

1 Effect of cellular structure on the optical properties of wood

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6 To construct robust calibrations of wood properties by near-infrared spectroscopy, one must  
7 independently evaluate the spectral contributions of light absorption and light scattering. However,  
8 the light propagation in wooded cellular structures is difficult to interpret because these structures  
9 are complex, heterogeneous, and anisotropic. This study investigates the reduced scattering  
10 coefficients of softwood and hardwood (with ring-porous or diffuse-porous vessels) at 846 nm by  
11 time-resolved spectroscopy. It also evaluates the effect of wooden cellular structure and dry air  
12 density on the light propagation. After determining the reduced scattering coefficients, we  
13 observed cross-sectional microscopic images of the wood samples. Eighty-five percent of the  
14 variation in the reduced scattering coefficients was explainable by the air-dry density, area ratio of  
15 the cell wall, and the median pore area. Monte Carlo simulations of the light propagation through  
16 wood revealed that most of the photon transport occurs in the cell-wall substance.

17 **Keywords**

18 Time resolved NIR spectroscopy, Multiple scattering, Turbid media, Wood, Monte-Carlo  
19 simulation

## 20 INTRODUCTION

21 The properties of wood (e.g., density, moisture content, grain angle, crystallinity and micro fibril  
22 angle) vary considerably between species and even among members of the same species. For  
23 quality assurance in industrial processes, nondestructive monitoring and control of the physical,  
24 mechanical, and chemical properties of wood are strongly desired. Near infrared (NIR) reflectance  
25 spectroscopy, which is mainly used in chemical composition analysis, is also an increasingly  
26 popular tool for monitoring the properties of wood. In many studies, the chemical, physical and  
27 mechanical properties of wood have been predicted by NIR reflectance spectroscopy aided by  
28 statistical methods (i.e., chemometrics).<sup>1-3</sup> However, such chemometric NIR approaches have  
29 several disadvantages. First, they cannot separate the spectral contributions of the light absorption  
30 and light scattering phenomena. Second, the construction of a calibration model requires a  
31 considerable amount of data, which is usually not transferable among instruments. Additionally,  
32 owing to its complex cellular structure, wood makes a significant light scattering contribution to  
33 the NIR spectra. Softwood possesses a mainly tracheid structure, arrayed along the longitudinal  
34 direction, whereas hardwood structures vary (e.g., tracheids, vessels, libriform wood fibers, or ray  
35 cells). The water retained in cell walls or cell lumens also significantly affects the optical properties  
36 of wood.<sup>4</sup> To construct a robust calibration of wood properties by NIR spectroscopy, we must  
37 independently evaluate the spectral contributions of light absorption (which results from  
38 harmonics or overtones of the fundamental absorptions of the molecular vibrations of cellulose,  
39 hemicellulose, lignin, extractives and water) and light scattering (caused mainly by the cellular  
40 structure).

41 Many studies have investigated light absorption and scattering in tissues such as human skin,  
42 fruit, leaves, and wood. Typically, light scattering is described by a scattering coefficient  $\mu_s$  and a

43 reduced scattering coefficient  $\mu'_s$ , which strongly depend on the physical structure of the tissue.  
44  $\mu'_s$  is defined as

$$45 \quad \mu'_s = (1 - g)\mu_s, \quad (1)$$

46 where  $g$  is the mean cosine of the scattering angle. The optical absorption is a linearly increasing  
47 function of concentration of the chemical components, whose slope defines the absorption  
48 coefficient  $\mu_a$ . D'Andrea et al. determined  $\mu_a$  and  $\mu'_s$  in the wavelength range 700–1040 nm for  
49 two kinds of wood species treated in different ways (dry, wet and degraded) by time-resolved  
50 reflectance spectroscopy with two different orientations of the optical fiber.<sup>5</sup> They obtained many  
51 interesting results. In all cases, the reduced scattering coefficient ( $\mu'_s = 10\text{-}100 \text{ cm}^{-1}$ ) was much  
52 larger than the absorption coefficient ( $\mu_a = 0.05\text{-}1.00 \text{ cm}^{-1}$ ), although the scattering spectra were  
53 constant over the corresponding wavelength ranges. Moreover,  $\mu'_s$  strongly depended on the wood  
54 species (silver fir or sweet chestnut wood). The  $\mu'_s$  was much smaller in wet wood than in dried  
55 wood because the refractive index was closer between the wood cell-wall substance and the water  
56 in the pores. D'Andrea et al. also evaluated the moisture content (MC) of wood through the  
57 absorption coefficient, and found a strong relationship between MC and the absorption coefficient  
58 at a specific wavelength.<sup>6</sup> We measured the optical properties of drying wood with MCs ranging  
59 from 10% to 200% using time-resolved NIR spectroscopy.<sup>4</sup> After independently determining  $\mu'_s$   
60 and  $\mu_a$ , we found that dry pores dominated the scattering phenomenon. Therefore, we determined  
61 the drying processes of large and small pores during the periods of constant and decreasing drying  
62 rate, respectively. To identify the origin of scattering in wood, Kienle et al. compared the  
63 experimentally measured and Monte Carlo-simulated light propagations on the microstructure of  
64 silver fir.<sup>7</sup> Solving Maxwell's equations, they determined the tracheid-contributed  $\mu'_s$  of wet and  
65 dry wood as  $1.79 \text{ mm}^{-1}$  and  $6.68 \text{ mm}^{-1}$  respectively. They also calculated the scattering coefficient

66  $\mu_{s-iso}$  sourced from scattering media other than tracheids (pits, ray cells, and rough borders between  
67 the lumen and wood cell-wall substance) by fitting the measured and simulated light propagations.  
68 Previously, we measured the true  $\mu'_s$  and  $\mu_a$  of the cell-wall substance in douglas fir using time-  
69 resolved NIR spectroscopy.<sup>8</sup> In that study, the samples were saturated with hexane, toluene or  
70 quinolone to minimize the multiple light reflections on the boundary between the pores and cell-  
71 wall substance in the wood.  $\mu'_s$  was minimized when the wood was saturated with toluene, which  
72 has a similar refractive index to the wood cell-wall substance. The optical parameters of the wood  
73 cell-wall substance were calculated as  $\mu_a = 0.030 \text{ mm}^{-1}$  and  $\mu'_s = 18.4 \text{ mm}^{-1}$ .

74 The cellular structures of wood are complex, heterogeneous, and anisotropic. Therefore, the  
75 cellular structure (which causes multiple light reflections) significantly differs between wood  
76 species; accordingly, the scattering coefficients highly depend on the wood species. Hardwood  
77 species especially have various cell arrangements, i.e., ring-porous, diffuse-porous, radial-porous,  
78 and figured-porous. Although the optical parameters of wood have been well clarified, the effect  
79 of cellular structure on  $\mu'_s$  has not been fully investigated. Hans et al. investigated the relation  
80 between the  $\mu_a$  and  $\mu'_s$  values and the air-dry density of softwood and hardwood. They reported a  
81 weak relation between  $\mu'_s$  and the air-dry density of wood, which was explained by the anatomical  
82 differences between the wood species.

83 In this study, we evaluate the softwood and hardwood (with ring-porous or diffuse-porous  
84 vessels) and evaluate the effects of wood structure and air-dry density on the light scattering. From  
85 cross-sectional microscopic images of the wood samples, we then determine the maximum pore  
86 diameter, the number of observed pores, the median and average pore areas, and the area ratio of  
87 the cell wall, and investigate their effects on  $\mu'_s$ .

## 88 MATERIAL AND METHOD

## 89 **Samples**

90 Thirteen species of air-dried wood samples - five softwood species (*Agathis alba* Foxw,  
91 *Araucaria heterophylla*, *Thuja plicata*, *Chamaecyparis obtusa*, *Cryptomeria japonica*) and eight  
92 hardwood species (*Triplochiton scleroxylon*, *Hevea brasiliensis*, *Liriodendron tulipifera*,  
93 *Cercidiphyllum japonicum*, *Paulownia tomentosa*, *Kalopanax pictus*, *Fraxinus mandshurica*,  
94 *Fagus sylvatica*) - were selected for the study (see Table 1). The sample dimensions were 2 mm  
95 thick (tangential or radial)  $\times$  80 mm (tangential or radial)  $\times$  150 mm (longitudinal). We prepared  
96 3 samples for each species.

## 97 **Time-resolved NIR spectroscopic measurements**

98 Time-resolved NIR spectroscopic measurements were performed with a picosecond pulsed laser  
99 with a wavelength of 846 nm, a pulse width of 70 ps, and a beam diameter on the sample of  
100 approximately 1.5 mm (PLP-10, Hamamatsu Photonics Co., Hamamatsu, Japan). The transmitted  
101 photons were dispersed with a spectroscopy equipped with gratings (C11119-02, A13302-02,  
102 Hamamatsu Photonics Co., Hamamatsu, Japan). To detect time-resolved data, the time variation  
103 of the transmitted radiation intensity was recorded by a streak camera with a time resolution of  
104 10.3 ps (C5680, Hamamatsu Photonics Co., Hamamatsu, Japan). The combination of NIR  
105 spectroscopy and streak camera (which directs the incoming photons onto a photocathode that  
106 emits electrons via the photoelectric effect) is also called time-of-flight (TOF) NIR spectroscopy.  
107 The wood sample was placed 90 mm from the pulsed laser, and the transmitted photons exiting  
108 the sample were collected by a 300  $\mu$ m-diameter optical fiber (length: 3 m, A5760-02, Hamamatsu  
109 Photonics Co., Hamamatsu, Japan) placed 2 mm from the sample, and passed to the spectrometer.  
110 The instrument response function (IRF) was measured with a neutral density filter with a 1%  
111 transmission ratio (A5760-02, Hamamatsu Photonics Co., Hamamatsu, Japan) placed directly in

112 front of the camera slit. The time-resolved profiles (TRPs) were acquired at the opposite side of  
113 the incident beam on the radial-longitudinal section with a time range of 1 ns, and measured 3  
114 times at different points. Each photon count was performed for 60 s. As we anticipated the position  
115 of incident light on wood has significant effect on the light propagation and  $\mu'_s$ , we used relatively  
116 big beam diameter (approximately 1.5 mm) and repeat the measure on three different point and  
117 averaged for each samples.

### 118 **TRP analysis**

119 The measured TRP can be expressed as a convolution between the IRF and true photons in the  
120 time-resolved distribution (TRD) as equation (2):

$$121 \quad \text{TRP} = \text{IRF} \times \text{TRD}. \quad (2)$$

122 where  $\times$  denotes the convolution operator. The absorption ( $\mu_a$  :  $\text{mm}^{-1}$ ) and reduced scattering  
123 coefficient ( $\mu'_s$ :  $\text{mm}^{-1}$ ) were computed by fitting the convolution between the IRF and the model  
124 TRD to the measured TRP. The model TRD was obtained by solving the diffusion approximation  
125 equation for an infinite slab with extrapolated transmittance boundary conditions.<sup>9</sup> When  
126 calculating the refraction indices  $n_{wood}$  of the wood samples, we assumed  $n_{cw} = 1.55$  and  $n_{air} = 1.00$   
127 as the refraction indices of the wood cell walls and air, respectively.<sup>8</sup> The TRP was analyzed in  
128 Matlab R2015b (MathWorks, Inc., MA, USA), and the sum of the differences between the  
129 theoretical and measured TRPs was minimized by a fitting procedure implemented by the interior  
130 point algorithm.

### 131 **Microscopic observations**

132 To investigate the relation between  $\mu'_s$  and the wood texture, we observed cross-sectional  
133 microscopic images of the wood samples after measuring their TRPs. Each wood sample was cut  
134 into 3 equally sized pieces, each including one incident point (giving a total of 39 small pieces).

135 The densities of the small pieces were calculated as the weight divided by the volume. The pieces  
136 were sliced by a microtome, then dyed with safranin solution for cross-sectional microscopic  
137 imaging (2560×1920 pixels corresponding to 1.12×0.84 mm) under a bright-field microscope  
138 (PrimoStar, Carl Zeiss Microscopy Co., Japan). We acquired 10 cross-sectional images at different  
139 positions on each piece. After binarizing the images, pores were identified as connected  
140 components more than 10 pixels across. We calculated the diameter of the maximum pore ( $\mu\text{m}$ ),  
141 the number of determined pores, the median, and average pore area ( $\mu\text{m}^2$ ), and the cell-wall area  
142 ratio in each image, and averaged them over 30 images. The binarization and parameter  
143 calculations were performed in Matlab R2015b.

#### 144 **Monte Carlo simulations of light propagation in wood**

145 To understand light propagation through the wood, we simulated the absorption distribution of  
146 the light propagation in a three-dimensional (3D) wood structure model. The simulations were  
147 performed in the Monte Carlo code, MCVM (Monte Carlo modeling of photon migration in  
148 Voxelized Media), which has been verified against the gold standard MCML (Monte Carlo  
149 modeling of light transport in Multi-Layered tissue),<sup>10</sup> and which effectively simulates light photon  
150 migration in a 3D heterogeneity model. The MCVM algorithm is detailed in the literature.<sup>11</sup> As  
151 wood is a natural product with a complex structure, the reflective indices of the cell wall ( $n_{cw} =$   
152 1.55) and air ( $n_{air} = 1.00$ ) are widely different, causing specular reflections and transmissions. The  
153 refractive-index mismatch at the boundaries are also considered to improve the precision of  
154 simulations in MCVM code. Figure 1 shows the steps of the MCVM simulations. First, the cross-  
155 sectional microphotograph of each wood sample was changed to a binary image through  
156 thresholding image processing. The resulting 2D binary image was copied to make a 3D structure  
157 model. The dimensions of the generated 3D wood structure model were (256×256×114) voxels,

158 with pixel intervals corresponding to 4.4  $\mu\text{m}$ . The tissue type was described by its optical  
159 properties: the reflective index  $n$ ,  $\mu_s$ ,  $\mu_a$  and,  $g$ . Adjacent voxels with the same optical properties  
160 were assigned to the same type of tissue. In this study, the 3D model comprised two tissue types  
161 (wood cell-wall and air). As the true optical parameters (at 846 nm) of the wood cell walls, we  
162 adopted the values calculated by Kitamura et al.<sup>9</sup> In the air parts, we assumed  $\mu_a = 0 \text{ mm}^{-1}$ ,  $\mu_s = 0$   
163  $\text{mm}^{-1}$ , and  $n = 1$ . The total number of incident photons was  $10^6$  and the vertical incident point  
164 (although the actual light source diameter was 1.5 mm which is not regarded as the point light)  
165 was the surface center of the 3D model. To obtain the time-resolved information, we set the time  
166 interval to 1 ps and acquired 5 snapshots from 1 ps to 5 ps. Tissue modeling and image processing  
167 were performed in Matlab2013a (The Mathworks Inc., Natick, MA, USA).

## 168 **RESULT AND DISCUSSION**

### 169 **Relation between air-dry density and reduced scattering coefficient**

170 Figure 2 shows the TRP of air-dry agathis wood (air-dry density  $\rho_{\text{airdry}} = 0.33 \text{ g/cm}^3$ ), and the  $\mu'_s$   
171 values computed by fitting the TRP to the IRF convoluted with TRD. Figure 3 shows the relation  
172 between the air-dry density and the acquired  $\mu'_s$  values of the softwood, ring-porous wood, and  
173 diffuse-porous wood. There is a significant positive relation between air-dry density and  $\mu'_s$   
174 (determination coefficient  $R^2 = 0.59$ ). The  $R^2$  of softwood, diffuse-porous vessels and ring-porous  
175 vessels were 0.55, 0.49, and 0.73, respectively. The acquired  $\mu'_s$  of air-dry wood ranged from 8.9  
176 to 30.9  $\text{mm}^{-1}$ , although Hans et al.<sup>12</sup> reported  $\mu'_s = 15.3 \pm 0.3 \text{ mm}^{-1}$  and  $\mu'_s = 17.4 \pm 0.9 \text{ mm}^{-1}$   
177 respectively for air-dry hinoki cypress (*Chamaecyparis obtusa*) and Japanese larch (*Larix*  
178 *kaempferi*) at 846 nm, and D' Andrea et al.<sup>5</sup> reported  $\mu'_s \approx 10 \text{ mm}^{-1}$  for air-dry silver fir at 840 nm.  
179 The light scattering in wood is complex and caused by multiple factors: (1) the interaction of light  
180 with small particles with different refractive indices from the surrounding materials, (2) a

181 refractive-index mismatch between the cell-wall substance and lumens in the wood, (3) scattering  
182 at the rough border between the lumen of the tracheid and the wood cell-wall substance, and (4)  
183 scattering due to the birefringent nature of the cellulose microfibril or the spatial distribution of  
184 chemical components in the wood cell-wall substances. As the types of cells (tracheids, ray cells,  
185 vessels), shapes of cells (among cell types and between earlywood and latewood), and vessel  
186 alignments (ring-porous, diffuse-porous, radial-porous, and figured-porous) differ widely among  
187 wood species, the scattering coefficients should also differ among the wood species. The  
188 significant positive relation between air-dry density and  $\mu'_s$  can be explained by the increased  
189 volume fraction of the wood cell-wall substance (which scatters the NIR light) as the wood density  
190 increases. The measured  $\mu'_s$  of ayous (*Triplochiton scleroxylon*) and rubber tree (*Hevea*  
191 *brasiliensis*: with diffuse-porous vessel structures) are much higher than estimated from the  
192 regression line, with air-dry densities of 0.44 g/cm<sup>3</sup> and 0.70 g/cm<sup>3</sup>, respectively. The higher  
193 scattering in these wood species is attributed mainly to light scattering between the lumen and the  
194 wood cell-wall substance for all cell types, which results from the index-mismatching effect. To  
195 investigate the relation between  $\mu'_s$  and the cell-shape parameters, namely, the maximum pore  
196 diameter ( $\mu\text{m}$ ), number of observed pores, median and mean pore areas ( $\mu\text{m}^2$ ) and the cell-wall  
197 area ratio, we computed the cell-shape parameters from the cross-sectional microscopic images.

#### 198 **Relations between parameters calculated from microscopic image and reduced scattering** 199 **coefficient**

200 Figure 4 shows representative microscopic images of (a) softwood (western red cedar: *Thuja*  
201 *plicata*), (b) diffuse-porous vessel hardwood (beech: *Fagus sylvatica*) and (c) ring-porous vessel  
202 hardwood (castor aralia: *Kalopanax pictus*). Their corresponding binary images are shown in  
203 panels (d)–(f). The density,  $\mu'_s$  and texture parameters calculated from the microscopic images

204 were averaged over the three samples and are summarized in Table 1. Correlation coefficient  
205 between cellular structure parameters calculated from microscopic cross-sectional images of the  
206 wood samples were summarized in Table 2. The correlation coefficient value between  $\rho_{\text{airdry}}$  and  
207 area ratio of cell wall, which had been expected to be close to one, was not high as expected (0.77),  
208 because only the connected components more than 10 pixels across was recognized as pores.

209 Among the five calculated parameters, the cell-wall area ratio and median pore area were  
210 significantly related to  $\mu'_s$  (see Figure 5). When all samples were included in the calculation,  $\mu'_s$   
211 was a quadratic function of the cell-wall area ratio ( $R^2 = 0.76$ ), and an exponential function of the  
212 median pore area ( $R^2 = 0.54$ ). We calculated the  $R^2$  values between measured  $\mu'_s$  and estimated  
213 value from the exponential, linear, logarithmic, quadratic regression for each five calculated  
214 parameters and decide the best relation (quadratic function for the cell-wall area ratio and  
215 exponential function for the median pore area ) giving the highest  $R^2$ . However,  $\mu'_s$  was weakly  
216 linearly correlated with both parameters in softwood ( $R^2 = 0.044$  and  $0.110$  for area ratio and  
217 median pore area respectively; see Figure 5 (c) and (d)), but significantly linearly correlated with  
218 both parameters in the diffuse-porous and ring-porous hardwoods. In hardwood, the positive  
219 relation between  $\mu'_s$  and the area cell-wall ratio can be explained by the high volume fraction of  
220 the wood cell-wall substance, which scatters the NIR energy. Meanwhile, as the median pore area  
221 increases, the light is less likely to penetrate the boundary between the cell wall and air, so the  
222 decreases. However, as softwoods are also much simpler with more periodic anatomical features  
223 than hardwoods, the effect of both parameters on  $\mu'_s$  was small.

224 Considering the relationships in Figure 5, we estimated  $\mu'_s$  from the density, cell-wall area ratio,  
225 and median pore area of the wood samples. The equation is given by

226 
$$\mu'_s = a \times \rho_{\text{airdry}} + b \times r^2 + c \times r + d \times S^e + f. \quad (3)$$

227 where  $r$  and  $S$  denote the area ratio of the cell wall and the median pore area, respectively, and  
 228 the coefficients  $a$ ,  $b$ ,  $c$ ,  $d$ ,  $e$  and  $f$  were determined by a nonlinear curve-fitting method, (i.e., the  
 229 simplex method) that minimizes the residue between the measured  $\mu'_s$  and those predicted by Eq.  
 230 (3). Figure 6 (a) plots the relation between the measured  $\mu'_s$  and those predicted by Eq. (4).

$$231 \quad \mu'_s = 23.54 \times \rho_{\text{airdry}} + 196.79 \times r^2 - 232.33 \times r + 45.03 \times S^{68.01} + 69.90. \quad (4)$$

232 where the coefficients minimize the residues between the measured and predicted values of all  
 233 wood samples. These three parameters (density, cell-wall area ratio and median pore area) explain  
 234 85% of the variation in the  $\mu'_s$  of wood ( $R^2 = 0.85$ ).

235 We also constructed the regression curves of the separate woods (softwood, diffuse- porous  
 236 hardwood and ring-porous hardwood) by Eq. (5):

$$237 \quad \mu'_s = g \times \rho_{\text{airdry}} + h \times r + i \times S + j \quad (5)$$

238 The  $R^2$  values of softwood, diffuse-porous vessel hardwood and ring-porous vessel hardwood  
 239 were 0.57, 0.93, and 0.83, respectively. The individual plots are shown in Figure 6(b).

#### 240 **Light propagation simulations by the Monte Carlo method**

241 Figure 7 shows the simulated light propagation in japanese cedar (*Cryptomeria japonica*),  
 242 agathis (*Agathis alba* Foxw), empress tree (*Paulownia tomentosa*), yellow poplar (*Liriodendron*  
 243 *tulipifera*), and rubber wood. In the simulation the vertical incident point light was emitted on the  
 244 wood surface although the actual light source diameter was 1.5 mm. However, we can roughly  
 245 recognize the light propagation in the wood from the simulation. These five representative wood  
 246 species cover a wide range of  $\mu'_s$ ,  $\rho_{\text{airdry}}$ ,  $r$  and  $S$ . As absorption distribution were simulated in this  
 247 figure, there are no photons on the pixel corresponding to air. The Monte Carlo code, MCVM  
 248 simulated the light propagation in wood extremely well; in particular, the photons spread through  
 249 a small area in woods with relatively small  $\mu'_s$ , i.e., japanese cedar (Figure 7(a)) and agathis (Figure

250 7(b)), and through a wide area in woods with relatively large  $\mu'_s$ , i.e., yellow poplar (Figure 7(d))  
251 and rubber tree (Figure 7(e)). Note also that the photons spread further when the cell walls were  
252 continuously connected, as observed in yellow poplar and rubber tree (Figure 7(d) and (e)).  
253 Moreover, the photons spread around the pore, which explains the significant effect of the area  
254 cell-wall ratio  $r$  and median pore area  $S$  on  $\mu'_s$ . As the cell wall thickens and the degree of  
255 continuous connectivity increases, the  $r$  enlarges and the  $S$  reduces, thereby increasing the  $\mu'_s$ .

256 This study investigated the effect of air-dry density and wood texture properties on the reduced  
257 scattering coefficient  $\mu'_s$ . We believe that the interpretation of scattering phenomenon in wood  
258 enable us to construct robust regression model for the estimation of moisture content or chemical  
259 concentration without using chemometrics approach such as PLSR. Three fiber based diffuse  
260 reflectance spectroscopy (TFDRS),<sup>13</sup> which is possible to construct the handheld device using  
261 LEDs as a light source, is one of the prominent method, because the a proposed parameter  $\gamma$  in this  
262 method, which is calculated using the ratio of light intensity detected at two difference distances  
263 from light source, is independent of the optical path length and exhibits good linear correlation  
264 with the analyte material concentration. The interpretation and determination of scattering  
265 properties in wood lead to the determination of the optimal optical system for TFDRS.

## 266 CONCLUSIONS

267 This study investigated the effect of air-dry density and wood texture properties on the reduced  
268 scattering coefficient  $\mu'_s$ , measured by time-resolved spectroscopy at 846 nm. The wood texture  
269 parameters were calculated from cross-sectional microscopic images of the prepared wood  
270 samples.  $\mu'_s$  was linearly related to the air-dry density ( $R^2 = 0.56$ ), quadratically related to the cell-  
271 wall area ratio ( $R^2 = 0.76$ ), and exponentially related to the median pore area ( $R^2 = 0.54$ ). Eighty-  
272 five percent of the variation in the  $\mu'_s$  of wood samples can be explained by these three parameters.

273 Next, the light propagation was simulated in the cross-sectional microscopic images. In these  
274 simulations, the photons spread further in woods with continuously connected cell walls. The  
275 significant effect of cell-wall area ratio and median pore area on  $\mu'_s$  were attributable to the thicker,  
276 more connected cell walls associated with large cell-wall area ratio and small median pore area.  
277 Accordingly, increasing the area ratio of the cell wall and decreasing the pore area increased the  
278  $\mu'_s$ .

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315

316

317 **Figure captions**

318 **Figure 1.** Modeling the photon migration in a voxelized 3D wood structure model.

319 **Figure 2.** Measured time-resolved profiles of 70-ps 846-nm pulses transmitted through air-dry  
320 wood samples. Black dots show the normalized numbers of photons transmitted through the wood  
321 sample, and the red solid curve is fitted by the diffusion model.

322 **Figure 3.** Relation between wood air-dry density and  $\mu'_s$ . Filled square, open square, and open  
323 triangle are the data from softwood, ring-porous vessel hardwood and diffuse-porous vessel  
324 hardwood, respectively.

325 **Figure 4.** Microscopic images of (a) western red cedar (softwood), (b) beech (diffuse-porous  
326 vessel hardwood), and (c) castor aralia (ring-porous vessel hardwood). (d), (e) and (f) are the binary  
327 images of (a), (b) and (c), respectively.

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329 The quadratic and exponential regression lines in (a) and (b) respectively describe the variation of  
330  $\mu'_s$  among all wood samples, while the linear regression lines in (c) and (d) were determined for  
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334 predicted by Eq. (3) for each kind of wood. Filled square, open square, and open triangle denote  
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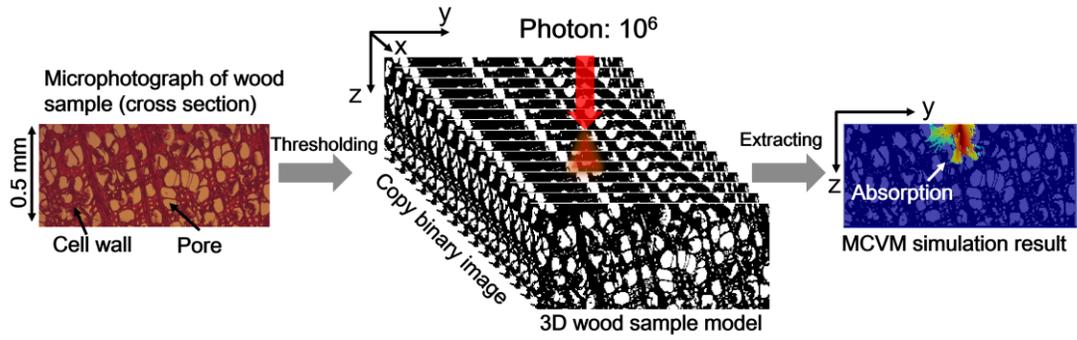
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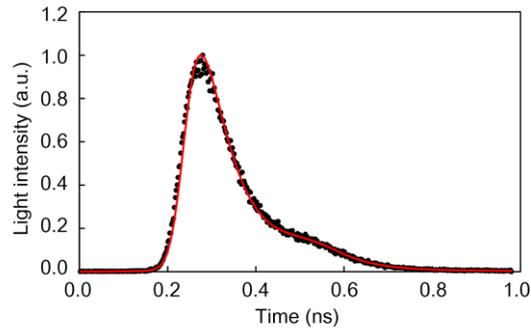
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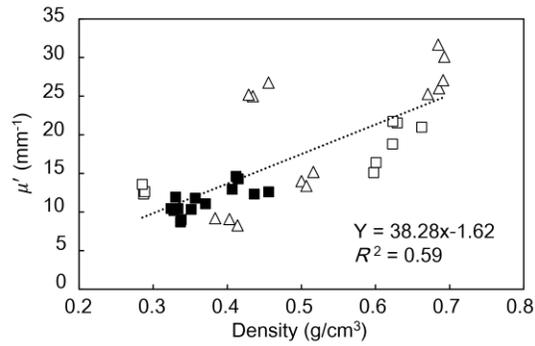
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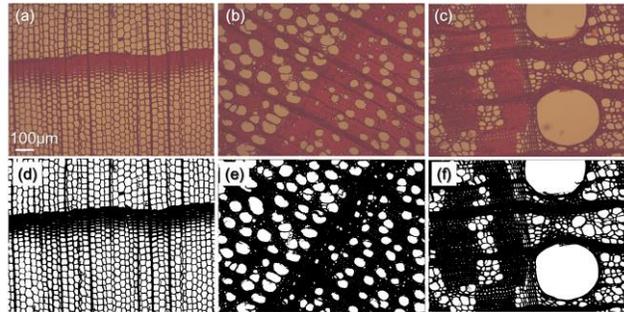
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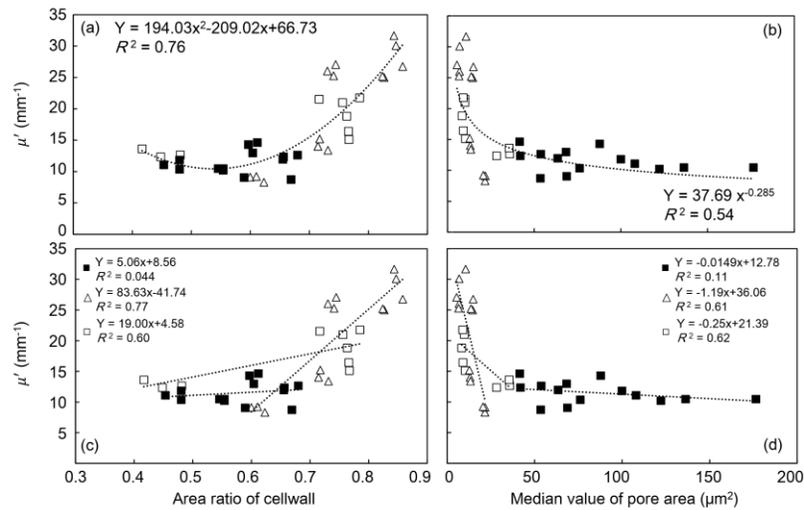
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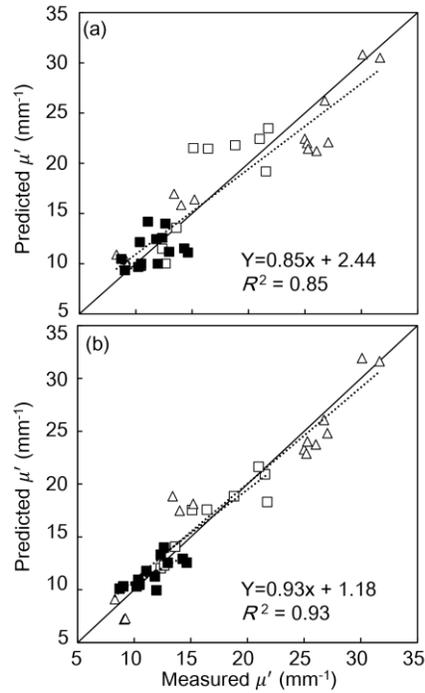
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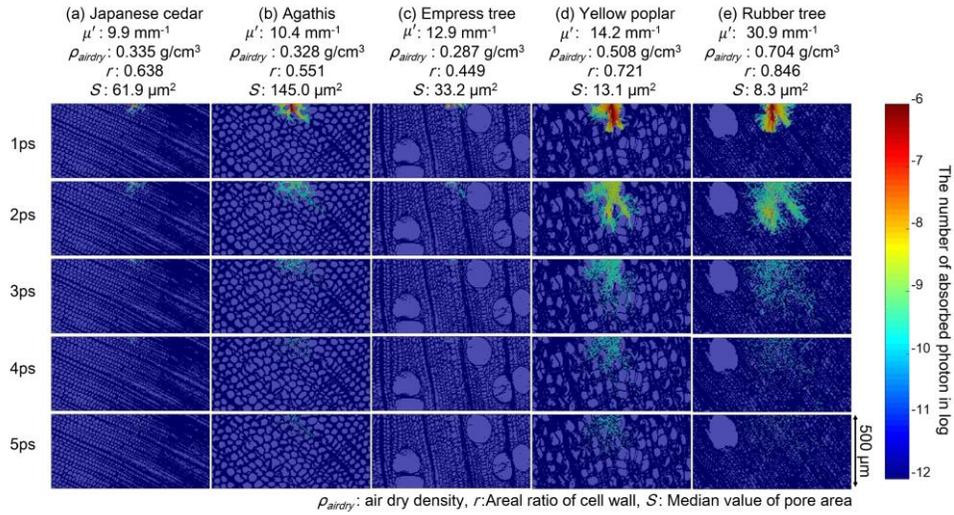
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442 **Table 1.** Air-dry densities,  $\mu'_s$  values and cellular structure parameters calculated from  
 443 microscopic cross-sectional images of the wood samples.

Wood type	Name	Density (g/cm <sup>3</sup> )	$\mu'_s$ (mm <sup>-1</sup> )	Regarded pore	Max. diameter ( $\mu$ m)	Mean pore rea ( $\mu$ m <sup>2</sup> )	Median pore area ( $\mu$ m <sup>2</sup> )	Cellwall area ratio
Softwood (No vessel)	Agathis	0.33±0.00	10.38±0.15	469±74	24.75±1.30	161.67±26.77	145.00±28.17	0.55±0.00
	Norfolk island pine	0.41±0.00	13.96±0.88	883±147	17.30±0.70	76.12±13.33	65.89±23.20	0.60±0.01
	Western red cedar	0.36±0.01	11.09±0.73	894±78	19.60±0.85	98.35±11.49	94.71±16.56	0.47±0.02
	Hinoki cypress	0.45±0.01	12.49±0.20	1113±126	13.04±0.65	50.16±3.91	48.55±6.06	0.66±0.01
	Japanese cedar	0.33±0.00	9.90±1.78	931±52	14.52±0.26	63.93±5.98	61.93±7.74	0.64±0.04
Hardwood (Diffuse- porous)	Ayous	0.44±0.01	25.65±0.97	769±77	76.39±5.00	33.85±0.60	14.37±0.64	0.84±0.02
	Rubber tree	0.70±0.03	30.88±1.10	1033±130	82.43±4.42	25.79±3.35	8.32±2.02	0.85±0.00
	Yellow poplar	0.51±0.01	14.21±0.92	598±45	33.20±0.39	71.95±9.54	13.08±0.31	0.72±0.01
	Katsura tree	0.40±0.02	8.88±0.50	820±23	30.40±1.29	75.70±2.78	21.33±0.63	0.61±0.01
Hardwood (Ring-porous)	Beech	0.68±0.01	26.13±0.89	689±151	29.65±0.47	63.40±17.27	6.32±0.75	0.74±0.01
	Empress tree	0.29±0.00	12.87±0.66	1368±152	82.27±2.30	70.93±7.66	33.19±4.27	0.45±0.03
	Castor aralia	0.61±0.01	16.78±1.88	842±30	73.11±4.29	50.07±1.05	9.26±1.01	0.77±0.00
	Ash	0.64±0.02	21.42±0.39	513±14	91.88±8.48	71.59±17.90	9.63±0.54	0.75±0.03

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	Density (g/cm <sup>3</sup> )	Regarded pore	Max. diameter (μm)	Mean pore rea (μm <sup>2</sup> )	Median pore area (μm <sup>2</sup> )	Cellwall area ratio
Density	1.00					
Regarded pore	-0.31	1.00				
Max. diameter	0.39	0.11	1.00			
Mean pore rea	-0.46	-0.45	-0.40	1.00		
Median pore area	-0.64	-0.17	-0.54	0.83	1.00	
Cellwall area ratio	0.77	-0.33	0.39	-0.62	-0.64	1.00

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