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Sapwood Amount and its Predictive Equations for Young Hinoki Cypress (*Chamaecyparis obtusa*) Trees

Stephen ADU-BREDU and Akio HAGIHARA

Abstract

Sapwood, which is peripheral to heartwood in tree trunks, serves as a water conduction and storage organ, and energy is needed to maintain the living ray parenchyma cells. The sapwood amount in hinoki cypress (*Chamaecyparis obtusa* (Sieb. et Zucc.) Endl.) was examined in relation to tree size on the basis of 14 sampled trees. The sapwood cross-sectional area was related to the over-bark stem cross-sectional area by a generalized allometric function, with an asymptotic value of 212.4 cm^2. The sapwood mass per tree was power functionally related to the corresponding stem volume. Sapwood mass of sample discs was proportionally related to the corresponding sapwood volume, with a proportional constant of 0.4154 g cm^{-3} denoting the sapwood bulk density. The relationship between sapwood mass and stem mass per tree was described by a power function with an exponent value of less than unity, suggesting that the proportion of sapwood mass per tree decreases with increasing stem mass per tree. With the predictive equations, sapwood mass for any section of stem could be fairly estimated.

Keywords : cross-sectional area, bulk density, heartwood, hinoki, sapwood

Introduction

Sapwood which is peripheral to heartwood, the inactive woody centre of tree trunk, is the physiologically active part of xylem. It functions as water conduction and storage tissues. Woody plants store reserves in the sapwood and utilize them as demand arises. Starch is the main dominant non-structural carbohydrate in the sapwood (MAGEL *et al.*, 1994). Besides carbohydrates, fats and oils play certain roles as storage products (ZIMMERMANN and BROWN, 1974). Large scale resorption of some essential nutrients, like phosphorus and potassium, takes place during transition from sapwood to heartwood. The resorbed nutrients which are stored in the sapwood become available to newly formed tissues. Such resorption avoids the immobillization of large amounts of nutrients in the heartwood (BAMBER, 1976; BAMBER and FUKAZAWA, 1985). ATTIWILL (1980), for instance, found that 14.3% of the annual phosphorus demand of a *Eucalyptus obliqua* forest was provided by heartwood formation. Accumulated and storage materials are utilized to resume growth before significant positive rates of net photosynthesis are achieved in early spring (DOUGHERTY *et al.*, 1979), and also to maintain respiration during

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periods when photosynthesis is reduced or ceases (KOZLOWSKI *et al.*, 1991). The living ray parenchyma cells of the sapwood serve as storage tissue, and so energy is needed to support and keep them functional.

HAGIHARA and HOZUMI (1981) showed for *Chamaecyparis obtusa* trees that respiration rate per unit fresh mass of stem decreased with increases in the square of stem girth. This result presupposes that the amount of inactive tissues, *i.e.*, heartwood, is substantial in larger-sized stems compared with smaller-sized stems. Stem respiration is usually expressed in terms of surface area (LANDSBERG, 1986), apparently because of the largely peripheral distribution of living tissues and the mass of internal non-living tissues in trees. However, RYAN (1990) found that in *Pinus contorta* and *Picea engelmannii* stems, sapwood but not cambium was the major contributor to maintenance respiration, and SPRUGEL (1990) also found no evidence of significant cambial maintenance respiration in *Albies ambilis* (Dougl.) Forbes trees.

Accurate estimation of sapwood amount would enable energy cost of storage and stem growth to be assessed. This study was aimed at documenting how sapwood amount changes with tree size, and to develop equations for accurate estimation of the amount of sapwood in young hinoki cypress (*C. obtusa*).

Materials and Methods

Trees were sampled from a 12-year-old (as of 1995) hinoki cypress (*Chamaecyparis obtusa* (Sieb. et Zucc.) Endl.) stand in an experimental field of the School of Agricultural Sciences, Nagoya University, Japan, in October and November 1995.

Fourteen different-sized trees were sampled, their general features being given in Table 1. The trees were harvested and subjected to the stratified clipping method, in

Table 1. General features of the sampled trees.

Tree no.	H (m)	G_B (cm)	$G_{1.3}$ (cm)	v_S (dm^3)	w_S (kg)	v_{SW} (dm^3)	w_{SW} (kg)
1	5.6	26.9	26.0	18.38	7.182	11.54	4.992
2	5.7	25.0	23.7	15.96	5.887	11.90	4.324
3	5.6	20.4	22.3	13.10	5.501	8.455	3.643
4	5.4	21.3	22.2	12.73	5.432	8.724	5.432
5	5.7	18.9	20.6	11.28	4.744	7.791	3.300
6	5.2	19.3	19.9	10.74	4.555	7.190	3.028
7	5.1	23.2	18.6	9.154	3.417	5.672	2.207
8	5.3	19.8	19.0	8.644	3.064	5.169	1.961
9	5.1	15.0	17.8	8.563	3.363	5.447	2.235
10	5.0	15.3	16.7	6.892	2.695	4.505	1.966
11	4.9	18.2	14.3	5.472	2.041	4.023	1.486
12	3.3	15.4	11.2	3.050	1.344	2.082	0.9489
13	4.3	9.8	10.6	2.988	1.137	1.976	0.8353
14	4.0	8.5	9.1	2.047	0.7482	1.411	0.6209

H, tree height ; G_B, stem girth at the crown base ; $G_{1.3}$, stem girth at a breast height of 1.3 m above the ground ; v_S, stem volume ; w_S, stem mass ; v_{SW}, sapwood volume ; w_{SW}, sapwood mass.

which strata were 0–0.3, 0.3–1.3 m, and at intervals of 1.0 m upwards. Stem discs of thickness 1.5 to 4.0 cm from the crown base, 0.0, 0.3, 1.3 m, and at intervals of 1.0 m upwards were taken for sapwood measurement. Sapwood was differentiated from heartwood by colour and staining with ferric chloride solution (*e.g.*, RYAN, 1989). Stem samples were also taken from each stratum for stem dry to fresh mass ratio analysis.

Over-bark and under-bark girth of the discs were measured with a steel measuring tape, whereas heartwood girth was measured with a Digital Curvi-Meter (S 880, Uchida, Tokyo). Disc thickness was measured at four perpendicular points with a Digmatic Caliper (500–301, Mitutoyo, Kanagawa), and the average taken. Sapwood cross-sectional area was calculated as the difference between under-bark cross-sectional area and heartwood cross-sectional area. From sapwood cross-sectional area and disc thickness, sapwood volume of a disc was calculated. Stem and sapwood volume at each stratum was calculated by the Smalian's formula (*e.g.*, AVERY and BURKHART, 1994), with the stem top being regarded as a cone.

The discs were split into four to facilitate removal of heartwood. The sapwood, as well as the stem dry mass samples, was oven-dried at 85℃ for 48 h, and then mass measured after 24 h desiccation. From the ratio of sample dry to fresh mass and stem fresh mass of a stratum, stem dry mass at the stratum was estimated. On the other hand, from disc sapwood bulk density, *i.e.*, ratio of sapwood dry mass to volume, and sapwood volume of a stratum, sapwood dry mass of the stratum was estimated. Some characteristics of the sample discs are given in Appendix 1.

Results and Discussion

A relationship between sapwood cross-sectional area, A_{SW} (cm^2 per disc), and over-bark stem cross-sectional area, A_{OB} (cm^2 per disc), is given in Fig. 1. The relationship could be well represented by a generalized allometric function (OGAWA and KIRA, 1977) as

$$\frac{1}{A_{SW}}=\frac{1}{0.8004A_{OB}}+\frac{1}{212.4} \quad (R^2=0.962)$$

or

$$A_{SW}=\frac{0.8004A_{OB}\cdot 212.4}{0.8004A_{OB}+212.4}. \qquad (1)$$

The significance of this equation is that as A_{OB} becomes smaller the relationship tends to be proportional, with a constant of 0.8004, whereas as A_{OB} tends to infinity A_{SW} approaches an asymptotic value of 212.4 cm^2 per disc. The biological implication of the asymptotic value is that trees require a particular amount of sapwood for the conduction of sap and the storage of reserve materials. As sapwood is continually laid down concurrently with growth of crown, heartwood formation acts as a regulatory mechanism for controlling the amount of sapwood at an optimum level (BAMBER, 1976). Sapwood volume at any section of stem can be estimated from this relationship and the length of the section. However, it may not be valid to extrapolate the results of this study to older hinoki trees. This is because older trees contain a substantial amount of heartwood compared with younger trees, so a case study on older hinoki trees should be undertaken.

Sapwood mass per tree, w_{SW} (kg per tree), was related to stem volume per tree, v_S (dm^3 per tree), as shown in Fig. 2. The relationship, which was power functional, was given as

$$w_{SW}=0.3002v_S^{0.9601} \quad (R^2=0.976). \qquad (2)$$

From a knowledge of stem volume of a tree, sapwood mass can be estimated from Eq. (2).

Sapwood mass of the sample discs, w (g per disc), was related to the corresponding

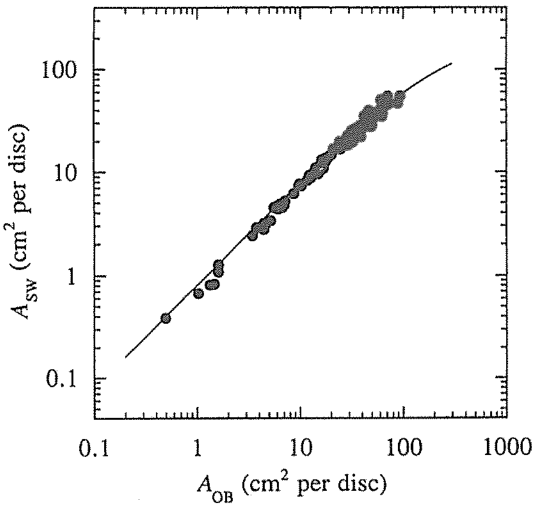

Fig. 1. Relationship between sapwood cross-sectional area, A_{SW}, and stem cross-sectional area, A_{OB}, of sample discs. The regression curve is based on Eq. (1).

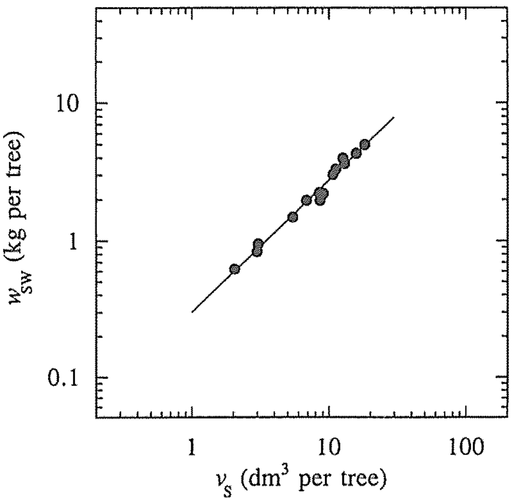

Fig. 2. Relationship between sapwood mass, w_{SW}, and stem volume, v_S. The regression line corresponds to Eq. (2).

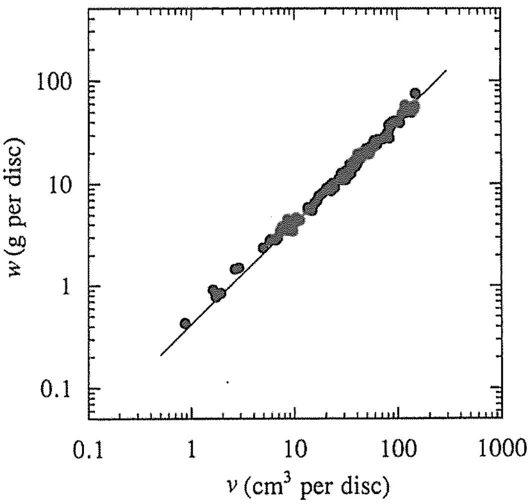

Fig. 3. Proportional relationship between sapwood mass, w, and volume, v, of sample discs. The regression line corresponds to Eq. (3).

sapwood volume, v (cm^3 per disc), as shown in Fig. 3. This relationship is represented as

$$w = 0.4154v \quad (R^2 = 0.977). \tag{3}$$

Because of the proportionality of this relationship, the coefficient value of 0.4154 g cm^{-3} denotes sapwood bulk density. RYAN (1989) also found sapwood bulk density of lodgepole pine (*Pinus contorta*) to be 0.42 g cm^{-3}, which is very similar to the value given in this study. Considering Eqs. (1) and (3), sapwood mass at any section of stem can be fairly estimated. For the estimation of the overall stem bulk density, total stem mass, w_S (kg per tree), was proportionally related to total stem volume, v_S (dm^3 per tree), as shown in Fig. 4. The relationship was given as

$$w_S = 0.3966v_S \quad (R^2 = 0.983), \tag{4}$$

where the proportional constant of 0.3966 kg dm^{-3} denotes overall stem bulk density. The overall stem bulk density value is smaller than the sapwood bulk density value of 0.4154 g cm^{-3} (Eq. 3). This is because sapwood is substantial in younger trees, compared with older trees, and it is surmised that the sapwood density exceeded that of bark resulting in the overall stem bulk density being lighter. However, since heartwood is substantial in older trees the overall stem bulk density in older trees is expected to be greater than that of sapwood.

In studying stem growth and maintenance respiration, non-destructive respiration measurement of the same stem over a long period is desirable. Hence models are needed to non-destructively predict the active sapwood from which maintenance respiration virtually results. The given equations will enable sapwood amount in young hinoki trees to be estimated with a fair degree of accuracy. Thus stem maintenance and growth respiration studies would be enhanced.

To find out the amount of sapwood in hinoki stem, sapwood mass, w_S (kg per tree), is related to stem mass, w_S (kg per tree), in Fig. 5. The relationship was given in the

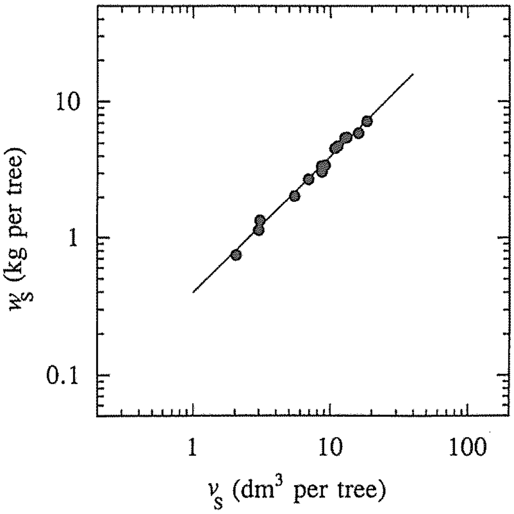

Fig. 4. Proportional relationship between stem mass, w_S, and stem volume, v_S. The regression line is given by Eq. (4).

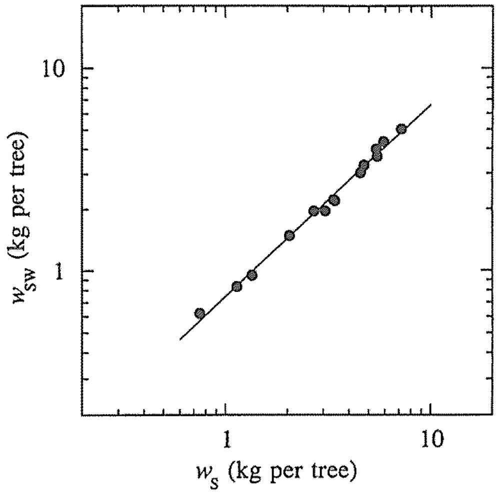

Fig. 5. Regression of sapwood mass, w_{SW}, on stem mass, w_S, of the sampled trees. The regression line is based on Eq. (5).

form,

$$w_{SW} = 0.748 w_S^{0.944} \quad (R^2 = 0.998). \tag{5}$$

The exponent of this power functional relationship, which is less than 1.0 (*i.e.*, 0.944), suggests that proportion of sapwood mass in a stem decreases with increasing total stem mass. Even though younger sapwood tissues are produced, older sapwood tissues are continually transformed into heartwood. Hence, cumulative increases of heartwood amount result in decreases in proportion of sapwood mass with increasing total stem mass. Since heartwood cells are inactive, while the ray parenchyma cells of the sapwood are active, stem maintenance respiration virtually results from the sapwood (RYAN, 1990; SPRUGEL, 1990). Maintenance respiration is proportional to sapwood amount, whereas growth respiration is related to growth rate (*e.g.*, HESKETH *et al.*, 1971; AMTHOR, 1989). Because sapwood to heartwood ratio declines with stem growth, in pursuing respiration of woody plants, especially maintenance respiration, sapwood mass but not total stem mass should be considered. Thus accurate estimation of sapwood amount is important for the assessment of energy cost of storage and stem growth.

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ヒノキ若齢木の幹に占める辺材の割合

Stephen ADU-BREDU・萩原秋男

幹の材のうち，周辺部にある辺材は，水分の通道組織として，また，養分の貯蔵組織として機能している。この生きた柔組織を維持するためにはエネルギーが必要となり，幹の中心部の死んだ細胞である心材とは区別されるべきである。12年生ヒノキの14本のサンプル木をもとに，辺材の量が樹木のサイズに関連して調べられた。個体当たりの辺材重は幹材積とべき乗関係にあった。任意の位置での辺材の断面積と樹皮を含んだ幹総断面積との間には，拡張された相対成長関係が認められた。単位生材積当たりの乾燥幹重である容積密度数は，辺材で0.4154 g cm^{-3} であった。個体の辺材重の割合は，幹重が増加するにつれて減少する傾向にあった。求められた実験式により，任意の位置での辺材重を精度良く推定することが可能になった。

キーワード：断面積，容積密度数，心材，ヒノキ，辺材

Appendix 1. Characteristics of the sample discs.

Tree no.	Section (m)	A_{OB} (cm^2)	A_{UB} (cm^2)	A_{SW} (cm^2)	v (cm^3)	w (g)
1	0.0	94.72	82.00	54.91	146.6	56.97
	0.3	89.31	67.85	46.63	149.7	75.37
	1.3	49.74	41.01	37.38	103.2	40.43
	2.3	32.79	26.07	24.77	61.91	25.11
	3.3	16.50	12.04	11.80	31.38	10.94
	4.3	4.476	3.158	3.158	7.296	3.490
	C_B	55.04	46.22	35.14	82.23	32.67
2	0.0	71.14	61.50	54.42	136.6	49.99
	0.3	61.50	52.97	50.31	144.4	53.31
	1.3	42.46	36.79	35.17	83.71	28.01
	2.3	31.83	26.60	25.09	72.75	27.52
	3.3	17.91	14.29	13.62	28.87	10.98
	4.3	6.163	4.358	4.358	8.628	3.803
	C_B	46.99	41.01	39.60	105.3	39.60
3	0.0	63.73	52.56	37.41	93.51	40.78
	0.3	50.94	43.57	32.87	112.1	48.09
	1.3	40.29	31.51	26.23	85.77	38.02
	2.3	24.93	20.12	17.75	55.22	23.23
	3.3	14.29	11.08	10.91	23.12	9.316
	4.3	3.789	2.865	2.865	4.927	2.373
	C_B	32.79	25.78	19.65	44.60	19.20
4	0.0	60.62	48.55	40.351	119.4	57.69
	0.3	48.16	39.57	37.50	123.8	55.47
	1.3	35.09	28.73	26.63	82.56	37.69
	2.3	26.07	20.12	18.94	49.62	22.15
	3.3	11.84	9.111	8.281	17.14	7.625
	4.3	5.221	3.362	3.362	7.565	3.795
	C_B	33.44	27.83	25.55	59.79	26.63
5	0.0	63.28	49.34	34.94	89.11	39.87
	0.3	45.84	37.47	30.14	84.39	37.74
	1.3	31.83	26.94	24.64	58.64	23.16
	2.3	21.14	18.14	16.69	40.55	15.70
	3.3	12.84	9.455	8.785	20.91	9.148
	4.3	4.596	3.059	3.069	5.812	2.846
	C_B	27.83	22.19	19.72	43.97	17.82

Tree no.	Section (m)	A_{OB} (cm^2)	A_{UB} (cm^2)	A_{SW} (cm^2)	v (cm^3)	w (g)
6	0.0	71.62	59.31	45.44	116.8	48.83
	0.3	51.75	41.37	37.44	86.10	36.19
	1.3	30.26	23.00	22.35	51.86	21.67
	2.3	16.27	13.45	13.05	28.59	12.02
	3.3	5.615	4.476	4.476	10.34	4.668
	4.3	1.611	1.089	1.089	2.876	1.497
	C_B	29.03	22.73	22.30	64.88	27.07
7	0.0	50.94	41.37	33.91	74.94	28.50
	0.3	38.52	30.88	28.13	62.73	24.20
	1.3	24.93	18.87	17.05	35.13	14.11
	2.3	14.72	11.84	10.95	22.56	8.539
	3.3	7.032	5.221	4.734	11.15	4.444
	4.3	1.338	0.815	0.815	2.636	1.46
	C_B	41.01	31.83	28.37	79.71	31.19
8	0.0	49.34	40.29	27.49	59.38	23.33
	0.3	37.82	30.26	22.22	54.00	20.27
	1.3	25.50	21.143	14.52	33.63	12.11
	2.3	16.05	11.84	10.41	27.16	11.31
	3.3	6.735	4.718	4.494	9.571	3.480
	4.3	1.471	0.975	0.830	1.726	0.778
	C_B	29.64	23.27	18.30	48.50	19.73
9	0.0	50.54	41.37	28.63	64.43	26.60
	0.3	40.65	33.12	28.02	55.49	22.22
	1.3	24.93	19.87	16.76	31.00	13.11
	2.3	15.16	11.65	9.540	16.60	6.871
	3.3	7.182	5.482	5.164	8.675	3.496
	4.3	1.031	0.669	0.669	1.620	0.911
	C_B	16.96	13.66	10.74	22.02	8.733
10	0.0	39.57	27.53	22.18	44.14	19.92
	0.3	26.65	19.87	18.66	37.87	16.66
	1.3	20.37	15.16	14.67	29.77	12.76
	2.3	14.08	10.34	10.04	22.49	9.696
	3.3	6.023	4.596	4.596	6.573	2.827
	C_B	19.37	14.50	14.24	23.50	10.10

Tree no.	Section (m)	A_{OB} (cm^2)	A_{UB} (cm^2)	A_{SW} (cm^2)	v (cm^3)	w (g)
11	0.0	33.12	26.07	24.81	53.09	19.62
	0.3	24.37	19.87	19.61	35.50	12.71
	1.3	16.27	13.04	12.89	24.48	9.167
	2.3	9.982	7.643	7.588	14.80	5.541
	3.3	4.476	3.158	3.158	6.822	2.961
	C_B	24.93	19.62	19.36	39.10	14.84
12	0.0	26.36	19.12	18.58	41.25	19.54
	0.3	18.14	13.66	13.51	34.45	15.45
	1.3	10.34	7.334	7.276	13.39	5.916
	2.3	3.466	2.407	2.407	8.522	4.505
	C_B	17.67	12.43	12.35	28.40	12.66
13	0.0	18.87	14.72	13.74	27.63	11.56
	0.3	12.43	9.455	9.251	15.73	6.53
	1.3	8.773	6.590	6.139	10.07	4.243
	2.3	6.303	4.476	4.476	8.192	3.665
	3.3	1.611	1.273	1.273	1.923	0.841
14	0.0	13.45	9.805	9.653	18.63	8.132
	0.3	9.805	7.334	7.334	20.32	8.973
	1.3	6.446	4.842	4.842	8.569	3.587
	2.3	4.476	2.770	2.770	5.762	2.817
	3.3	0.497	0.385	0.385	0.871	0.428
	C_B	6.590	4.842	4.842	13.51	5.657

A_{OB}, over-bark stem cross-sectional area ; A_{UB}, under-bark stem cross-sectional area ; A_{SW}, sapwood cross-sectional area ; v, sapwood volume per disc ; w, sapwood mass per disc ; C_B, crown base.