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Longitudinal transmittance of visible and near-infrared light in the wood of 21 conifer species

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Summary – Light transmittance and reflectance were measured in 21 conifer species using a spectrophotometer equipped with an integrating sphere and light within a wavelength range of 500–1200 nm, to clarify the variety of longitudinal light transmitting properties among wood species. Transmittance values varied not only among different species but also between the sapwood and heartwood within certain species. Transmittance intensity increased from about 600–700 nm and showed peaks or shoulders in the ranges of 870–900 nm and 930–950 nm, and at around 1100 nm in all samples. The spectra tended to show similar patterns for 2 species within the same genus (*Chamaecyparis*, *Abies*, *Picea*, *Pinus*, *Pseudotsuga* and *Tsuga*).

Light transmittance differed between the sapwood and the heartwood in several species, and, patterns of the difference differed among the different genera.

Peaks at around 1100 nm were observed in both the sapwood and heartwood of all samples. Maximum conductivities of light at these peaks were relatively lower in wood species with helical thickenings (genera *Pseudotsuga*, *Torreya* and *Taxus*). Based on these results, it can be seen that the anatomical characteristics of wood influence the transmittance of light. The density of wood and secondary metabolites occurring in heartwood are also thought to influence the transmittance of light.

Keywords – near-infrared spectroscopy, visible and near-infrared light, conifer, transmittance, reflectance, wood.

Introduction

Near-infrared spectroscopy (NIRS) is an effective and non-invasive method for investigating the properties of materials and it can be used for the identification of wood species (Brunner *et al.* 1996; Schimleck *et al.* 1996; Tsuchikawa *et al.* 2003; Gierlinger *et al.* 2004; Flæte *et al.* 2006; Adedipe *et al.* 2008; Watanabe *et al.* 2011; Horikawa *et al.* 2015; Abe *et al.* 2015, 2016, 2020). We have utilized NIRS for the identification of wood species used in ancient and culturally significant wooden Buddhist statues to which invasive techniques cannot be applied. In doing so, we were able to achieve a successful separation of wood species using multivariate analysis (Watanabe *et al.* 2011; Abe *et al.* 2015, 2020). Through a series of studies, we obtained higher accuracy using relatively shorter NIR wavelengths (830–1150 nm) than longer ones (1150–2500 nm), for the separation of two anatomically similar species (*Torreya nucifera* and *Chamaecyparis obtusa*, *Chamaecyparis obtusa* and *Chamaecyparis pisifera*, *Cryptomeria japonica* and *Thuja standishii*) (Watanabe *et al.* 2011, Abe *et al.* 2015). We have postulated that differences in the conductivity of light could be the reason for the higher accuracy of these separations (Abe *et al.* 2016). We discovered that conductivities

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in wood of light with wavelengths in the range of 874–1000 nm differed significantly between two conifer species (*Chamaecyparis obtusa* and *Torreya nucifera*) and that the light conductivity in *Chamaecyparis obtusa* wood was 3–5 times higher than that in *Torreya nucifera*. We also found that this difference depended more on the species than on the wood density. It was thus concluded that the differences in light conductance between two species arise from a difference in the anatomical characteristics of wood.

Until now, no sufficient study has not been reported regarding the light conductivity of NIR in wood. Tsuchikawa and Tsutsumi (1996) indicated that light with a wavelength of 1100 nm had high transmittance in the wood of *Picea sitchensis*. The longitudinal light-transmitting properties of shorter NIR (<950 nm) have been investigated in the fresh branches and roots of some wood species (Sun *et al.* 2003, 2004). However, there had been no comprehensive study investigating the transmittance of shorter NIR in wood, by species, using xylarium-authorized wood samples. The purpose of the present study was to comprehensively clarify the variety of longitudinal light transmitting properties among wood species. To do this, we investigated the transmittance of light with wavelengths in the range of 500-1200 nm in the wood of 21 conifer species. We then considered the factors which influence the longitudinal transmittance of the light in the wood of conifer species.

Materials and methods

Sample preparation

We selected twenty native Japanese conifer species and one American conifer species (*Pseudotsuga menziesii*) (Table 1) for use in this study. Five wood specimens (3 specimens for *Tsuga diversifolia*) containing both the sapwood and heartwood of each species stored were used for the analyses (Table 1). These specimens had been kept at a temperature of 23 ± 2°C and a humidity of 50 ± 10% for more than 3 years, at the xylarium of the Forestry and Forest Products Research Institute (TWTw), in Tsukuba, Japan. The equilibrium moisture content was 9–11% (Forest Products Laboratory 1987). Wood samples (1 cm (L) × 2 cm (T) × 2 cm (R)) were prepared from the sapwood and heartwood of each specimen. Sapwood samples were not prepared from *Taxus cuspidata*, because the sapwood was too narrow.

Spectra measurement

For the estimation of the longitudinal light conductivities of wood samples, the transmittance and reflectance of light were measured. A spectrophotometer (UV-2600, Shimadzu, Tokyo, Japan) equipped with an integrating sphere (ISR-2600 Plus, Shimadzu) was used to acquire spectra at the xylarium mentioned above (Figure 1). For measurement, a selected transverse surface of the sample was irradiated with light. Four spectra in the wavelength range of 500–1200 nm were acquired from each wood sample, rotating the sample 90° clockwise before each acquisition. The integration time for each acquisition was 0.75 s/nm. The average of these four acquired spectra was used to represent the spectrum of the sample.

Light propagation on wood

Using the above-mentioned measurement device, we obtained the wood transmittance and reflectance as the analytical parameters. Furthermore, the propagation of light on wood in these measurements was defined approximately as the following relation;

$$\text{Total light irradiance} = \text{Transmittance} + \text{Absorbance} + \text{Reflectance} \quad (1)$$

Incident light was firstly reflected on the wood surfaces. The remaining light was transmitted inside the wood and partially absorbed. Finally, the light which passed through the wood was measured as the transmittance.

Table 1. Wood samples used in this study (TWTw).

Genus	Species	Family	ID No (TWTw)
Chamaecyparis	*obtusa*	Cupressaceae	15, 75, 652, 6371, 18 791
Chamaecyparis	*pisifera*	Cupressaceae	90, 874, 9294, 24 266, 26 272
Thuja	*standishii*	Cupressaceae	595, 649, 875, 9295, 26 128
Thujopsis	*dolabrata*	Cupressaceae	864, 876, 1300, 20 341, 25 023
Cryptomeria	*japonica*	Cupressaceae	6427, 6428, 9289, 9292, 14 914
Ginkgo	*biloba*	Ginkgoaceae	50, 79, 6430, 14 918, 26 758
Abies	*firma*	Pinaceae	83,1201, 9274, 21 864, 24 587
Abies	*sachalinensis*	Pinaceae	82, 672, 673, 1301, 9275
Larix	*kaempferi*	Pinaceae	872, 9279, 12 425, 21 806, 24 590
Picea	*jezoensis*	Pinaceae	675, 805, 981, 1302, 14 480
Picea	*glehnii*	Pinaceae	674, 806, 1303, 9502, 14 407
Pinus	*densiflora*	Pinaceae	92, 9285, 9287, 24 854, 26 529
Pinus	*parviflora*	Pinaceae	103, 851, 9286, 21 819, 26 534
Pseudotsuga	*japonica*	Pinaceae	78, 837, 880, 1268, 9465
Pseudotsuga	*menziesii*	Pinaceae	8895, 13 456, 16 329, 16 336, 21 804
Tsuga	*sieboldii*	Pinaceae	650, 9284, 28 374, 28 861, 18 887
Tsuga	*diversifolia*	Pinaceae	887, 1203, 24 312
Podocarpus	*macrophyllus*	Podocarpaceae	807, 881, 9273, 15 177, 21 015
Sciadopitys	*verticillata*	Sciadopityaceae	648, 833, 850, 9348, 9473
Taxus	*cuspidata*	Taxaceae	653, 670, 830, 9271, 26 262
Torreya	*nucifera*	Taxaceae	4332, 9272, 13 662, 14 505, 14 507

Measuring both reflectance and transmittance was important because absorbance was often measured in ordinal NIR measurement.

Measurement of wood density

Sample volume was calculated by measuring the length of each direction of the sample with a caliper. Sample weight was determined using a balance scale. Sample density was calculated by volume and weight. Measurements were conducted under the same conditions as mentioned above.

Results

Transmittance

Figure 2 shows the average and standard deviation of the transmittance spectra for all species. Transmittance values were very different not only among species (in some cases by more than 10 times) but also between the sapwood and heartwood in some species. All spectra showed increased transmittance intensities from about 600–700 nm with peaks or shoulders in the ranges of 870–900 nm and 930–950 nm, and at around 1100 nm. However, light transmittance in the heartwood of species with dark-coloured heartwood (*Cryptomeria japonica*, *Thuja standishii*, *Larix kaempferi*, *Pinus densiflora*, *Pinus parviflora*, *Pseudotsuga japonica*, *Pseudotsuga menziesii*, *Tsuga diversifolia*, *Tsuga sieboldii* and *Taxus cuspidata*) began to increase at longer wavelengths than in the sapwood (Fig. 2c, d, h, k–p, s). The patterns of the peaks and shoulders in the ranges of 870–900 nm and 930–950 nm, and at around 1100 nm, were different not only among wood species but also between the sapwood and heartwood of the same species. In particular, spectra of the heartwood of *Cryptomeria japonica*, *Thuja standishii* and *Taxus cuspidata* did not show

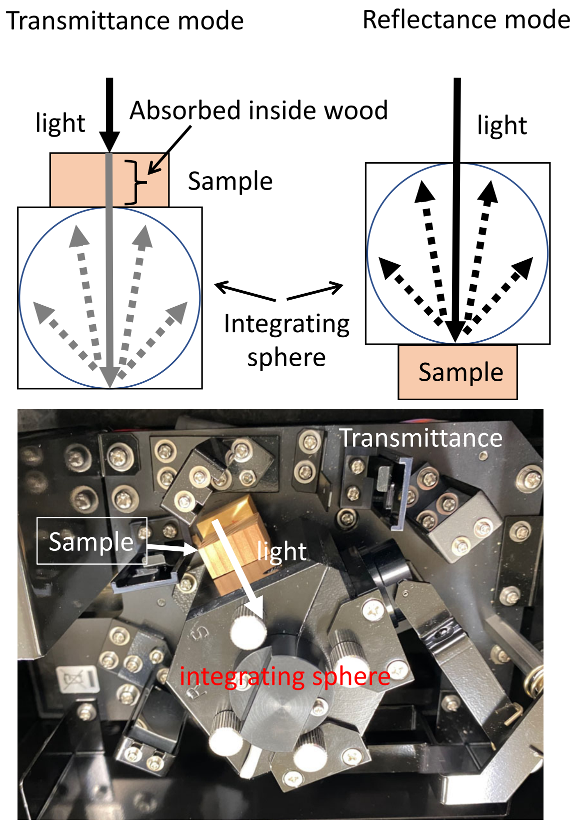

Fig. 1. Schematic drawing of the measurement of transmittance and reflectance of the light in wood, and an image of the measurement of transmittance.

clear peak signals in the wavelength range of 870–900 nm (Fig. 2c, d, s). Peaks at wavelengths of around 1100 nm were consistently observed in all measurements. Spectra tended to show similar patterns between two species of the same genus (*Chamaecyparis*, *Abies*, *Picea*, *Pinus*, *Pseudotsuga* and *Tsuga*) (Fig. 2a, b, f, g, i–p).

A comparative investigation of sapwood and heartwood revealed higher values of transmittance in the sapwood than in the heartwood in species with dark-coloured heartwood (*Cryptomeria japonica*, *Thuja standishii*, *Larix kaempferi*, *Pinus densiflora*, *Pinus parviflora*, *Pseudotsuga japonica*, *Pseudotsuga menziesii*, *Tsuga diversifolia* and *Tsuga sieboldii*) (Fig. 2c, d, h, k–p, s). The differences between the spectra of sapwood and heartwood decreased with longer wavelengths in these species. On the other hand, the light transmittance of the heartwood tended to show higher values than that of the sapwood in *Thujopsis dolabrata*, *Abies firma*, *Abies sachalinensis* and *Torreya nucifera* (Fig. 2e–g, t).

Reflectance

Figure 3 shows the average and standard deviation of the reflectance spectra for all species. As with the transmittance spectra, most of the sample peaks and shoulders occurred in the ranges of 870–900 nm and 930–950 nm, and at around 1100 nm. The maximum values of reflectance were 70–90% at the peaks mentioned above. The shorter wavelength spectra (<900 nm) of the heartwood in *Cryptomeria japonica*, *Thuja standishii*, *Pinus densiflora*, *Pinus parviflora*, *Pseudotsuga japonica* and *Pseudotsuga menziesii* showed considerably lower values than those of the sapwood in the shorter wavelength range (Fig. 3c, d, k–n). However, with an increase in wavelength, differences between the sapwood and the heartwood decreased, and the heartwood spectra showed higher values

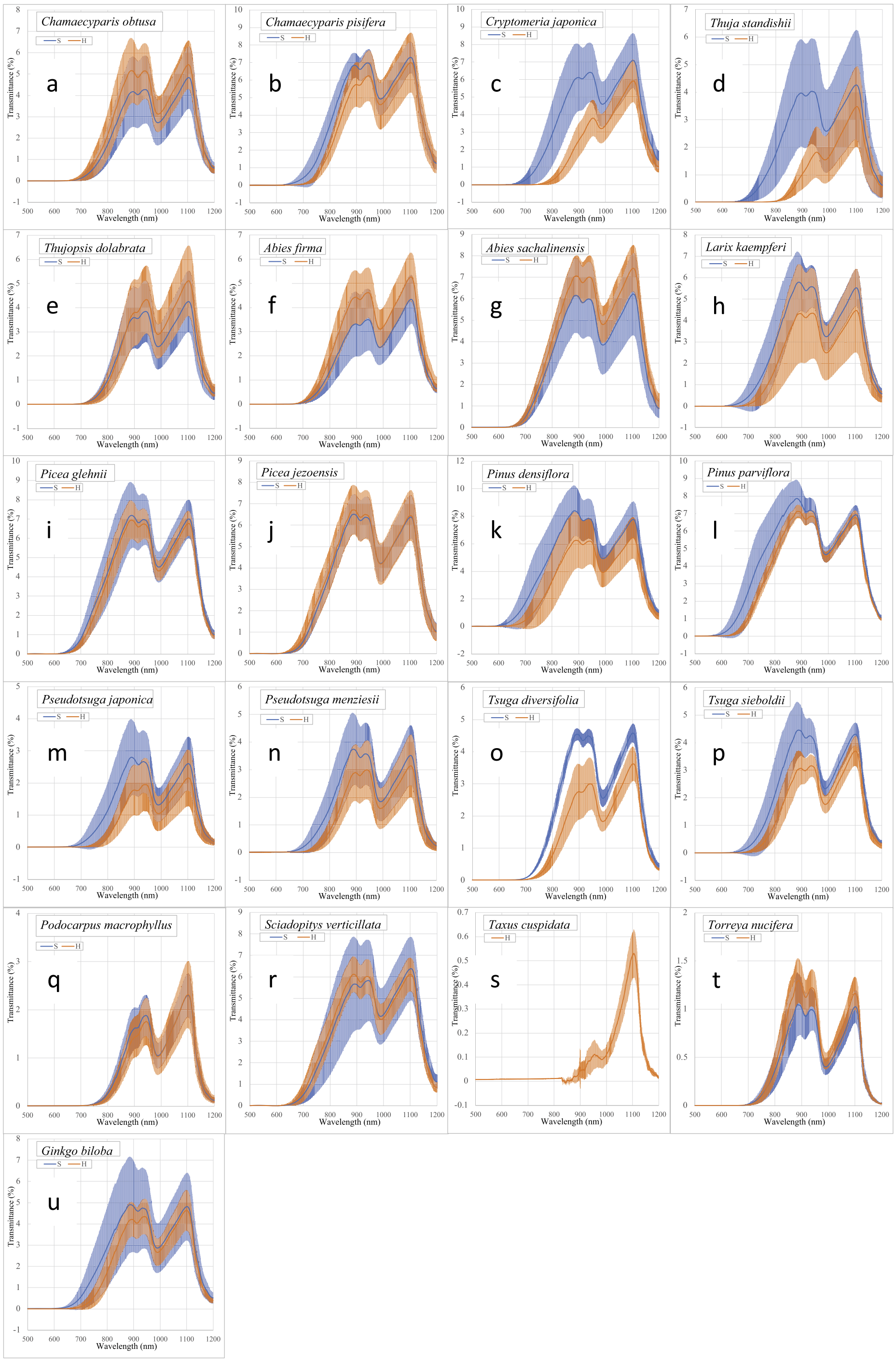

Fig. 2. Averaged transmitted light spectra and standard deviations. (a) *Chamaecyparis obtusa*, (b) *Chamaecyparis pisifera*, (c) *Cryptomeria japonica*, (d) *Thuja standishii*, (e) *Thujopsis dolabrata*, (f) *Abies firma*, (g) *Abies sachalinensis*, (h) *Larix kaempferi*, (i) *Picea glehnii*, (j) *Picea jezoensis*, (k) *Pinus densiflora*, (l) *Pinus parviflora*, (m) *Pseudotsuga japonica*, (n) *Pseudotsuga menziesii*, (o) *Tsuga diversifolia*, (p) *Tsuga sieboldii*, (q) *Podocarpus macrophyllus*, (r) *Sciadopitys verticillate*, (s) *Taxus cuspidata*, (t) *Torreya nucifera*, (u) *Ginkgo biloba*. Blue line, sapwood; orange line, heartwood.

than those of the sapwood in *Cryptomeria japonica*, *Pinus densiflora*, *Pinus parviflora*, *Pseudotsuga japonica* and *Pseudotsuga menziesii* (Fig. 3 c, k–n).

Discussion

Light transmittance spectra with wavelengths in the range of 500–1200 nm showed different patterns among the various wood species (Fig. 2). However, peaks at around 1100 nm occurred in both the sapwood and heartwood of all species. To compare longitudinal conductivities in the wood among the species, removing the effects of the sample surface conditions, the following parameter was used from equation (1):

$$\text{Total light before transmitting wood} = \text{Total light irradiance} - \text{Reflectance} \quad (2)$$

Furthermore, light conductivity was defined as the ratio of transmitted light to incident light.

$$\text{Conductivity (\%)} = \text{Transmittance/Incident light} \quad (3)$$

Table 2 shows the maximum wood conductivities at around 1100 nm. Averages of maximum conductivity at that light intensity differed greatly, with a range of 42.3% in the heartwood of *Chamaecyparis pisifera* to 3.9% in the heartwood of *Taxus cuspidata*. There were no obvious differences between the sapwood and heartwood in most of the species, except for the genera *Abies*, *Cryptomeria*, *Pinus*, *Thuja* and *Tsuga*. In *Abies*, the conductivity of the heartwood was higher than the conductivity of the sapwood. On the other hand, the conductivity of the sapwood was higher than the conductivity of the heartwood in *Cryptomeria*, *Pinus*, *Thuja* and *Tsuga*. These differences between the sapwood and heartwood showed the same patterns as those found in two studied species within the genera *Chamaecyparis*, *Abies*, *Picea*, *Pinus*, *Tsuga* and *Pseudotsuga*. Wood species with helical thickenings tended to show lower conductivity of light (*Pseudotsuga*, *Torreya* and *Taxus*) than other species. Tsuchikawa and Tsutsumi (1996) showed that scattering occurs in a direction perpendicular to that of incident light for short wavelengths in the near-infrared region. In species with helical thickenings, more scattering may occur than in species without helical thickenings on the lumen of the tracheids.

Figure 4 shows the relationship between wood density and the conductivity of light. Conductivity tends to decrease with an increase in wood density. Interestingly, this finding does not agree with those of Sun *et al.* (2003), who reported that in the fresh wood of conifer species, the light was conducted mostly in the cell walls of the latewood, not the lumen. Light pathways can differ between fresh wood and dry wood because of differences in the lumen contents and moisture in the cell walls. Further studies are necessary to clarify the wood microstructural pathways of light in wood.

In our studies, the longitudinal transmittances of 500–1200 nm light in wood showed different patterns among genera. Maximum conductivity of light at around 1100 nm is low in wood species with helical thickenings. From these results, it can be considered that the anatomical characteristics of wood influence the transmittance of light. It is possible that not only helical thickening, but also, other structures such as bordered pits, cross-field pits, and so on, affect the transmittance of the light. Sun *et al.* (2003) reported that resin canals also play an important role in conducting light in fresh wood branches. The conductivity of wood to liquids and gasses has been extensively studied (reviewed by Hansmann *et al.* 2002), while the light conductive paths in wood remain still little explored.

The transmittance of light differed between the sapwood and heartwood in several species, and, patterns of the difference varied among the different genera. It is possible to consider that substances accumulating during heartwood formation also affect the transmittance of light in certain species. Our results strongly suggest that the transmittance of light at wavelengths in the range of 500–1200 nm can be used to identify wood species non-invasively.

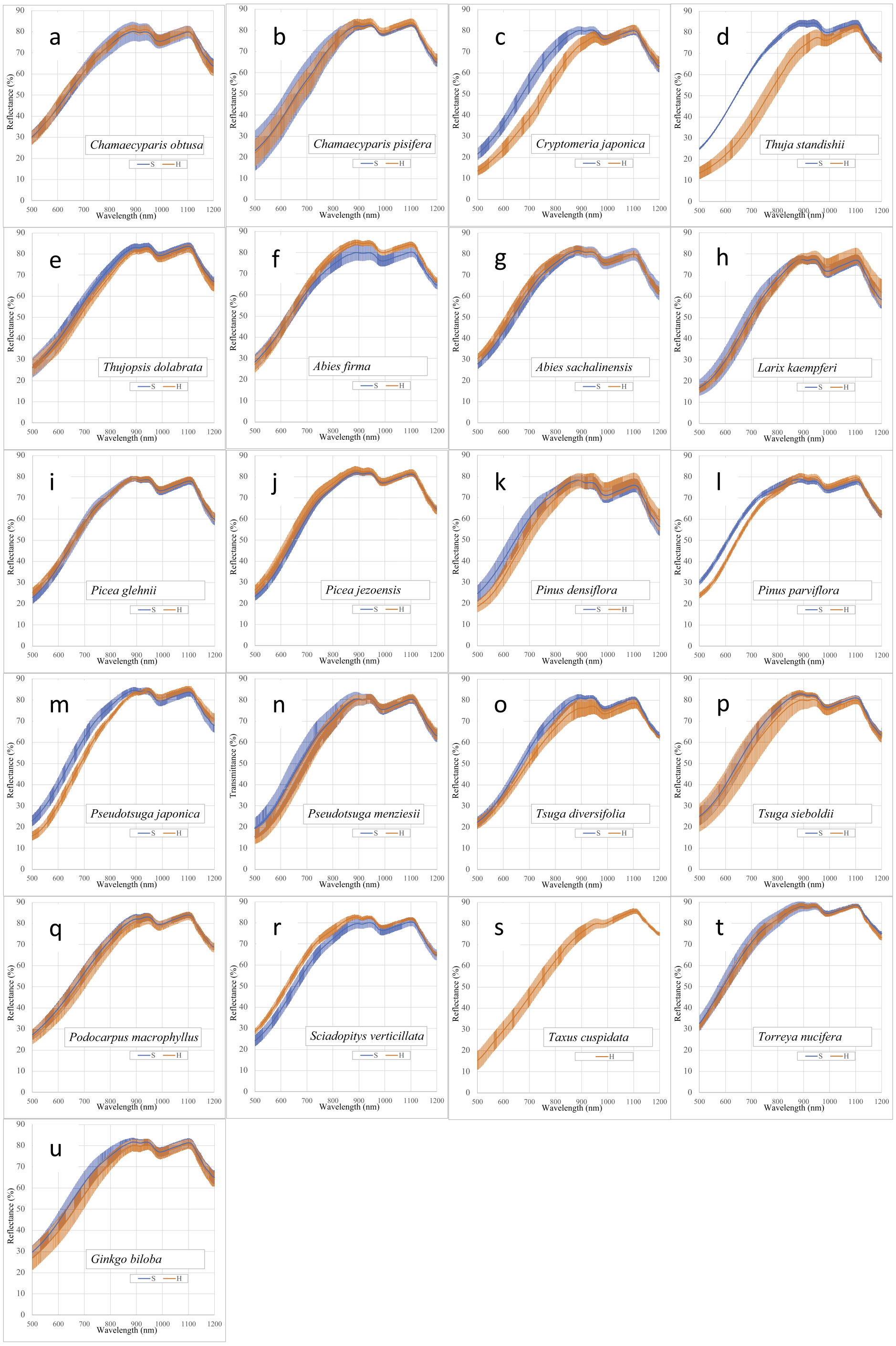

Fig. 3. Averaged reflected light spectra and standard deviations. (a) *Chamaecyparis obtusa*, (b) *Chamaecyparis pisifera*, (c) *Cryptomeria japonica*, (d) *Thuja standishii*, (e) *Thujopsis dolabrata*, (f) *Abies firma*, (g) *Abies sachalinensis*, (h) *Larix kaempferi*, (i) *Picea glehnii*, (j) *Picea jezoensis*, (k) *Pinus densiflora*, (l) *Pinus parviflora*, (m) *Pseudotsuga japonica*, (n) *Pseudotsuga menziesii*, (o) *Tsuga diversifolia*, (p) *Tsuga sieboldii*, (q) *Podocarpus macrophyllus*, (r) *Sciadopitys verticillate*, (s) *Taxus cuspidata*, (t) *Torreya nucifera*, (u) *Ginkgo biloba*. Blue line, sapwood; orange line, heartwood.

Table 2. Maximum conductivity of the light at around 1100 nm.

Species	Conductivity					
	All		Sapwood		Heartwood	
	Average	SD	Average	SD	Average	SD
Chamaecyparis pisifera	40.3	8.6	41.8	7.3	42.3	7.1
Chamaecyparis obtusa	36.8	6.5	36.0	8.6	37.5	5.2
Abies sachalinensis	35.1	6.2	30.9	6.2	39.3	2.1
Picea jezoensis	34.8	5.4	34.1	4.3	35.6	6.8
Sciadopitys verticillata	32.8	6.4	32.8	8.3	33.8	4.4
Picea glehnii	31.8	3.2	31.8	4.0	31.7	2.4
Cryptomeria japonica	31.4	8.5	35.1	5.9	30.4	4.0
Pinus parviflora	31.2	4.6	34.3	2.0	30.6	3.9
Pinus densiflora	30.4	3.2	32.0	1.7	29.1	3.7
Thujopsis dolabrata	26.5	6.9	25.6	6.7	28.9	7.6
Abies firma	25.6	8.2	19.7	5.5	31.6	5.6
Ginkgo biloba	24.6	4.9	25.2	6.6	24.0	3.0
Larix kaempferi	23.4	4.5	24.2	4.0	22.5	5.6
Thuja standishii	23.0	9.1	22.0	9.7	19.4	9.1
Tsuga sieboldii	20.9	2.9	22.7	1.3	18.6	2.7
Tsuga diversifolia	20.6	5.0	23.8	2.6	17.4	4.9
Pseudotsuga menziesii	17.6	4.1	17.5	4.2	16.0	4.7
Podocarpus macrophyllus	16.9	7.6	14.2	2.4	13.8	3.3
Pseudotsuga japonica	14.1	4.9	16.2	6.2	14.2	4.9
Torreya nucifera	10.4	1.9	9.8	2.3	10.8	1.7
Taxus cuspidata	3.9	1.1			3.9	1.1

Arranged by order of the conductivity. Underlining indicates species with helical thickenings.

Our results show that the peaks and shoulders of transmittance were found in the ranges of 870–900 nm and 930–950 nm, and at around 1100 nm. Sun *et al.* (2004) investigated longitudinal light-transmittances of shorter NIR (<950 nm) in the fresh wood of 6 conifer species (*Ginkgo biloba*, *Metasequoia glyptostroboides*, *Abies firma*, *Cryptomeria japonica*, *Chamaecyparis obtusa* and *Pinus densiflora*). They found three peaks in the wavelength ranges of 730–740 nm, 820–830 nm and 918–925 nm, respectively. These peak positions do not correspond to the peaks observed in our results. In fresh stems, water is present not only in the cell walls but also, in the lumens of tracheids. As water absorbs the light in these wavelength ranges, the absorbance may alter the spectral patterns of light transmittance (electromagnetic absorption by water, see https://en.wikipedia.org/wiki/Electromagnetic_absorption_by_water). Furthermore, the presence of water in wood affects the spatially resolved reflectance of wood (Kienle *et al.* 2008). Therefore, it can be considered that the presence of water in wood alters the peak positions of light in light transmittance.

Wood density affects the conductivity of light at around 1100 nm (Fig. 3). Each wood species is characterized by a particular wood density value (Forestry and Forest Products Research Institute 2004). Hans *et al.* (2015) demonstrated this by monitoring wood density using the absorbance and scattering coefficient of light with a wavelength of 846 nm. Abe *et al.* (2016) found that the conductivity of light in the 874–1000 nm range depends more on the species than on the density of the wood. Sugimoto *et al.* (2018) revealed that longitudinal transmittance of the light with a wavelength of around 750 nm is highest in the latewood near the boundary of annual rings and lowest in the transitional zone from the earlywood to the latewood in *Cryptomeria japonica*. This means the region with the highest wood density

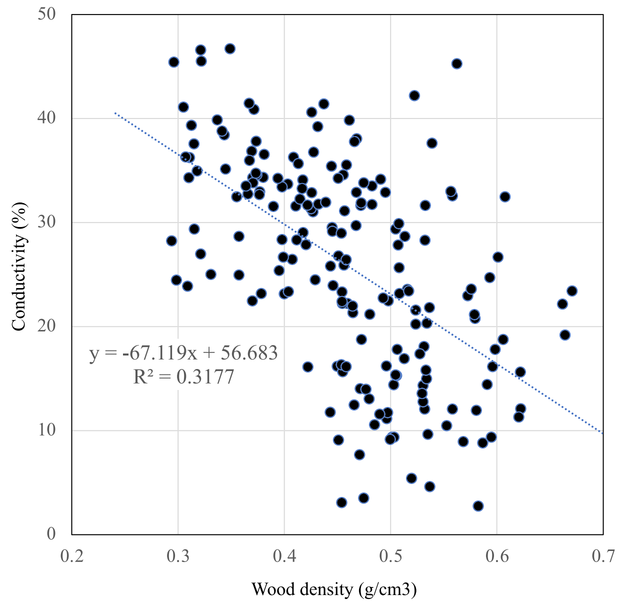

Fig. 4. Relationship between wood densities and maximum conductivities of the light at around 1100 nm.

shows the highest longitudinal transmittance in *Cryptomeria japonica*. Differences in the conductivity of light related to wood density may depend on wavelength. Further investigation will be necessary to achieve accurate non-invasive wood density estimations using light in the wavelength range of 800–1200 nm, because of the high conductivity of light within that range.

Conclusions

The transmittance and reflectance of light within the wavelength range of 500–1200 nm were measured in the wood of 21 conifer species and a variety of wood species-specific spectra with high values of transmittance in the range of 900–1100 nm were revealed. Our study has established the existence of clear differences between sapwood and heartwood, and among wood species. Furthermore, we found that the transmittance peak occurred at around 1100 nm in all wood samples. Anatomical and chemical characteristics, such as wood density, the occurrence of helical thickenings in tracheids, and coloration of the heartwood, were all linked to different patterns of light transmittance. Our results suggest that the transmittance properties of visible and near-infrared light in the longitudinal direction of wood have a potential for use in the non-invasive identification of wood species and the estimation of wood properties with further study.

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