effective in detecting and estimating deterioration in tree stems and wood structural members (Mattheck & Bethge 1993, Ross & Pellerin 1994, Schad et al. 1996, Yamamoto et al. 1998, Lin et al. 2000, Divos & Szalai 2002, Pellerin & Ross 2002). Reliable defect evaluation for imaging internal characteristics in trees is possible by X-ray and neutron radiography, computed tomography and magnetic resonance (Bethge et al. 1996, Bucur 2003, Nicolotti et al. 2003). These techniques can provide tomographic data on the spatial locations of various defects and internal wood characteristics. However, their

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of high costs, fear of X- and gamma rays, strict regulations and the control of radiation sources associated with their use.

Different tomographic devices actually represent an improvement of the diagnostic capability compared with the traditional digital measurements. Currently, there is interest in developing and using quick and cost-effective technologies to evaluate and display two-dimensional (2D) tomographic images of transverse sections of standing trees by ultrasonic techniques. Ultrasonic tomography allows the user to reconstruct the distribution of the ultrasonic wave velocity as it propagates through the investigated cross-section. Acoustic tomographic measurements in wood have proven to be effective variables for detecting and estimating deterioration in different tree stems (Ross 1999, Gilbert & Smiley 2004, Bucur 2005, Wang et al. 2005, 2007, Deflorio et al. 2008, Lin et al. 2008, Wang & Allison 2008, Wang et al. 2009). In this context, the most important constraint is data interpretation in relation to the strong anisotropy of wood. However, it is vital that tree managers understand the status and health levels of royal palms. The wood anatomy of royal palm differs completely from trees. Little information is known about the application of non-destructive techniques on royal palms. So, it is vital to compare measurements of other broadleaves and conifers.

Although acoustic tomography was proven to be the most effective technique for detecting internal decay, locating the position of defects and estimating their sizes, shapes and characteristics must be verified by corresponding cross-section inspection. For example, a resistance microdrilling technique can be used to determine the nature of the defect and correctly interpret the tomographic results. The test is considered minimally invasive.

No report has been published on detecting the wood quality and decay in royal palm by non-destructive evaluation. Therefore, the purpose of this study was to assess the internal wood quality of standing royal palm using ultrasonic tomographic and resistance microdrilling techniques. Another objective was to determine the correlation between tomographic results and the amount and location of actual deterioration in the palm. A final objective was to adjust and display the confirmed ultrasonic wave tomogram of the cross-section of a trunk.

MATERIALS AND METHODS

The structural stability of two normal royal palms in Chiayi, Taiwan, was evaluated. The palms were felled and two 10 cm thick discs were cut from each tree at 30 and 130 cm above ground level. Four sample discs were cut in total. The discs were identified as disc nos. 1–4. All discs were transported to the Taiwan Forestry Research Institute in Taipei, Taiwan. A digital picture of the cross-section was taken from each disc. To understand and screen for internal trunk defects and characteristics, visual inspection, single-path ultrasonic wave and resistance micro-drilling techniques were conducted to look for anomalies.

The experiment was also carried out *in situ* on 25 royal palms in Tainan (22 palms) and Taipei (3 palms), Taiwan. The palms in this study were identified as palm nos. 1–25. A digital picture of the trunk surface was also taken from each palm. To understand and screen for internal trunk defects and characteristics, ultrasonic wave and resistance microdrilling techniques were used.

The ultrasonic equipment used for data acquisition was a Sylvatest Duo with a frequency of 22 kHz. An electric signal was transformed by the transmitter probe into an ultrasonic pulse that travelled through the wood. It was received by the receiver probe, which allowed for travel time measurements.

Multiple ultrasonic measurements on wood discs and trunks were carried out at eight equidistant points (Figure 1). Specially made stainless steel nails were driven into the wood of each sample disc and standing palm. All nails were placed in the palms in the weakest section (by visual inspection) or about 30 cm above the ground at an angle of 90° between the nail and the trunk axis to connect the transducer that detected propagated ultrasonic wave. The transmitter probe was located at point 1 and the ultrasonic pulse was acquired by the receiver probe at all other points; then the transmitter was moved to point 2. The measurements were repeated for all other positions of the transmitter probe, allowing for 56 (for a full round trip; 7 receiving probes × 8 transmitter probes) independent propagation time measurements for each investigated section. A complete data matrix was obtained through this measurement process at each test location.

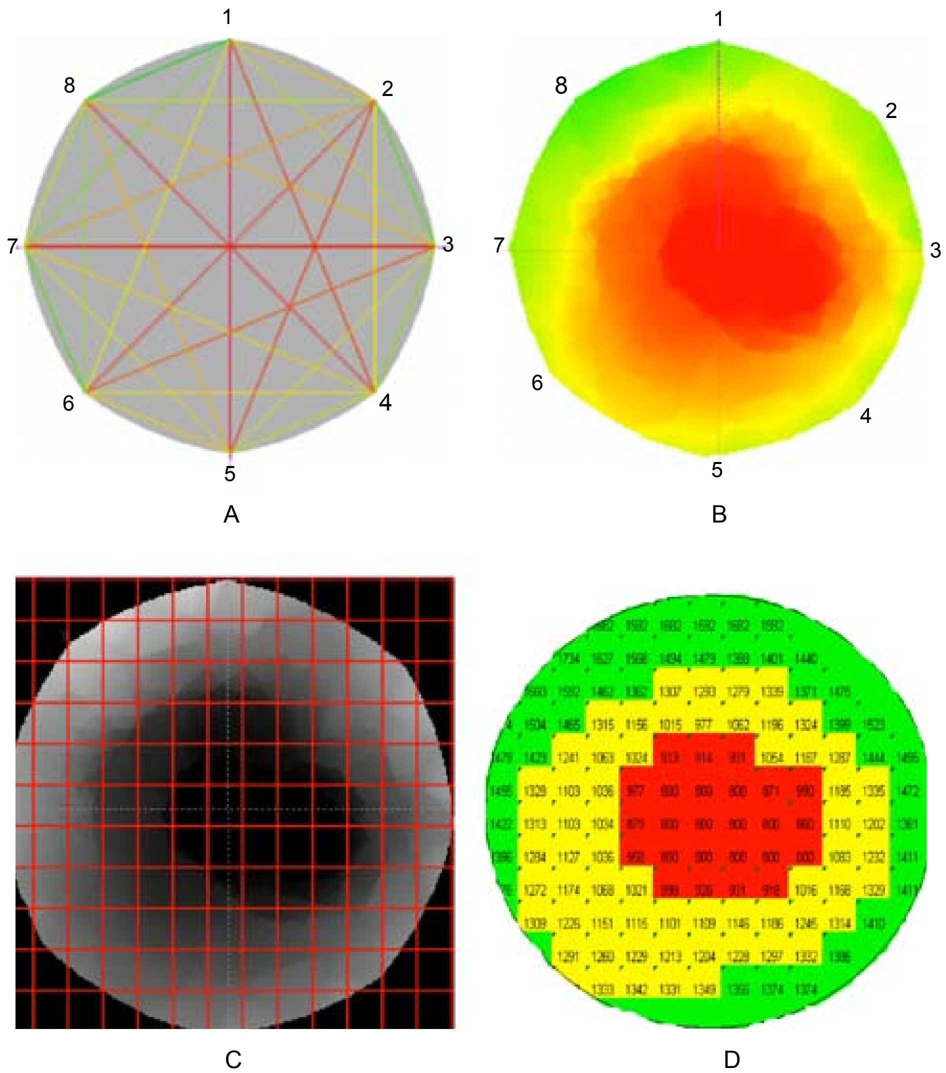

Figure 1 Sensor arrangement, paths of ultrasonic wave measurement and 2D tomogram of the experimental procedure. Transfer procedure (from A to D) of defect evaluation: (A) acoustic tomographic test on royal palm (*Roystonea regia*) using multichannel Sylvatest ultrasonic waves (eight probes), (B) constructed 2D image by Arbotom® software, (C) conversion of the 2D image into 256 gray shades, and (D) corresponding ultrasonic wave velocity calculated for every grid square.

According to the positions of two measured ultrasonic test points, four types of ultrasonic travel routes in the discs were first divided into path A (two measured points adjacent to each other such as from points 1 to 2), path B (with a one-point interval between two measured points such as from points 1 to 3), path C (with a two-point interval between two measured points such as from points 1 to 4) and path D (in the virtual radial direction with a three-point interval between two measured points such as from points 1 to 5).

For each section, the circumference and distances between sensors were measured using a tape measure. This information was used as input for the system software to map the approximate geometric form of the cross-sections. On completing the acoustic measurements, a tomogram was constructed for each cross-section using Arbotom 1.51 software.

Tree defect tomograms in different colours, indicating various ultrasonic velocities, obtained from the Arbotom software, were converted into 256 gray shades. The ultrasonic velocity at each pixel of the tomogram was further calculated by custom-made software developed in this study using the Borland C++ builder (Borland Software Corporation, Austin). Finally, the tomogram file was exported to Microsoft Excel for further assessment. The sensor arrangement, paths of the ultrasonic wave measurements and 2D tomogram of the experimental procedure in this study are shown Figure 1.

After information provided by the tomograms regarding the ultrasonic characteristics of each disc and tree cross-section was tabulated, resistance microdrilling was conducted using a F500 resistograph. The drilling paths were selected from the bark side to the centre of a trunk cross-section (radial direction), and the orientations were in the east, west, south and north directions of the trunk as displayed in the tomogram as possible deterioration. The four resistance profiles of directions represent average wood quality in four quadrants of cross-section. The circular deterioration was assumed in the trunk by drilling resistance. The wood quality was divided into three groups. The areas of high drilling resistance values represented wood with high density, sound wood; low drilling resistance values represented wood with low density, unsound wood; and very low drilling resistance values represented wood with a very low density or the absence of wood. These measurements were used to evaluate the area and location of the deterioration.

The discs and palms with a range of internal physical conditions were selected to develop ultrasonic wave velocity maps of the cross-sections. The vertical grids on the discs and cross-section of palms were aligned east to west, while the horizontal grids were aligned south to north (10 × 10 mm grids, Figure 1). An acoustic tomogram showed the distribution of velocities in a cross-section of a palm by acoustic measurement.

Acoustic tomograms of the discs and palms were generated in colour schemes: green represented areas of high acoustic velocity with high density, sound wood; yellow represented areas of low velocity with low density, unsound wood; and red represented very soft wood, with a very low velocity or the absence of wood (sound, green; deteriorated, yellow and red). These measurements were used to evaluate the area and location of the deterioration. The area of the deterioration was calculated as percentage of squares identified as the deteriorated area divided by the total area of the wood. The correlation between the amount of deterioration indicated by the tomogram and that identified by resistance microdrilling was calculated by linear regression analysis.

The accuracy of the tomogram in locating deterioration was determined by comparing the actual location of deterioration in the photographic cross-sections and resistance microdrilling profiles with the tomograms (Gilbert & Smiley 2004). Grid squares where the tomogram showed deterioration and the photograph and drill-resistance profile showed no deterioration (false positives) were counted. Likewise, grid squares where the photo and resistance profile showed deterioration but the tomogram did not (false negatives) were counted. The areas of the squares were recorded as percentage of the total area of the cross-section. The accuracy was calculated by dividing the area of false positives plus the area of false negatives with the total cross-sectional area (i.e. percentage accuracy (%) = 100 – percentage of false positives and negatives).

When the ultrasonic tomogram of a tested royal palm was found to not closely match the visual or resistance microdrilling method, the tomographic features of the program were adjusted and the tomographic cross-section was reconstructed.

RESULTS AND DISCUSSION

Area and location of deterioration in the discs

The periphery of the discs were sound, high-density wood, with a thickness of about 2–3 cm. Deterioration, low-density and low-resistance profile areas of the internal wood are displayed by visual evaluation and resistance microdrilling in Figure 2. Deterioration in this experiment is defined as wood quality lower than that of the periphery of a healthy tree. From the drill-resistance profile, the deterioration area had low resistance value. The average corresponding ultrasonic wave velocities of the peripheral and internal wood in the discs were 1406–1503 and 1062–1166 m s^{-1} respectively, according to the tomographic map grids (Table 1).

The acoustic velocity within a cross-section strongly correlates with modulus of elasticity and density (Bucur 2003). The ultrasonic tomogram shows the distribution of the acoustic velocity in a cross-section of a tree and the transmitted acoustic signals strongly correlate with the modulus of elasticity and wood density (Wang et

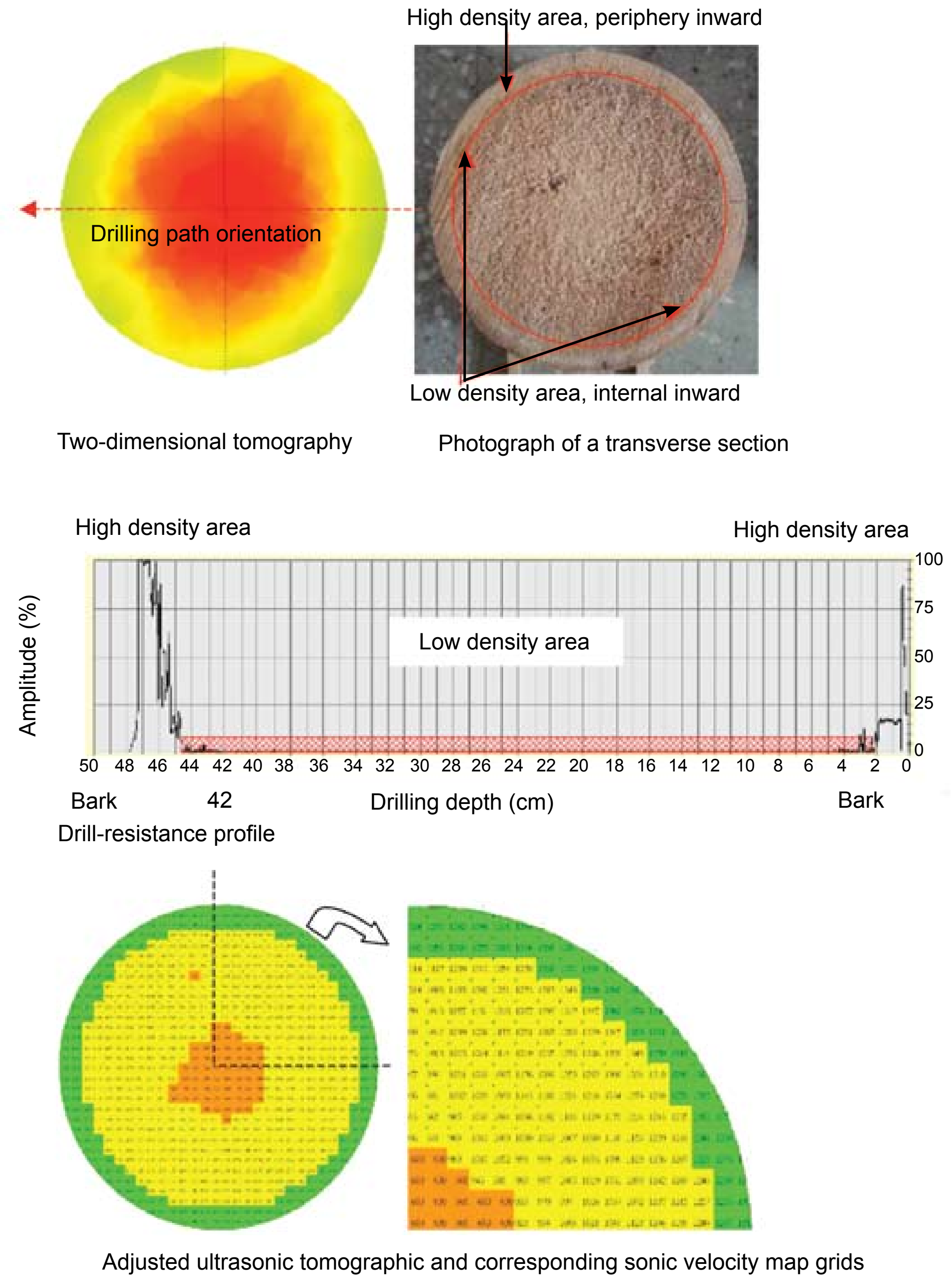

Figure 2 Comparison of ultrasonic wave tomography and resistance profiles to verify the tomogram, and a photograph of a corresponding cross-section of royal palm disc no. 4

al. 2009). Tomogram can also be interpreted as a density map of the cross-section (Wang et al. 2009).

The percentages of deterioration of the wood area determined by ultrasonic tomographic and drill-resistance profile examinations are shown in Table 2. The percentages of the deteriorated area as measured by the microdrilling method (75.4–86.8%) were higher than those by the tomographic method (63.3–82.3%). It was found that ultrasonic tomography underestimated internal deterioration. This was similar to the results of Gilbert and Smiley (2004) and Wang et al. (2009) who indicated that acoustic tomography underestimated heartwood and internal decay.

In discs where deterioration was present, an average of 5.2% of the total area of the sample was false positives where the tomogram showed that deterioration was present but the cross-

Table 1 Ultrasonic wave velocities of four normal discs

Disc no.	Peripheral wood (about 2–3 cm)			Internal wood		
	Minimum	Average	Maximum	Minimum	Average	Maximum
1	1405	1441	1539	900	1166	1397
2	1348	1406	1489	900	1062	1348
3	1356	1481	1734	900	1099	1349
4	1403	1503	1608	900	1152	1392

Values in m s^{-1}

Table 2 Comparison of area and location of deteriorated wood determined by ultrasonic wave and resistance microdrilling examinations

Disc no.	Average diameter (cm)	Deteriorated area (%)			Total area (%)		Accuracy (%)
		Tomographic	Microdrilling	Difference	False positive	False negative	
1	53.2	63.3	75.4	12.1	1.8	14.3	83.9
2	47.4	82.3	83.6	1.4	4.9	6.5	88.6
3	42.3	69.4	77.6	8.2	5.4	13.8	80.8
4	36.9	81.8	86.8	5.0	8.7	10.0	81.3
Average	45.0	74.2	80.9	6.7	5.2	11.2	83.7

section did not. However, false negatives were present on average in 11.2% of the readings (Table 2). The average percentage accuracy for discs where decay was present was 83.7%.

Determining the transition zone between sound and deteriorated wood is important for correctly calculating deteriorated areas of a disc cross-section. As the highest ultrasonic wave velocity of the cross-section tomogram occurs near the bark, the transition position and velocity between sound and deteriorated wood are decided by the drilling-resistance profile and visual evaluation. The established ultrasonic wave velocity of the sound–deteriorated wood transition zone is shown in Figure 3.

The acoustic velocities of sound wood near the bark increased with an increase in the velocities of demarcation between sound and deteriorated wood. The relationship was represented by a positive linear regression formula ($r^2 = 0.90$; $p < 0.01$). The position of the velocity and the drilling-resistance profile were provided to improve the percentage accuracy of decay detection.

Area and location of deterioration in a palm

The internal wood quality and deterioration detection in sound royal palms using ultrasonic tomographic, visual evaluation and resistance microdrilling techniques are shown in Figure 4. The palms diagnosed as having defect had different types of structural defects, including decay, splitting, gaps and aerial roots, according to visual trunk surface evaluation. In general, more defects and more serious extent of decay occurred on the trunk near the ground.

Of the 25 royal palms tested, 15 palms (palm nos. 2, 5, 7, 9, 12, 13, 14, 17, 18, 20, 21, 22, 23, 24 and 25) were predicted to have slight to serious decay defects, while the remaining palms were predicted to be sound and normal. Palm nos. 4, 11 and 12 had aerial roots; the ultrasonic wave velocities of the cross-section grids using tomography were < 1100 m s^{-1} and the thickness of the periphery was also thinner (< 2 cm) by resistance microdrilling.

The thickness of sound peripheral wood in palms was 2–3 cm. Deteriorated and low-density areas of internal wood and defects were displayed by resistance microdrilling. Therefore, a sound thickness of 2–3 cm of the peripheral wood in royal palms is very important for tree hazard evaluation and conservation.

There was high correlation between the amount of decay detected by ultrasonic tomography and the amount actually present in the cross-section of discs and palms by visual inspection

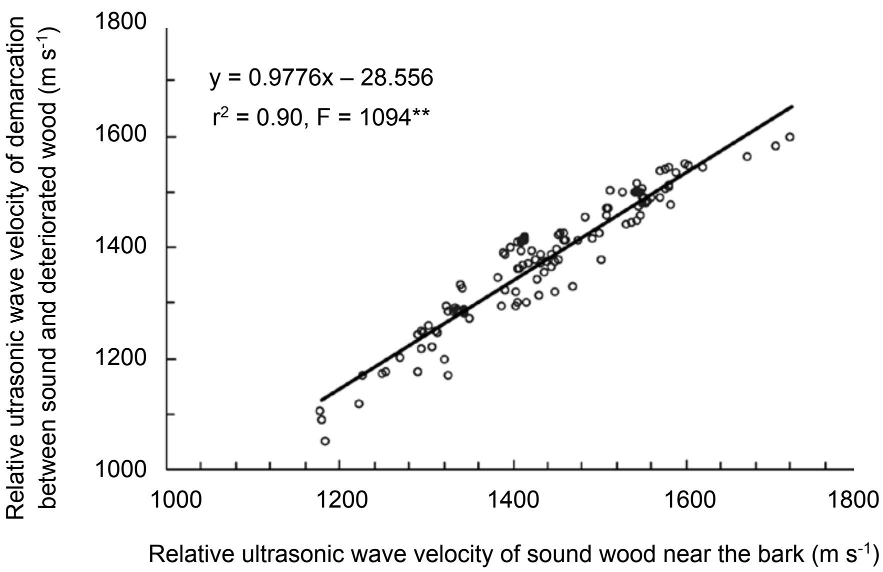

Figure 3 Established ultrasonic wave velocity of the sound–deteriorated wood transition zone

and the drill-resistance profile (coefficient of determination $r^2 = 0.99$, $p < 0.01$, Figure 5). This was similar to the results of Gilbert and Smiley (2004), who reported high correlation between the amount of decay detected by Picus and the amount actually present in the cross-sections ($r^2 = 0.94$).

The percentages of deteriorated wood by ultrasonic tomography and drilling-resistance profile examination are shown in Table 3. The average percentage value of the deteriorated area calculated by the microdrilling method (80.5%) was higher than that of the tomographic method (73.9%). Ultrasonic tomography was found to underestimate internal deterioration.

In palms where deterioration was present, an average of 5.9% of the total area of the sample was false positive where the tomogram showed that deterioration was present but the cross-section did not. However, false negatives were present on average in 11.7% of the readings (Table 3). The average percentage accuracy for palms where decay was present was 82.4%. Less decay was detected by Picus than was observed visually (Gilbert & Smiley 2004). Picus acoustic tomography was reported to underestimate heartwood and internal decay (Wang et al. 2009). However, in this study, when defects (decay, splitting, gaps) were present in the periphery of the trunk, acoustic tomography tended to overestimate the size of the defects. For ultrasonic tomography, a low-velocity peripheral zone is always present on tomographic images and this low-velocity ring is probably the result of wood anisotropy (virtual radial and tangential velocity) (Nicolotti et al. 2003). Gilbert and Smiley (2004) reported that the tomographic quality near the bark appeared to be lower than in other portions of the cross-section. The decreased quality was probably due to a lack of straight-line sound transmissions in this curved area. Improvement of the handling of the edges would be beneficial because this is a critical area in terms of stability of the palm. Picus acoustic tomography may not be suitable for detecting the initial decay stages from the periphery inwards, as acoustic waves more often meet in the tree core than in the tree periphery (Deflorio et al. 2008). We suggest that detecting wood decay in trees should include tomographic method which should be verified by other exploratory techniques.

The criteria used for assessing deterioration of cross-section on tomograms by the corresponding ultrasonic velocity could be categorised as sound (> 1350 m s^{-1}), deteriorated (≤ 1350 m s^{-1} and > 900 m s^{-1}) and seriously deteriorated (≤ 900 m s^{-1}). The tomographic method provides information on the deterioration expansion as well as knowledge of the physical properties of the sound. Nicolotti et al. (2003) reported that when considering the results of ultrasonic tomography, the velocity values estimated for decayed areas of trees were 600–100 m s^{-1}. The estimated velocity value is then diagnostic of decay but it is not able to discriminate between the different degrees

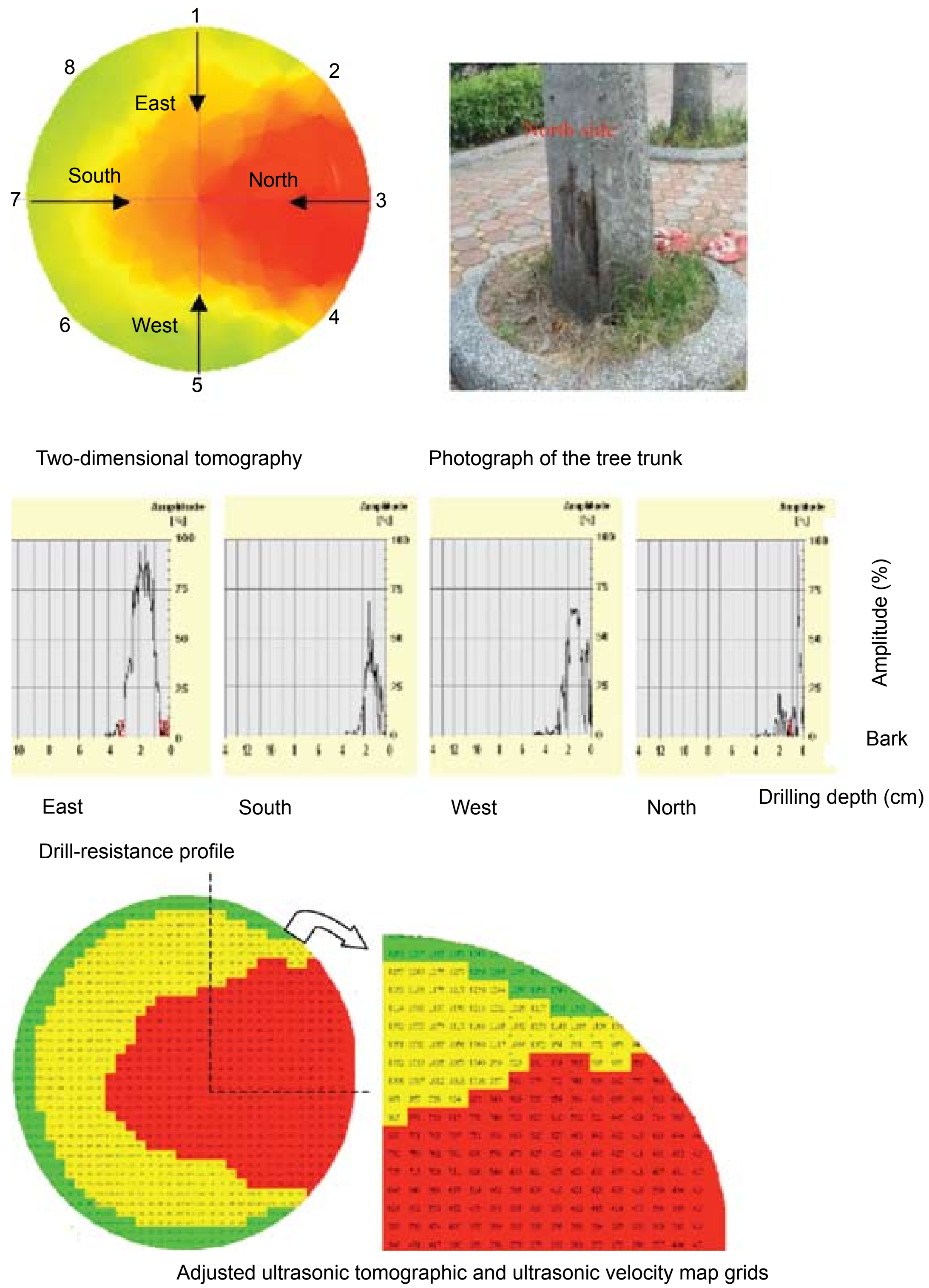

Figure 4 Comparison of ultrasonic wave tomography and resistance profiles to verify the tomogram and a photograph of the corresponding cross-section for royal palm tree no. 16. East, south, west and north show the drilling path orientations.

of decay. Therefore, the ultrasonic velocity may be affected by the tomographic accuracy, wood species, wood anisotropy, wood moisture content, whether the tree is leaning and environmental conditions.

For precise and efficient detection of defects by tomography in live royal palms, the following procedures are suggested. Firstly, by visual evaluation to detect the health of the palm by the appearance of the trunk helps select an

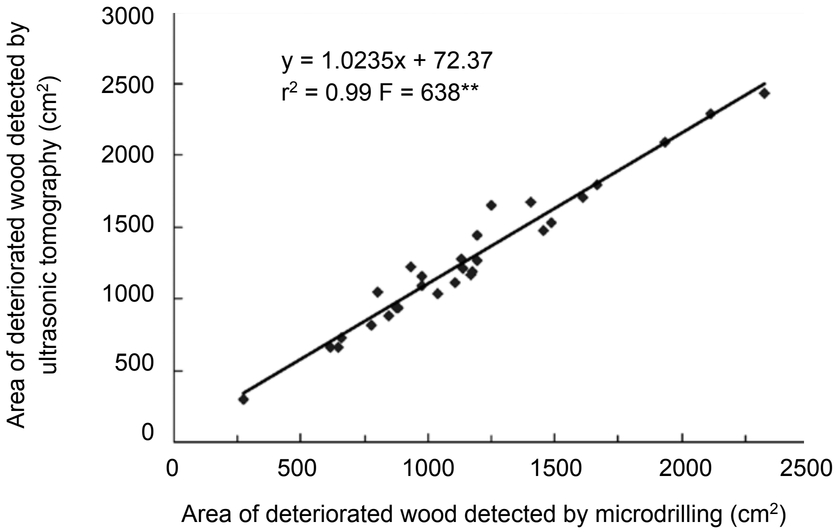

Figure 5 Relationship between areas of deteriorated wood detected by ultrasonic tomography and microdrilling

Table 3 Comparison of area and location of low-density wood determined by ultrasonic wave and resistance microdrilling techniques

Palm no.	Average diameter (cm)	Low-density wood area (%)			Total area %		Accuracy (%)
		Ultrasonic	Microdrilling	Difference	False positive	False negative	
1	61.6	78.3	81.5	3.3	7.8	10.4	81.8
2	36.2	75.3	79.1	3.7	9.1	11.9	79.0
3	43.3	80.0	80.4	0.3	5.9	6.4	87.7
4	33.1	75.3	77.2	1.8	6.8	8.6	84.5
5	56.0	78.5	84.5	6.0	7.7	11.6	80.7
6	25.4	54.3	58.3	4.1	3.9	7.8	88.3
7	37.1	57.3	61.5	4.2	7.3	10.9	81.9
8	35.3	67.0	73.6	6.6	4.8	11.0	84.2
9	41.5	65.3	69.1	3.8	7.1	11.2	81.7
10	57.9	80.2	86.8	6.6	4.2	7.8	88.0
11	50.3	83.8	90.3	6.5	5.1	11.9	83.0
12	40.3	76.6	90.3	13.7	4.7	17.1	78.2
13	36.9	79.1	82.8	3.7	5.5	8.8	85.6
14	50.0	63.8	84.3	20.4	2.1	21.4	76.5
15	47.8	66.8	80.1	13.3	3.3	15.1	81.5
16	45.2	74.4	78.6	4.2	7.9	10.9	81.3
17	39.5	65.7	85.3	19.6	5.9	24.0	70.1
18	47.1	85.2	87.6	2.3	4.8	6.5	88.7
19	43.9	61.5	80.6	19.0	2.1	19.9	78.0
20	40.7	85.1	85.3	0.1	8.8	8.9	82.3
21	41.4	77.1	77.2	0.1	9.7	9.9	80.4
22	44.9	73.8	73.9	0.2	7.6	8.2	84.1
23	42.3	80.7	86.3	5.6	4.4	9.7	85.9
24	43.3	76.8	86.6	9.8	6.1	14.8	79.1
25	48.7	86.4	91.8	5.4	3.8	8.5	87.8
Average	43.6	73.9	80.5	6.6	5.9	11.7	82.4

appropriate section for analysis. In general, more defects and more serious decay are shown on the trunk at < 1.6 m above the ground and one should select the weakest cross-section. Secondly, detecting deterioration in royal palm by a single-path ultrasonic wave test can provide initial screening to confirm the need for more advanced testing. The acoustic tomogram obtained using Arbotom tomography provided strong evidence of structural defects. The defect position and areas identified by the tomogram showed significant correspondence to the wood properties of the cross-section. Although the deterioration properties of the cross-section were reflected in the tomogram, the deterioration zone displayed in the tomogram was smaller than the actual deterioration area present in the cross-section. Therefore, the area and location of the defects need to be further identified. Tree tomographic inspection in combination with resistance microdrilling can provide direct displays of 2D image shadows. Finally, the tomogram should be adjusted and reconstructed so that the acoustic shadows in the tomogram show good agreement with the physical conditions of the cross-section according to visual observation and resistance microdrilling. All the techniques proposed were able to ascertain the presence of internal decay and all evaluation parameters showed obvious correspondence to conditions of decayed wood. We suggest this for detecting deterioration in royal palms. Wang et al. (2007) also reported that acoustic tomography could not distinguish between large internal cracks and heartwood decay in red oak trees. To make better assessments of the internal conditions of urban trees, other approaches such as visual inspection and resistance microdrilling should also be employed.

CONCLUSIONS

There was high correlation ($r^2 = 0.99$) between the amount of decay detected by ultrasonic tomography and the amount actually present in the cross-section of discs and living palms on drill-resistance profiles. The average percentage value of the deteriorated area measured by the microdrilling method (80.5– 80.9%) was higher than that of tomographic method (73.9–74.2%). The average percentage accuracy for discs where decay was present was 82.4–83.7%. Ultrasonic tomography underestimated the internal deterioration of royal palms. However, when defects were present in the periphery of the trunk, acoustic tomography tended to overestimate the size of the defects. Therefore, detection of the location and area of deterioration need to be improved for corresponding confirmation of the characteristics.

As ultrasonic tomography detected less deterioration than was observed by visual evaluation and drilling-resistance technique, ultrasonic tomograms alone did not well identify the deteriorated location and area in royal palms. A combination of ultrasonic tomography and resistance micro-drilling was shown to accurately reveal the general location and area of the deterioration within the cross-sections tested.

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