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Detection of Electric Resistivity Tomography and Evaluation of the Sapwood-Heartwood Demarcation in Three Asia Gymnosperm Species

Cheng-Jung Lin, Chih-Hsin Chung, Te-Hsin Yang and Far-Ching Lin

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The proportions of sapwood and heartwood of trees have significant impacts on various uses. Electric resistivity tomography (ERT) and corresponding electrical resistance (ER) value maps were examined in Japanese cedar (*Cryptomeria japonica* D. Don), Taiwania (*Taiwania cryptomerioides* Hayata), and Luanta fir (*Cunninghamia konishii* Hayata) trees. The position of the sapwood-heartwood demarcation was measured on incremental cores from living trees and the corresponding ER of the sapwood-heartwood boundary was acquired from the ER map. A positive significant relationship was found between the maximum ER plus minimum ER values (ERmax + ERmin) and ER of the sapwood-heartwood demarcation from the tomographic data. The position of the sapwood-heartwood demarcation was determined by corresponding ER, and the critical ER can be established by the ERmax + ERmin value of the tomographic data. The results from this study indicate that ERT technique can be used to determine the position of the sapwood-heartwood boundary and can serve as a methodology in undamaged living trees of Gymnosperm species.

Keywords *Cryptomeria japonica*, *Cunninghamia konishii*, electrical resistance, nondestructive technique, *Taiwania cryptomerioides*
Addresses Taiwan Forestry Research Institute, Taipei Taiwan
E-mail d88625002@yahoo.com.tw
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1 Introduction

Examination of a stem cross-section often reveals a dark-colored central portion (heartwood) surrounded by a lighter-colored outer zone (sapwood), and the sapwood tissue also serves to conduct water upward in living trees (Bowyer et al. 2007). Sapwood contains living cells and reserve materials; and heartwood have ceased to contain living cells, and in which the reserve materials have been removed or converted into heartwood substance (Hillis 1987). Sapwood contains both living and dead cells and functions primarily as the storage of carbohydrates and nutrients and handles transport of the sap; however, heartwood consists of inactive cells that do not function in either water conduction or carbohydrates and nutrients storage; and the transition from sapwood to heartwood is accompanied by an increase in extractive content (Forest Products Laboratory 1999). It is generally known that in coniferous trees, the moisture content of sapwood is significantly higher than that of heartwood, furthermore, the wood properties of sapwood and heartwood significantly differ (Hillis 1987, Tsoumis 1991).

Sapwood thickness information is primarily of interest in treating forest products with preservatives because sapwood generally takes up preservatives better than heartwood (Lassen and Okkonen 1969). In living trees, sapwood is responsible for conducting sap and synthesizing and storing biochemicals; and the living cells of the sapwood are also the agents of heartwood formation. Moreover, heartwood functions in the long-term storage of biochemicals of many varieties depending on the species (Rowell 2005). Sapwood also stores carbohydrates, water, and nutrients, and sapwood storage helps buffer environmental fluctuations and may contribute to the resiliency and longevity of trees; and tree size and leaf area are correlated with sapwood area (Ryan 1989). Therefore, understanding the proportions and properties of sapwood and heartwood can contribute to better effective utilization of wood and understanding of tree growth performance.

There were some researches about the application of electrical resistance value (ER) in living trees. Shigometer ER was used to evaluate the health of canyon live oaks (*Quercus chrysolepis* Liebm.) (Paysen et al. 1992). Cambial ER (with a Shigometer) as an objective measure of the vitality of silver fir (*Abies alba* Mill.), and a decrease in the radial ring growth could be detected as an increase in the cambial ER (Torelli et al. 1999). There was a relationship between tree vigor and the fire history of trees (whether or not they had been burned in the past), and the ER was used as an index of the general metabolic activity of the Caribbean pine (*Pinus caribaea* Morelet) (Paysen et al. 2006). ER measurements were related to the occurrence of both discolored and decayed wood in red spruce (*Picea rubens* Sarg.), balsam fir (*Abies balsamea* (L.) Mill.), Norway spruce (*Picea abies* (L.) H. Karst.), and eastern red cedar (*Juniperus virginiana* L.) (Shortle and Smith 1987, Larsson et al. 2004, Shortle et al. 2010). Electrical resistivity tomography (ERT) can be used as a nondestructive technique to evaluate standing trees, discolored wood, decay, and roots (Bieker and Rust 2010a, b). Thus, ERT is valuable and has been used to measure tree vigor (vitality) or pathology (injury).

The ER is affected by the wood moisture content, secondary compounds, amount of ions, cell structure, and other factors (ex. reaction wood) (Shigo and Shigo 1974, Kubo and Ataka 1998, Meerts 2002, Rowell 2005, Bieker and Rust 2010a, b). Intra-specific reading are affected by weather conditions (water content and temperature), tree phenology, and tree diameter, it is necessary to standardize the ER data from healthy trees (Paysen et al. 1992). The ER was correlated with pH, potassium, and magnesium, and correlated with neither the wood moisture content nor wood density in the English oak (*Q. robur* L.) (Bieker and Rust 2010a). The changes of ER with changing moisture content (MC) is great in the region between zero and the fiber saturation point (FSP); about the point, the change is relatively very small (Tsoumis 1991). The ER tends to decrease with increase in MC, and the effect of MC on the ER below the FSP was stronger than above the FSP.

The ER is primarily correlated with the wood moisture content below the fiber saturation point (FSP) and is mainly affected by the concentration of mobile ions in the wood above the FSP. Moreover, significant differences in wood moisture contents between sapwood and heartwood that are found in most conifers allow the accurate separation of these two zones (Lin 1967, Shigo and Shigo 1974). Living cells of sapwood are also agents of heartwood formation and the tree's accumulation of biochemicals. Moreover, these chemicals are collectively known as extractives, and extractives are responsible for imparting several larger-scale characteristics to wood (Rowell 2005). Secondary compounds tend to accumulate in the heartwood, while storage products, including soluble sugars, amino acids, and mineral elements, are removed from senescing sapwood rings (Meerts 2002). Moisture content and inorganic compounds in tree stems varies with the species, site, and environmental conditions as well as with the age of the stem (Hillis 1987).

Sapwood and heartwood widths in Scots pine (*Pinus sylvestris* L.) was estimated, and the sapwood-heartwood boundary was defined as the center of the narrow green ring on tomography, corresponding to a steep rise in the ER from sapwood to heartwood (Bieker and Rust 2010b). However, the position of the sapwood-heartwood demarcation was not identified and estimated by the ER.

The first objective of this study was to investigate ERT and resolve corresponding ER maps of Japanese cedar (*Cryptomeria japonica* D. Don), Taiwania (*Taiwania cryptomerioides* Hayata), and Luanta fir (*Cunninghamia konishii* Hayata) trees. A secondary objective was to establish the relationship between the ER values and the sapwood-heartwood demarcation in the ER maps.

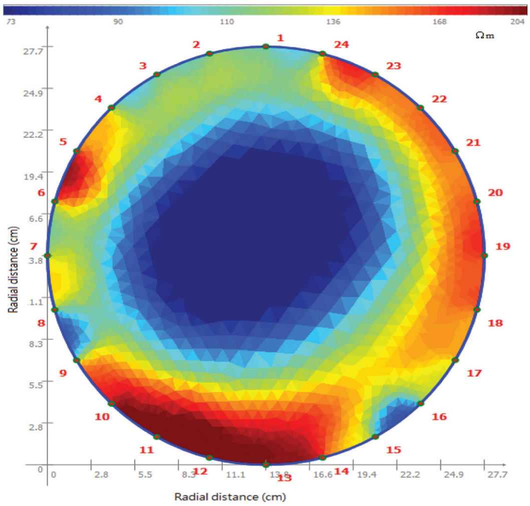
2 Materials and Methods

In this experiment, 21 Japanese cedar trees (*Cryptomeria japonica* D. Don) (with diameters at breast height [DBHs] of 16~35 cm and ring numbers of 20~40 at the DBH position) growing in the Taiping Mt. Working Circle, Chilan Mt., Ilan County, Taiwan; 7 Taiwania (*Taiwania cryptomerioides* Hayata) trees (with DBHs of 20~45 cm and ring numbers of 25~35 at the DBH position) growing on Sansia Mt., New Taipei City, Taiwan; and 11 Luanta fir (*Cunninghamia konishii* Hayata) trees (with DBHs of 22~29 cm and ring numbers of 25~30 at the DBH position) growing on Lienhuachih Mt., Nantou County, Taiwan were chosen. All measurements were conducted on undamaged trees with no visual signs of stem decay or deterioration on December 18 (Japanese cedar) and 28 (Taiwania), 2010, and February 16, 2011 (Luanta fir). The experimental dates were in winter, thus the tree has a dormant period according to no growing of inter-node length. All sampled trees were growing on gradually sloping or level terrain to avoid abnormal tree growth.

In total, 39 sample trees (three softwood species) were nondestructively tested using a multichannel electric resistance measurement system: Electric Resistivity Tomography (ERT) of Picus Treetronic (Argus Electronic, Rostock, Germany). All sampled cross-sections of the trees were tested at about 50~130 cm above the ground (undamaged cross-section). The Picus ERT measurement system consisted of 24 electrodes evenly placed around the trunk in a horizontal plane during testing. Each electrode was clipped and attached to a nail (with a 2-mm diameter) that had been tightly forced into the bark and sapwood. Upon completion of the ER measurements at each level, a tomogram was constructed for the cross-section using Picus Q72 software. The entire process including the calculation was completed within about 15 minutes per tree (for ER measurements of 24 sensors, $24 \times 23 = 552$ values per cross-section).

After the ERT tests were completed, an incremental corer was used to remove 5-mm-diameter cores from the trees. From the east-west and north-south aspect of each sample tree, we extracted two bark-to-bark (which passed the center of the trunk) incremental cores. The length and diameter of the core were diameter of tree and 5 mm, respectively. The sample core was subsequently labeled with the tree and core number. The coring paths were selected from the bark side to the center of a trunk cross-section (radial direction), and the orientations were in the east, west, south, and north directions of the trunk. The position of the sapwood-heartwood demarcation was based on colour and detected by a visual method using the naked eye. For Japanese cedar, the heartwood varies from russet-brown to dull brown, while sapwood is wide, yellowish-white and clearly distinguishable from the dark heartwood. For Taiwania, the heartwood is yellow to yellowish-red with purplish-brown streaks and clearly distinguishable from the sapwood which is pale yellowish-red. For Luanta fir, the heartwood is pale yellowish-brown, and sapwood is pale yellow (Wang 1983). The sapwood width (distance from the bark, not included transition zone or intermediate wood) in the four directions represented average measurements in the four quadrants of the cross-section. Thus, four average sapwood width values were measured with a ruler and identified as the position of the sapwood-heartwood demarcation in the cross-section of a tree.

To quantitatively assess the tomograms of these trees, all corresponding ERs at each pixel of the tomogram were further calculated by the tomogram's visualization and inversion, and ER maps of the cross-sections were displayed using custom-made software developed for this study. The ERT and schematic of the corresponding ER map grids (1.0 × 1.0 cm, the size can be adjusted by software for requirement and practice) are shown in Figs. 1–3. The sapwood width (distance from the bark) was calculated on incremental cores from living trees by an incremental coring method, and the corresponding ER value was resolved by the position of the sapwood width in the tomogram. The four corresponding ERs of the sapwood-heartwood boundary were acquired from the ER map. ERs of the sapwood-heartwood demarcation in the four directions were equalized and represented an average value of the cross-section of the sampled tree.



											122	123	122	131	114	113	140										
								117	124	135	138	136	134	131	126	130	148	171	162								
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					113	125	136	140	139	136	133	128	126	126	128	131	140	151	160	164	166	161					
				146	134	134	138	137	133	126	120	116	113	113	115	118	123	131	143	150	157	165	168				
			142	156	146	140	136	129	122	114	106	101	98	100	100	101	108	115	123	135	146	157	166	166			
		135	161	156	146	136	128	118	107	99	91	85	83	81	81	84	91	98	106	117	132	147	158	168	159		
		180	165	153	139	127	116	105	96	84	77	75	73	73	73	74	77	82	92	106	121	136	149	162	169	154	
	160	186	166	146	130	115	104	91	80	75	73	73	73	73	73	73	73	74	82	95	112	127	142	157	165	158	
	175	179	161	138	119	104	90	77	73	73	73	73	73	73	73	73	73	73	76	88	103	120	136	152	163	169	137
	167	161	147	128	109	94	80	73	73	73	73	73	73	73	73	73	73	73	73	84	101	115	133	149	162	171	163
119	142	143	134	118	102	87	76	73	73	73	73	73	73	73	73	73	73	73	73	82	98	115	131	148	162	172	161
119	135	135	127	112	97	80	73	73	73	73	73	73	73	73	73	73	73	73	74	82	98	113	129	147	162	173	177
130	140	136	124	109	93	77	73	73	73	73	73	73	73	73	73	73	73	73	74	86	100	114	131	148	163	174	180
143	148	140	125	108	92	78	73	73	73	73	73	73	73	73	73	73	73	73	81	92	105	119	134	152	165	173	176
137	152	142	128	110	95	81	74	73	73	73	73	73	73	73	73	73	73	79	88	101	114	127	140	153	166	173	173
133	150	139	128	114	101	87	75	73	73	73	73	73	73	73	73	75	78	87	98	111	122	133	145	158	167	173	162
	129	128	126	118	109	98	84	76	73	73	73	73	73	74	77	81	90	98	109	119	130	141	151	161	167	170	162
	101	114	125	125	119	108	96	86	79	77	76	77	78	81	86	94	101	111	122	130	139	148	157	163	166	165	135
	95	110	131	138	132	121	110	100	93	89	87	87	91	94	100	107	114	125	131	139	147	154	160	164	164	156	
		133	152	153	146	136	125	116	108	104	103	104	108	110	114	121	128	135	142	148	153	158	162	161	161	147	
		145	171	169	163	154	143	135	129	124	121	118	122	124	129	135	141	147	151	155	156	157	157	154	143		
			161	181	180	172	165	158	152	146	142	138	139	142	146	149	155	158	158	156	149	147	147	145			
				184	195	190	185	180	175	168	163	159	159	159	162	165	167	166	162	153	137	121	125	134			
					182	201	200	197	195	188	181	177	176	176	176	178	177	172	161	148	118	96	95				
						165	200	202	202	201	198	193	191	190	190	187	181	172	160	144	112						
								173	196	202	202	201	200	199	197	195	185	168	146	127							
										174	174	180	182	190	179	175	173										

Fig. 1. Electric resistivity (ER) tomogram and corresponding ER value map (Ωm) of a Japanese cedar tree (*Cryptomeria japonica* D. Don) (no. CJ1).

3 Results

All tomograms of Japanese cedar and Taiwania trees displayed a distinct pattern of high ER at the stem perimeter and low ER in the stem center (Figs. 1 and 2). However, all tomograms of Luanta fir trees displayed a distinct pattern of low ER at the stem perimeter and high ER in the stem center (Fig. 3). The average minimum ER values were 76.6, 68.6, and 326.9 Ωm; and the maximum ER values were 186.9, 130.7, and 1261.3 Ωm for Japanese cedar, Taiwania, and Luanta fir trees, respectively (Tables 1–3). Average sapwood widths were 4.3, 3.5, and 2.7 cm (sapwood-heartwood demarcation); and the corresponding average ER values were 132.0, 99.8, and 586.4 Ωm for Japanese cedar, Taiwania, and Luanta fir trees, respectively (Tables 1–3).

Average ER values of heartwood were 76.6~132.0 Ωm and of sapwood were 132.0~186.9 Ωm for Japanese cedar; average ER values of heartwood were 68.6~99.8 Ωm and of sapwood were 99.8~130.7 Ωm for Taiwania; and average ER values of heartwood were 586.4~1261.3 Ωm and of sapwood were 326.9~586.4 Ωm for Luanta

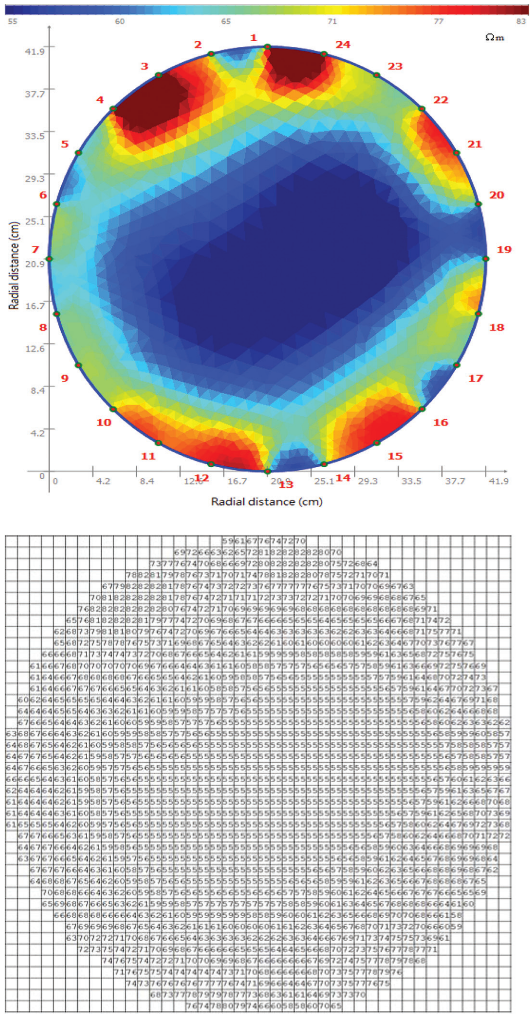

Fig. 2. Electric resistivity (ER) tomogram and corresponding ER value (Ωm) map of a Taiwania tree (*Taiwania cryptomerioides* Hayata) (no. TC8).

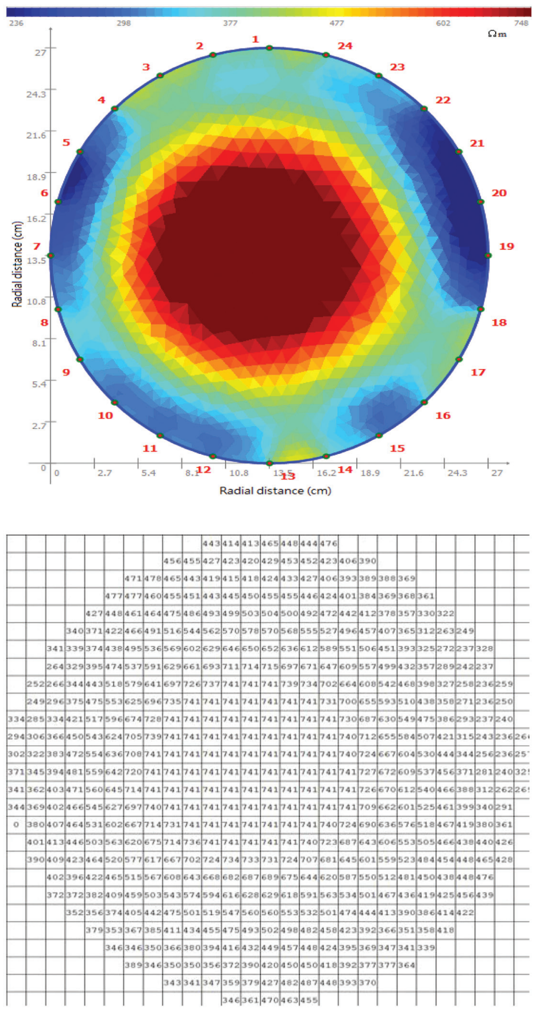

Fig. 3. Electric resistivity (ER) tomogram and corresponding ER value (Ωm) map of a Luanta fir tree (*Cunninghamia konishii* Hayata)(no. CL1).

fir (Tables 1–3). Average ER values of sapwood/heartwood in Luanta fir were clearly higher than those of Japanese cedar and Taiwania trees.

To estimate the position of the sapwood-heartwood demarcation, relationships between maximum ER plus minimum ER values (ERmax + ERmin) and corresponding ER values of the sapwood-heartwood demarcation of the tomographic data of Japanese cedar, Taiwania, and Luanta fir trees were explored, and results are shown in Figs. 4–6. These ER values of the sapwood-heartwood demarcation tended to increase with an increase in ERmax + ERmin values of the tomographic data. When expressed as a linear regression relationship, the coefficients of determination (R^2) were 0.925 (Japanese cedar), 0.989 (Taiwania), and 0.80 (Luanta) ($p<0.01$).

In this experiment, abnormal ERT and extracted increment core with a non-central pith of Japanese cedar (no. CJ16, this irregular tree was excluded from the above analyses) were found and is shown in Fig. 7.

Table 1 Minimum and maximum electric resistivity values of the tomographic data and corresponding electrical resistivity (ER) values of the sapwood-heartwood demarcation in sampled Japanese cedar (*Cryptomeria japonica* D. Don) trees.

Code	DH	ERmin	ERmax	SW	ERV
CJ1	27.7	73.0	204.0	4.6	128.5
CJ2	28.5	58.0	151.0	4.5	103.0
CJ3	33.6	61.0	125.0	3.8	101.8
CJ4	27.0	103.0	272.0	4.4	196.8
CJ41	33.0	70.0	143.0	5.6	101.0
CJ42	32.0	49.0	108.0	4.5	78.8
CJ43	25.5	100.0	234.0	4.1	168.3
CJ44	24.5	62.0	151.0	4.5	96.8
CJ45	26.5	54.0	153.0	3.5	137.8
CJ46	32.5	67.0	160.0	4.8	116.3
CJ49	25.0	122.0	216.0	4.0	173.0
CJ50	22.5	81.0	201.0	3.4	149.0
CJ51	33.0	91.0	200.0	3.4	153.3
CJ52	25.8	99.0	209.0	5.1	142.5
CJ55	26.5	67.0	189.0	5.0	109.3
CJ57	16.8	123.0	381.0	2.6	243.0
CJ47	30.3	83.0	194.0	4.6	139.5
CJ48	32.3	53.0	140.0	4.8	92.5
CJ53	27.5	49.0	126.0	4.2	88.5
CJ54	21.5	89.0	235.0	4.3	149.0
CJ56	33.0	54.0	133.0	3.9	104.3
Average	27.8	76.6	186.9	4.3	132.0
SD	4.4	22.4	60.5	0.7	39.4

DH, mean diameter of the detected cross section (cm); ERmin, minimum electrical resistivity in a tomogram (Ωm); ERmax, maximum electrical resistivity in a tomogram (Ωm); SW, mean sapwood width of a sampled incremental core from eastern, western, southern, and northern aspects (cm); ERV, corresponding ER values of the sapwood-heartwood demarcation (Ωm); SD, standard deviation.

Table 2 Minimum and maximum electric resistivity (ER) values of the tomographic data and corresponding ER values of the sapwood-heartwood demarcation in sampled Taiwania (*Taiwania cryptomerioides* Hayata) trees.

Code	DH	ERmin	ERmax	SW	ERV
TC3	37.5	65.0	119.0	3.3	93.5
TC4	21.0	82.0	172.0	2.3	132.5
TC5	23.3	97.0	247.0	2.8	164.5
TC7	38.3	58.0	93.0	3.8	78.8
TC8	42.5	55.0	83.0	4.4	66.0
TC9	41.5	53.0	76.0	3.3	65.3
TC10	46.0	70.0	125.0	4.6	98.0
Average	35.7	68.6	130.7	3.5	99.8
SD	9.7	16.0	60.7	0.8	36.7

Abbreviations are explained in the footnotes to Table 1.

Table 3 Minimum and maximum electric resistivity (ER) values of the tomographic data and corresponding ER values of the sapwood-heartwood demarcation in sampled Luanta fir (*Cunninghamia konishii* Hayata) trees.

Code	DH	ERmin	ERmax	SW	ERV
CL1	27.0	236.0	748.0	3.2	408.8
CL2	22.0	269.0	949.0	2.9	481.3
CL3	27.0	325.0	1411.0	2.5	604.8
CL4	28.0	280.0	1257.0	3.2	608.3
CL5	26.5	366.0	1237.0	2.8	558.0
CL6	25.3	327.0	1440.0	2.9	663.5
CL7	28.3	349.0	1343.0	2.5	680.8
CL8	21.0	308.0	1308.0	2.1	575.5
CL9	26.3	388.0	1428.0	2.6	603.3
CL10	22.5	463.0	1643.0	2.2	683.5
CL11	26.5	285.0	1110.0	2.9	582.5
Average	25.5	326.9	1261.3	2.7	586.4
SD	2.5	63.4	249.2	0.4	83.0

Abbreviations are explained in the footnotes to Table 1.

4 Discussion

In this study, tomograms of Japanese cedar and Taiwania trees displayed a distinct pattern of high ER at the stem perimeter and low ER in the stem center; in contrast, tomograms of Luanta fir trees displayed a distinct pattern of low ER at the stem perimeter and high ER in the stem center (Figs. 1–3). These results indicated that the moisture content of heartwood was higher than that of sapwood in Japanese cedar and Taiwania; however, the moisture content of sapwood was higher than that of heartwood in Luanta fir trees. This result is similar to that reported by Chen et al. (1998), who indicated that the moisture content of heartwood was higher than that of sapwood in Japanese cedar trees. In general, the heartwood is drier than sapwood in softwood species.

In this study, the distribution of electrolyte concentrations from the stem center to the sapwood-heartwood demarcation might also describe the low ER value around the pith in Japanese cedar and Taiwania trees. Bieker and Rust (2010a) showed that increasing concentrations of K and Mg decreased the ER in the heartwood of English

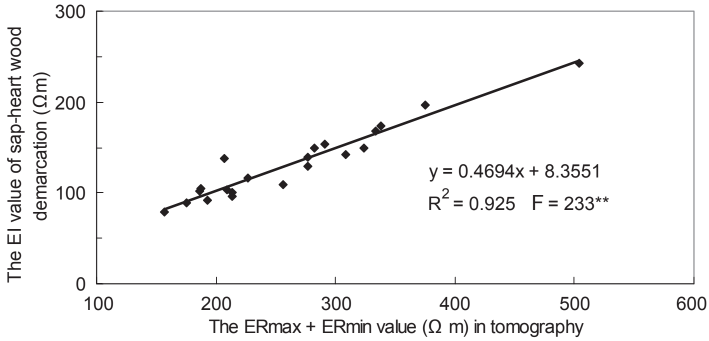

Fig. 4. Relationship between the maximum ER plus minimum ER (ERmax + ERmin) values and the corresponding electric resistivity (ER) value of the sapwood-heartwood demarcation of the tomographic data (Japanese cedar (*Cryptomeria japonica* D. Don), *n* = 21).

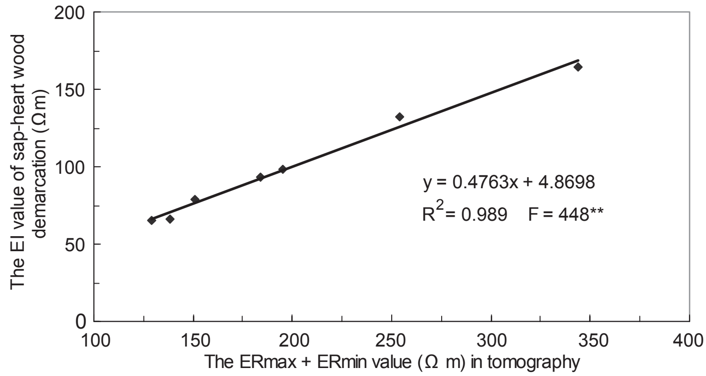

Fig. 5. Relationship between the maximum ER plus minimum ER (ERmax + ERmin) values and the corresponding electric resistivity (ER) value of the sapwood-heartwood demarcation (of an increment core) of the tomographic data (Taiwania (*Taiwania cryptomerioides* Hayata), *n* = 7).

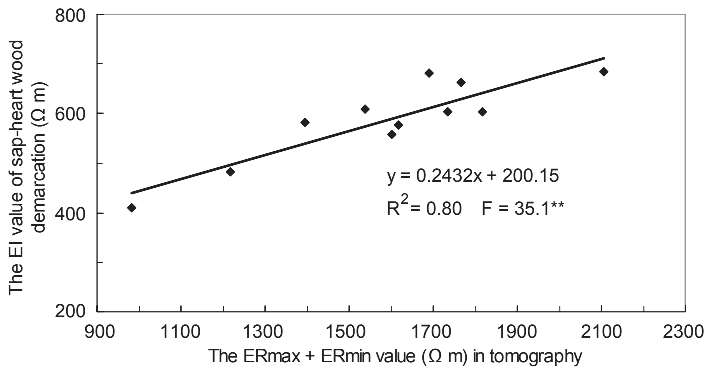

Fig. 6. Relationship between the maximum ER plus minimum ER (ERmax + ERmin) values and the corresponding electric resistivity (ER) value of the sapwood-heartwood demarcation (of an incremental core) of the tomographic data (Luanta fir (*Cunninghamia konishii* Hayata), *n* = 11).

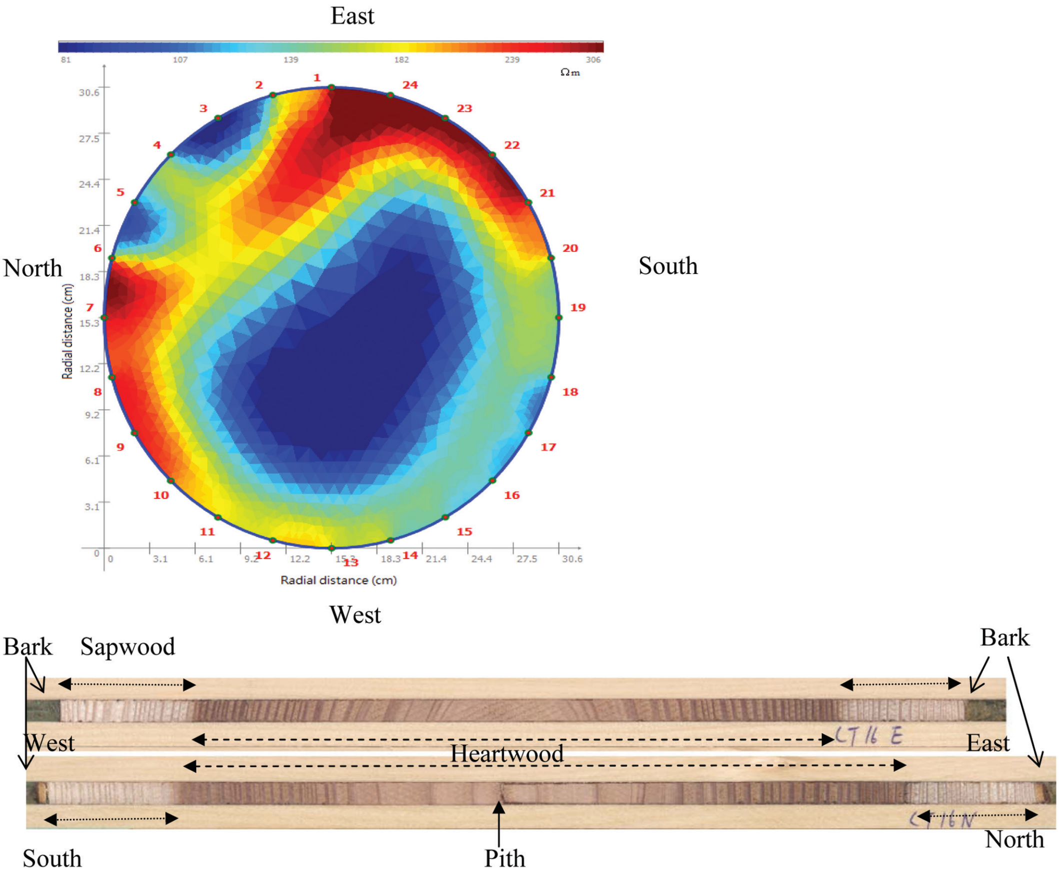

Fig. 7. Electric resistivity (ER) tomographic data and increment core with a non-centralized pith of Japanese cedar (*Cryptomeria japonica* D. Don) at a position of the detected cross-section (no. CJ16).

oak, while the wood moisture content remained constant. Kubo and Ataka (1998) reported that the moisture content of Japanese cedar tree has a tendency to increase in the blackened heartwood, so it seems that the large accumulation of potassium is associated with a high moisture content in the heartwood.

In this study, average ER values of the map (sapwood/heartwood) of Luanta fir were clearly higher than those of Japanese cedar and Taiwania trees (Tables 1–3). These results indicate that the moisture content and amount of ions in Luanta fir should be lower than those in Japanese cedar and Taiwania trees.

The determination of sapwood-heartwood boundary is mainly based on color differences in this study. This method is easy and effective to determine the sapwood-heartwood boundary. Moreover, the moisture content, wood density, and other physical and chemical properties between sapwood and heartwood may be significantly different and they do not perform similarily with other wood properties. Overall, the entire wood properties (combined action) of sapwood and heartwood are different, and can be distinguished in Japanese cedar, Taiwania, and Luanta fir trees according to ERT method.

Bieker and Rust (2010b) reported that the decentralized pith in Scots pine trees, which were located on a steep hillside, could be illustrated in a tomogram, which indicated that the ERT is able to show reaction wood. Thus, the ERT can express the tree growth performance, and the entirety of the ER result may be affected by various factors (ex. compression wood, cell structure, dead weight, and others).

Electrical properties were affected by moisture content, extractives, temperature, PH, ion concentration, wood density, cell structure, tree defects and other factors (ex. seasons) in standing tree. In this study, the combined action of the high difference in ER between heartwood and sapwood was reflected and existed in Japanese cedar, Taiwania, and Luanta fir trees. The demarcation of sapwood-heartwood can be determined by using ER values and the calculating method was introduced as a methodology. The position of spatial resolution estimate for the demarcation was verified by 2D ERT and the function of ERmax and ERmin values. Thus, the resolution can be settled according to necessity and practice. Furthermore, the ER values may be affected by several factors included species. The sapwood/heartwood border in different tree species (standard value) should be detected by the ERT method, respectively.

Although the ERT and corresponding ER value maps displayed distinct patterns of high and low ER values at the stem perimeter and central area, there were within-tree variations in ER values of sapwood and heartwood areas of the ERT and maps. ER values of the cross-section were totally (combined action) influenced by the distribution of the tree moisture content, amount of ions, cell structure, reaction wood, and other factors in the tree which might limit the ability to use of ERTs. Further research is needed to clarify the intensities of individual factors in future.

5 Conclusions

The purpose of this study was to investigate ERTs and evaluate the sapwood-heartwood demarcation of Japanese cedar, Taiwania, and Luanta fir trees by a nondestructive ER technique. The critical ER value can be established by the tomographic ERmax + ERmin value, and the position of the sapwood-heartwood demarcation was determined by the corresponding ER value. The ER technique can be used to determine the position of the sapwood-heartwood boundary as a methodology and nondestructive evaluation indicator of undamaged living trees of Japanese cedar, Taiwania, and Luanta fir.

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