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ORIGINAL ARTICLE

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Soft X-ray observation of water distribution in the stem of *Cryptomeria japonica* D. Don II: Types found in wet-area distribution patterns in transverse sections of the stem*

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Abstract Using soft X-ray photography, two-dimensional observations were made of the water distribution within the green stem of *Cryptomeria japonica* D. Don. Variations in the distribution pattern of the "wet area" in the horizontal plane of the lower stem were described. The distribution patterns showed extreme variation among individual trees, with broad wet-area distribution types appearing, namely, the regularly distributed wet area and the irregularly distributed wet area. We defined five basic types of wet-area distribution patterns on the basis of their regularity or irregularity. It was concluded that the between-tree variation in the wet-area distribution causes the between-tree variation in the mean moisture content of the heartwood. The distribution patterns of the wet area were similar for individual trees within each plus-tree clone.

Key words *Cryptomeria japonica* · Wetwood · Soft X-ray photography · Water distribution · Heartwood

Introduction

Trees from the species *Cryptomeria japonica* D. Don contain much more water in their heartwood than is found in other coniferous species.[1] However, the moisture content of the heartwood varies greatly among individual *C. japonica* trees.[2,3] Some authors have reported within-tree variations in the moisture content of *C. japonica*, including several types of radial variation in moisture content within a single tree trunk.[3–8] Each author group independently defined several types of radial moisture distribution, resulting in differences in the type definition among authors.

In our previous paper,[9] it was reported that water in the heartwood was generally maldistributed. In that study, three types in water presence were distinguishable: wet areas, dry areas, and moderate-moisture areas. The wet area contained much free water, and it was estimated that almost all tracheid lumens were saturated with water. It was suggested that, in a transverse section in a tree trunk, the wet-area distribution pattern accounted for the mean moisture content in the heartwood of the section and for the radial variation of moisture content throughout the section.

In this paper, some features of the wet-area distribution patterns as observed in horizontal planes in tree stems are described, and five basic types of the wet-area distribution patterns are defined.

Materials and methods

Altogether 681 trees of 364 plus-tree clones (tree numbers per clone varied, but mostly two trees per clone were investigated) of the *C. japonica* species were used in this study. The age and stem diameter 1.2 m above the ground of sample trees at the time of collection ranged from 25 to 34 years, and 9 to 39 cm, respectively.

A total of 394 trees of 212 plus-tree clones were harvested from clonal archive 11 of *C. japonica* plus-trees at the Forest Tree Breeding Center (Mito, Ibaraki Prefecture, Japan) between December 1990 and March 1991. Another 287 trees of 152 plus-tree clones were harvested from clonal archive 15 between July and October 1991. One disk was sawed from the stem of each tree 2.5 m above ground. The sample stands were flat, and it was judged that the environmental differences among individual trees in each stand were small. The distance between stands 11 and 15 was about 500 m, so it was assumed that the environmental differences between the two stands were small.

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The sample disks were cut into strips 3 cm wide. Then cross sections 5 mm thick were prepared for X-ray photography. The prepared sections were put directly onto X-ray film packs (Kodak x-omat TL ready-pack) and irradiated with a soft X-ray radiator (Softex). Irradiating conditions were 4 min 40 s irradiating time, 17 kVP voltage, 13 mA current, and 2.5 m distance from the focusing plane to the film. The processed film was observed with the naked eye with transparent light and on the monitor screen of a computer system after being input by a flat-bed scanner.

In addition, 2 cm thick sections that were close to the X-ray specimens were also taken from the strips so their moisture content could be measured. Each section was divided into pieces of heartwood for measuring. The definition of the border between the heartwood and the intermediate wood was based on the heartwood color. The moisture content was calculated using the equation: $Mc = (Wg - Wd)/Wd \times 100$, where Mc (%) is the green moisture content as a percentage of the oven-dried wood, Wg (g) is the weight of the specimen in a green condition, and Wd (g) is the weight of the specimen in an oven-dried condition.

Results

Features of the wet-area distribution

Water in the heartwood was generally maldistributed and was concentrated in a wet area.[9] The wet area could be observed anywhere in the heartwood. Two kinds of wet areas, regularly distributed and irregularly distributed, were observed.

The regularly distributed wet areas appeared to be concentric and symmetrical to the pith (Fig. 1). The regularly distributed wet areas tended to be continuous in the tangential direction and along the growth ring boundary. The border line of the regularly distributed wet area tended to curve smoothly.

The irregularly distributed wet areas were seen to have a spot-like and scattered appearance (Fig. 2) and to vary in size and form. Various specialized forms were observed (Fig. 3). Symmetry with the pith was not observed in the irregularly distributed wet areas, representing the most significant difference between these and regularly distributed wet areas. Almost all wet areas that were connected to knots had irregular shapes.

It was frequently observed that both types of wet area appeared simultaneously within a section.

Five basic types of wet areas that appeared in the transverse sections

We defined the following five basic types of wet-area distribution patterns (Fig. 4).

Type 1: Dry areas or moderate-moisture areas are present in the heartwood without a regularly distributed wet area.

Type 2: The regularly distributed wet area is formed circularly around the pith.

Fig. 1. Soft X-ray photograph of a sample section showing regularly distributed wet areas in the heartwood. Tree no. 11-761, clone name Chichibu (Ken) 6, MC (mean moisture content of the heartwood) is 213%. [NOTE: All soft X-ray photographs in this paper are represented in negative. Thus, darker portions in the photographs show portions of low X-ray absorption and little water presence in the sample section; lighter portions show high X-ray absorption and much water]

Fig. 2. Soft X-ray photograph of a sample section showing irregularly distributed wet areas in the heartwood. Tree no. 11-540, clone name Kuji 38, MC is 204%

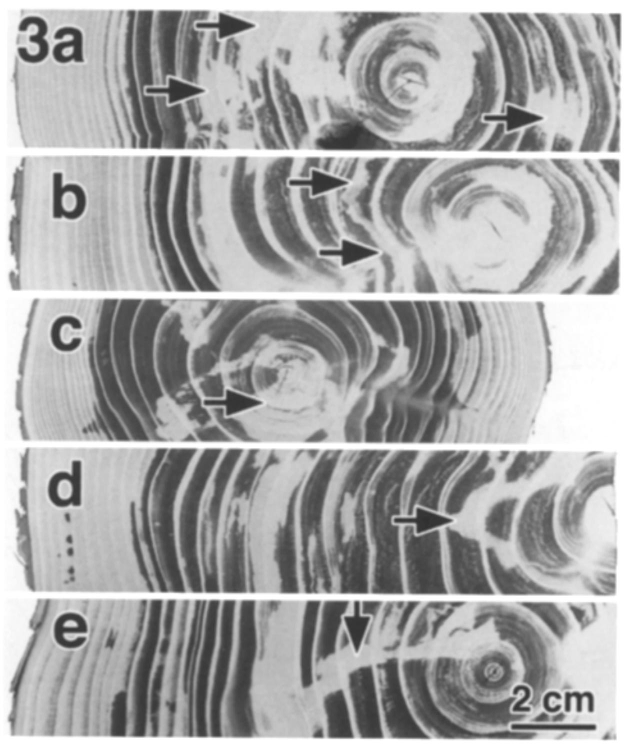

Fig. 3. Remarkable forms of irregularly distributed wet areas. Soft X-ray photographs. **3a** Spot-like forms (*arrows*): tree no. 11-499, clone name Takahagi 15. **3b** Wavy forms (*arrows*): tree no. 11-833, clone name Ashigara-kami 5. **3c** Fan-shaped form (*arrow*): tree no. 15-570, clone name Minami-aizu 6. **3d** Wet area that appears on the margin of the wedge (*arrow*): tree no. 15-817, clone name Tanzawa 5. **3e** String of wet areas that runs radially (*arrow*): tree no. 11-777, clone name Kuno 2

Type 3: The regularly distributed wet area has a donut-like shape. The wet area is located toward the outer portion of the heartwood, and the dry area or moderate-moisture area (or both) appears at the inner portion.

Type 4: Almost all of the heartwood is occupied by the wet area.

Type 5: All types that do not fit into the above four categories are included here. There is little or no regularly distributed wet area. Irregularly distributed wet areas are mostly observed.

In many cases, patterns that fell between these types or consisted of complexes of these types were observed (Fig. 5). These intermediate or complex patterns were named as shown in Fig. 5. Type 2/3 (Fig. 5b), which was a combination of types 2 and 3 (its wet area appeared circularly around the pith and at the periphery of the heartwood), was frequently observed.

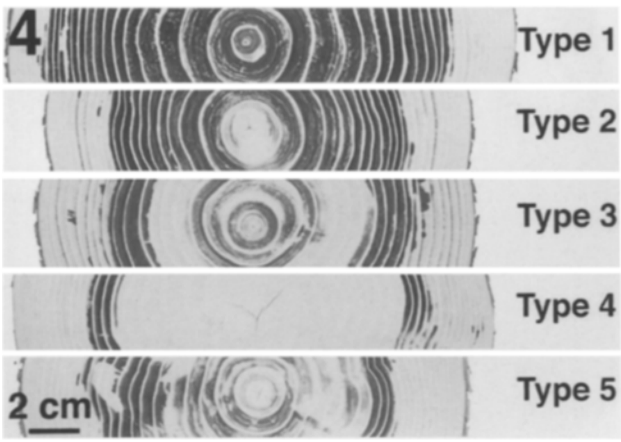

Fig. 4. Five basic types of wet-area distribution patterns in the heartwood. Soft X-ray photographs. *Type 1*: tree no. 11-678, clone name Kuji 7, MC 73%. *Type 2*: tree no. 11-874, clone name Higashi-kamo 9, MC 99%. *Type 3*: tree no. 15-738, clone name Kodama 5, MC 149%. *Type 4*: tree no. 11-781, clone name Naka 9, MC 218%. *Type 5*: tree no. 11-560, clone name Naka 10, MC 148%

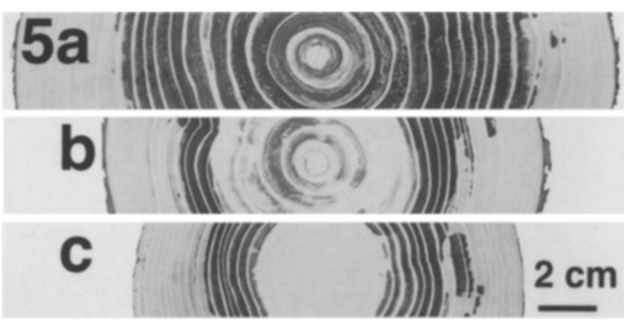

Fig. 5. Intermediate and complex patterns of the five basic types of wet-area distribution. Soft X-ray photographs. **a** Type 1/2, an intermediate pattern of type 1 and type 2, with a small wet area or an incomplete circle of wet area appeared around the pith: tree no. 11-853, clone name Tenryu 8, MC 95%. **b** Type 2/3, a complex pattern of type 2 and type 3, with circular wet areas around the pith and at the periphery of the heartwood: tree no. 11-845, clone name Ooi 8, MC 195%. **c** Type 2/4, an intermediate pattern of type 2 and type 4, with a large circular wet area at the center of the section and not at the periphery of the heartwood: tree no. 11-508, clone name Chichibu 3, MC 178%

Frequencies of the types of wet areas appearing in a forest stand

Figure 6 represents the frequencies of the five basic wet-area types and of the intermediate or complex patterns of the types as they appeared in two forest stands. The intermediate or complex patterns were categorized as either type 1/2, type 2/3, or type 2/4 for the sake of convenience.

Types 1, 2, and 5 were seen frequently; and type 3 was rarely observed in this investigation. Types 2 and 4 and the related intermediate or complex patterns (i.e., types 1/2, 2/3, and 2/4), were frequently observed.

The two stands exhibited a statistically significant difference in the frequencies of wet-area types (chi-square test, $P < 0.05$). In particular, type 4 appeared more frequently in stand 11 than in stand 15.

Figure 7 represents the frequency distribution of the mean moisture content in the heartwood of individual trees of each type. There were statistically significant differences among the five basic types in terms of the mean moisture content of the heartwood (ANOVA, $P < 0.01$). In Fig. 7 the frequency distributions of the moisture content for the intermediate patterns (types 1/2 and 2/4) are positioned between those of the basic types. For example, type 1/2, which is intermediate between types 1 and 2, had its frequency distribution represented between those of type 1 and type 2. The moisture content of the combination pattern (type 2/3) had a larger value than did its basic constituent types (types 2 and 3).

Similarity in the appearance of wet areas within each clone

One pair of individual trees from each clone was investigated for each of the 283 clones. In 91 of the clones (32%),

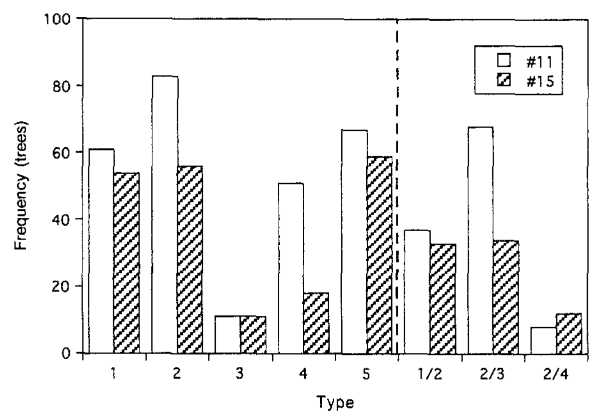

Fig. 6. Frequencies for the five basic types and the intermediate or complex patterns of wet-area distribution in two forest stands. *#11*, *#15*, stand numbers of the two forest stands (clonal archives) sampled in this study

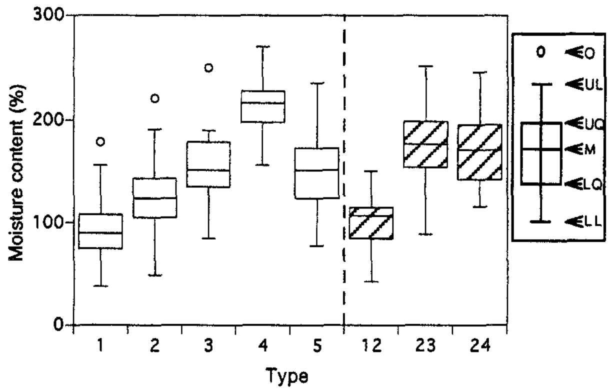

Fig. 7. Box-whisker plots showing the frequency distribution of the mean moisture content of the heartwood of individual trees of each basic type and intermediate or complex patterns. *O*, outlier; *UL*, maximum value within upper limit; *UQ*, upper quartile; *M*, median; *LQ*, lower quartile; *LL*, minimum value within lower limit. Upper and lower limits are defined as follows: upper limit = $UQ + 1.5 \times (UQ - LQ)$; lower limit = $LQ - 1.5 \times (UQ - LQ)$

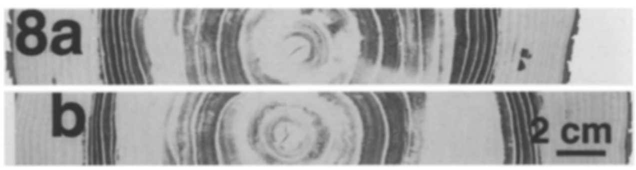

Fig. 8. Soft X-ray photographs of two individual trees of a clone (Futaba 1). Tree nos. 11-668 and 11-669: MC was 189% and 196%, respectively

the two trees of each clone exhibited the same wet-area distribution type (Fig. 8). In 73 of the clones (26%), each of the two trees studied fell into a different type. However, in these cases the two distribution types showed similarity, (e.g. types 2 and 1/2, types 2/3 and 4, or types 2/4 and 4); 76 of the clones (27%) contained type 5 tree and one other type. Type 5 is defined as those trees with irregular wet areas that were unlike other types. In 43 of the clones (15%), the two trees investigated exhibited completely different types of wet-area appearance.

For five of the clones, three individual trees were investigated. In four of these, two trees exhibited the same wet-area type and the third tree was different. Only one clone contained three types.

For one of the clones, four individual trees were investigated. In this clone, no similarity in wet-area distribution types was detected.

It was concluded that there was significant similarity among trees of each clone in terms of the appearance of their wet areas.

Discussion

In most previously published reports on this topic, the moisture content of the heartwood was defined as the mean value in the whole heartwood. If the water in the heartwood is distributed evenly, the mean value can be used with accuracy. However, the water in the heartwood is usually maldistributed, and the water content varies dramatically between portions in *C. japonica*, so the mean value of the moisture content of the heartwood is useful only as a "mean value." For complete and accurate understanding, it is necessary to grasp how water is maldistributed in the heartwood.

Miwa[7] and others[3–6,8] have reported several types of radial moisture distribution patterns in the *C. japonica* living stem. Miwa[7] defined three types of the moisture distribution in the heartwood: (A) evenly distributed with low moisture content; (B) unevenly distributed but gradually increasing from the intermediate wood toward the pith; and (C) evenly distributed with high moisture content. Kamei and Tsushima[5] described an additional type: (D) low moisture content at the center of the stem but changing gradually to become high at the periphery of the heartwood. Kawazumi et al.[6] and Fujisawa et al.[4] reported this fourth type also and found it to be as Kamei and Tsushima[5] had described it. However, Fujisawa et al.[4] investigated with soft X-ray densitometry and performed precise analysis, and they reported a modification to Kamei and Tsushima's type D: (D′), in which the moisture content is higher near the pith. Nakada and Yamada[8] determined one more additional type: (E), in which the moisture content varies within the heartwood at random.

Hirakawa et al.[3] established their classification on the basis of a combination of the mean moisture content and soft X-ray photography. At first, all sample trees were divided according to the mean moisture content of the heartwood into three ranges as follows: (X) under 100%; (Y) 100%–200%; and (Z) over 200%. Types Y and Z were then divided again into (Y1) evenly distributed and (Y2) accumulated near the pith, and (Z1) evenly distributed and (Z2) accumulated periphery of the heartwood. [*Note*: the letters representing each type (A, B, C, etc.) that are used here were chosen by the present authors to facilitate comparison with our types. The other researchers used different names for the types in their reports.]

With our classification, the types include all of the types described in former reports. The formally described types A, B, C, D, D′, and E correspond to our types 1, 2, 4, 3, 2/3, and 5, respectively. It was suggested that the difference between types D and D′ and the appearance of type E resulted from differences in the sample size in each investigation. The authors of these previous reports performed their investigation with the oven-dry method, which requires a specific size of sample wood blocks. The ratio of the wet area to the rest of the sample block is a major factor influencing the moisture content of the block. Our classification is precise and easy to examine, and through soft X-ray photography we were able to make the observation two-dimensionally. Soft X-ray photography was also advantageous in detecting any irregularity in the wet-area distribution.

Some confusion occurred in our classification of types because of the presence of the intermediate or complex patterns as described above. The classification by Hirakawa et al.[3] is convenient and advantageous for rectifying this problem but requires measurement of moisture content. The use of mean moisture content, though, is problematic. First, the density of the sample block affects the moisture content. Blocks of low density have more space for containing free water than blocks of high density. Thus, if an entire block is occupied by a wet area, a sample block with lower density will have a higher moisture content than a block with higher density. The effect of density on the moisture content also complicates the evaluation of the radial water distribution. Second, the division into types X, Y, and Z at 100% and 200% of moisture content is not appropriate. The frequency distribution of the mean moisture content of the heartwood is apparently continuous.[3,10] There is no scheme for determining the limit values. Third, most of the investigations, including this study, performed the measurement of mean moisture content with a narrow strip. Therefore, the moisture content in type 3 will be underestimated. The true value of the mean moisture content of the heartwood in a horizontal plane of the stem will be smaller in type 2 than the moisture content determined by a narrow strip and will be larger in type 3. Finally, it is difficult to detect the regularity or irregularity of the water distribution by measuring moisture content.

Moisture content measurement is more advantageous than soft X-ray photography for quantitative analysis. However, if there is a need to determine the radial distribution pattern of water in the heartwood, the type of the distribution pattern is subjectively determined by the investigator with a line graph, such as the type determined on soft X-ray photography. Thus, the distribution patterns from the moisture content measurement were not quantitative.

The frequency distributions of the mean moisture content in the heartwood could be divided into the five basic types of wet-area distribution patterns. The intermediate patterns were represented between the basic types to which they were related. These findings suggested that a rough estimation of the mean moisture content could be made simply from the types of wet-area distribution patterns.

It was concluded that the water distribution within the heartwood of *C. japonica* was explained better with soft X-ray photography than by measuring the moisture content.

In this study, similarities were found in wet-area distribution patterns between individual trees within each clone. Fujisawa et al.[2] reported that the broad sense heritability of mean moisture content in heartwood was high. It was suggested that the presence of water in the heartwood was regulated by genetic factors. Soft X-ray photography can contribute to the evaluation of individuals, clones, or families on the basis of their wet-area distributions. On the other hand, there were also differences between stands in terms of the frequencies with which the different wet areas appeared. The cause of this interstand difference is unknown, but differences in the clones growing in each stand might cause the difference in frequency of the various types.

Only the results obtained from lower stems are reported in this paper. The water distribution at greater heights was not determined in this study. Variation has been observed in the mean moisture content of heartwood in the vertical direction along the stem axis.[10] The tree is, of course, larger in longitudinal direction than in horizontal direction. It is therefore still necessary to study the longitudinal changes in the wet-area distribution in the stem. Those subjects will be discussed in a subsequent paper.

Conclusions

The following conclusions were reacted.

1. The wet-area distribution in heartwood varied among individual trees of the species *Cryptomeria japonica*.
2. Both regular and irregular wet-area distributions were observed.
3. Five basic types of the wet-area distribution pattern were distinguishable.
4. Soft X-ray photography was more useful than the oven-dried method for evaluating individual trees and clones for the genetic improvement of the wetwood in *C. japonica*.
5. The trees of each clone showed similarity in the wet-area distribution patterns that appeared on transverse sections taken from the lower stem.

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