ヒノキ林木の幹の呼吸について

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論　文

Respiration in Stems of Hinoki (*Chamaecyparis obtusa*) Trees

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MORI, Shigeta and HAGIHARA, Akio: **Respiration in stems of hinoki (*Chamaecyparis obtusa*) trees J. Jpn. For. Soc. 70: 481～487, 1988** The respiration rates of stem segments of hinoki trees were examined in relation to their circumferences. The respiration rates per unit length of stem segments were dependent on both their circumferences and the sizes of the trees from which they were taken. The relationship between the respiration rate on a length basis and stem circumference in a tree commonly consisted of three different sections, each of which was approximated by a straight line. On the basis of the relationship, a new equation is proposed to estimate the total stem respiration of a tree. The observed data fitted well with the relationship of the respiration rate per unit weight to the stem circumference and with the relationship of the respiration rate of the surface area to the stem circumference, both of which were converted from the relationship of the respiration rate per unit length to the stem circumference with consideration of the weight and surface area, respectively, of the stem segments. The respiration rate per unit length of stem segments had the closest connection with annual stem volume increment among these three kinds of respiration rates of different dimensions; it was approximately proportional to the stem volume increment, irrespective of both the circumference of the stem segments and the size of mother trees.

森　茂太・萩原秋男：**ヒノキ林木の幹の呼吸について　日林誌70：481～487，1988**　ヒノキ（*Chamaecyparis obtusa*）林で，幹の切断材の呼吸速度と切断材の周囲長の関係を調べた。切断材の長さ当りの呼吸速度は切断材の周囲長，切断材を採集した木のサイズの両方に依存していた。1本の木において，長さ当りの呼吸速度と周囲長の関係は一般に直線で近似される3つの部分から成り立っていた。この関係をもとにして，単木の幹の呼吸速度を推定する式を提案した。切断材の表面積と重量を考慮して，切断材の長さ当りの呼吸速度と周囲長の関係を，重量当りの呼吸速度および表面積当りの呼吸速度と周囲長の関係に変換した。測定値はこれらの変換された関係によく適合した。3つの異なった単位の呼吸速度の中で，長さ当りの呼吸速度が年間の材積成長量と最も深い関係にあった。切断材の周囲長および短材の採取木のサイズにかかわりなく，切断材の長さ当りの呼吸速度は，ほぼその材積成長量に比例していた。

I. Introduction

Because stems account for the largest part of the forest biomass, dry-matter budgets in forest communities are affected remarkably by the respiratory consumption of the stems. Therefore, many studies have attempted to understand the characteristics of stem respiration (NEGISI, 1977). To estimate stand respiration, YODA and others (1965, 1968) and YODA (1978) have formulated the relationship between the respiration rate per unit weight and the circumference of stem segments. On the other hand, for broadleaved trees such as *Ilex pedunculosa* Miq. and *Sapium sebiferum* (L.) Roxb. that the respiration rate on a length basis varies with the circumference of stem segments following a certain regularity (NAKAI and YODA, 1968; NAKAI, 1969).

We analyzed stem respiration rates on a length basis in relation to the stem circumferences for coniferous trees of hinoki (*Chamaecyparis obtusa* (Sieb. and Zucc.) Endl.). On the basis of the relationship between the two quantities, we suggest a new equation to estimate the stem respiration of a tree.

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Table 1. Some characteristics of sample trees

Sample No.	Sampling date	Stem girth at breast height [cm]	Tree height [m]	Stem weight [kg (fresh wt) tree^{-1}]
1	17 Nov. 1982	41.8	12.1	67.4
2	16 Nov. 1982	33.2	10.4	43.1
3	16 Nov. 1982	21.4	9.2	17.9
4	15 Nov. 1982	18.3	7.0	9.9
5	18 Nov. 1982	12.2	5.2	3.3

The respiration rate on a length basis can be converted to that on a weight basis or on a surface area basis. We examine the interrelationships among these three kinds of respiration rates of different dimensions, as related to the circumference of stem segments. Furthermore, we discuss the relationships between these respiration rates and stem growth.

II. Material and Methods

This study was conducted in a 26-year-old *C. obtusa* plantation (as of 1982) of the Nagoya University Forest at Inabu, Aichi Prefecture. The plantation was located at an elevation of 1000 m on a 35° slope with a north exposure. Tree density, mean tree height, mean stem diameter at breast height (1.3 m above the ground), and stem biomass were 6039 trees ha^{-1}, 8.7 m, 8.6 cm, and 85 t (dry wt) ha^{-1}, respectively.

Respiration measurements were made on five sample trees representing the size class distribution in November 1982 (Table 1). Fresh weights of stems were measured after the sample trees had been felled and attached branches had been cut off from the sample trees. The stem of each sample tree was cut into segments for determining their respiration rates. After the determination, the fresh weight, circumference at the center, and length of these segments, which ranged between 8 and 85 cm, were measured.

One-hundred tin cylinders of three different sizes (12.7, 4.4, and 2.8 liters) were prepared for the stem segments of various sizes. Immediately after the cut surfaces of the segments had been sealed with vaseline paste to prevent CO_2 changes, each segment was enclosed in a tin cylinder of an appropriate size. However, segments whose lengths were longer than 35 cm were cut into two or three pieces to be kept in a tin cylinder. Each cylinder had a petri dish containing 25 ml of a KOH solution to absorb CO_2. At the same time, blank tests were made to take into account extraneous factors which could cause a chemical reaction of the KOH solution. The concentration of the KOH solution was 0.2 N throughout this experiment. To keep air-tightness, the lid of each cylinder was sealed with adhesive tape. The cylinders were placed on the forest floor under dense tree-crowns to make the range of temperatures as small as possible. Thermometers were set in the cylinders. Mean values of maximum and minimum temperature readings were used for determining average temperatures during the period of enclosure. Average temperatures ranged from 7.6 to 9.4°C in this experimental period, during which it did not rain.

After an appropriate period of enclosure (about 16 h), the KOH solution was poured into plastic bottles. The bottles were taken to the laboratory, where the KOH solution was titrated with a HCl solution of 0.073 N. The respiration rates were calculated according to the procedures proposed by KIRITA and HOZUMI (1966).

Annual volume and circumference increments of stem segments were estimated from readings of the annual rings of the last 5 years at both ends of the segments.

III. Results

1. *Relationship between the respiration rate and circumference of stem segments*

Figure 1 shows that in each sample tree the respiration rate per unit length of stem segment, r_l (mg (CO_2) dm^{-1} h^{-1}), varies with the circumference at the center of the segment, x (cm). Although there is an exception, it may be recognized that the relationship is made up of three different sections approximated by

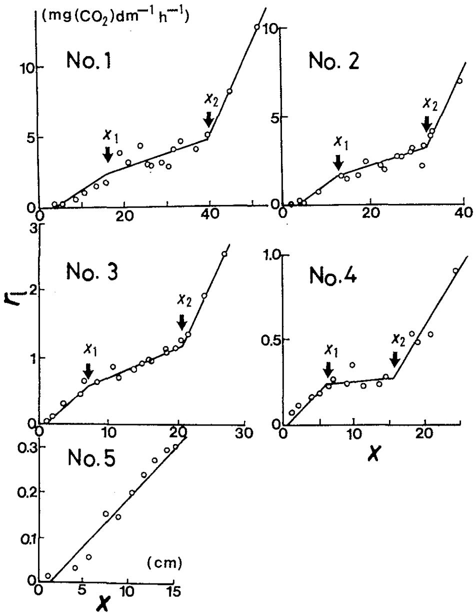

Fig. 1. Relationship between the respiration rate of a stem segment 10 cm long r_l (mg (CO_2) $dm^{-1}h^{-1}$) and its circumference x (cm)

The solid lines show approximations by Eq.(1). The numerals refer to sample tree numbers. The symbols x_1 and x_2 are the abscissas of intersections of the lines.

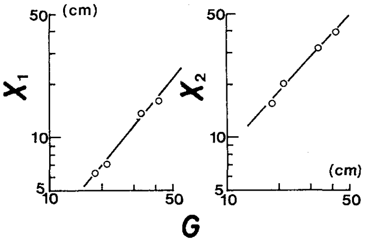

Fig. 2. Dependence of the abscissas of intersections in Eq. (1), x_1 and x_2 (cm), on stem girth 130 cm above the ground, G (cm)

The straight lines are approximations based on Eq.(2).

a series of straight lines,

$$r_l=\begin{cases} a_1x+b_1 & \text{when } x_{\min}\leqq x\leqq x_1, \\ a_2x+b_2 & \text{when } x_1<x<x_2, \\ a_3x+b_3 & \text{when } x_2\leqq x\leqq x_{\max}, \end{cases} \qquad (1)$$

where a_1, a_2, a_3, b_1, b_2, and b_3 are coefficients specific to a sample tree, and x_1 and x_2 are the abscissas of intersections of the lines. The symbol $x_{\min}$ stands for the observed minimum circumference of the sample tree. The symbol $x_{\max}$ stands for the maximum stem circumference which was estimated by extrapolating the stem taper between 130 and 30 cm above the ground (YODA and others, 1965). The exceptional case was where the relationship was approximated by a single straight line (Sample No. 5), observed in the smallest sample tree. The same tendencies have been reported by NAKAI and YODA (1968) for woody organs such as stems, branches, and roots of *S. sebiferum* and *I. pedunculosa.*

The values of the abscissas x_1 and x_2 were plotted against G, the stem girth at breast height of mother trees (Fig. 2). The results were formulated by

$$x_1=0.175G^{1.23}, \text{ and}$$
$$x_2=0.652G^{1.11}. \qquad (2)$$

The stem circumferences of a given tree which corresponds to the abscissas of the intersections in Eq. (1) can be found on the basis of Eq. (2). This suggests the possibility of estimating the stem respiration of a tree only by knowing the respiration rates at the positions of these two stem circumferences in addition to rates at the stem circumferences below x_1 and above x_2 (MORI and others, 1985).

2. Estimate of the stem respiration of a tree

The stem respiration per tree, R (mg (CO_2) $tree^{-1}h^{-1}$), is defined as the definite integral with respect to h, ranging from 0 to tree height H (dm) : namely,

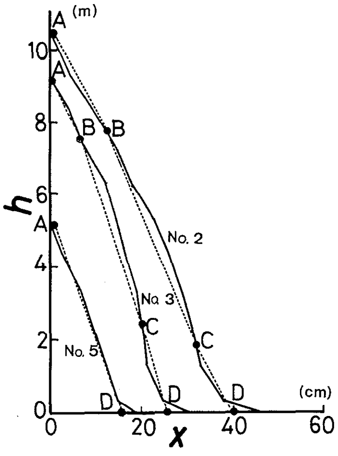

Fig. 3. Examples of the approximated (broken lines) and observed (solid lines) stem profiles

The points A, B, C, and D have coordinates ($x_{\min}$, H), (x_1, h_1), (x_2, h_2), and ($x_{\max}$, 0), respectively. The symbols are defined in the text.

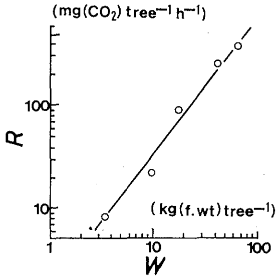

Fig. 4. Changes in the stem respiration of a tree, R (mg (CO_2) tree^{-1} h^{-1}), as related to the corresponding stem fresh weight, W (kg (fresh wt) tree^{-1})

The data were fitted to Eq.(5) : $R=1.5W^{1.3}$.

$$R=\int_0^H r_l dh, \tag{3}$$

where h (dm) is a height above the ground.

As shown in Fig. 3, it seems that a stem profile is divided into sections matching those appearing in Eq. (1). Assuming that each of the sections is expressed in a straight line, Eq. (3) is written as

$$R=(H-h_1)(a_1(x_{\min}+x_1)+2b_1)/2+(h_1-h_2)(a_2(x_1+x_2)+2b_2)/2+h_2(a_3(x_2+x_{\max})+2b_3)/2, \tag{4}$$

where h_1 and h_2 are heights above the ground at the positions corresponding to x_1 and x_2 in Eq. (1), respectively. The first, second, and third terms represent the respiration for the upper, middle, and lower parts of a stem, respectively. The respiration of each part is obtained by multiplying the average value of respiration rates at both ends of the part (that is, the respiration rate at the center of the part) by the corresponding stem length. In the case of an approximation by a single straight line, the respiration per tree is given by the first term where x_1 and h_1 are substituted by $x_{\max}$ and 0, respectively.

3. *Dependence of the stem respiration per tree on its size*

As illustrated in Fig.4, the respiration per tree, R, calculated from Eq.(4), can be related to the stem weight per tree, W (kg (fresh wt) tree^{-1}), in the power function,

$$R=AW^B, \tag{5}$$

where A and B are coefficients. The same relationship has been noticed for young *Pinus densiflora* S. and Z. (NEGISI, 1974) and *P. densi-thunbergii,* Uyeki (NINOMIYA and HOZUMI,1981) trees, and *C. obtusa* seedlings (OGAWA and others, 1985).

On the basis of Eq.(5), the stand respiration of stems can be assessed from the weight of individual trees, which is estimated by means of an allometric relationship between the fresh stem weight and the stem girth at breast height. The estimated respiration was 1.1 kg (CO_2) ha^{-1}h^{-1}, and the specific respiration rate per unit biomass was 0.014 kg (CO_2) t (d. wt)$^{-1}$h^{-1}, for the stem biomass of 81 t (d. wt) ha^{-1} in November 1982. The estimate was similar to the value of 0.017 kg (CO_2) t (d. wt)$^{-1}$h^{-1} of respiration per unit biomass of stems which was obtained by HAGIHARA and HOZUMI (1981) in November 1974 for the same stand when the stem biomass was 37 t (d. wt)ha^{-1}.

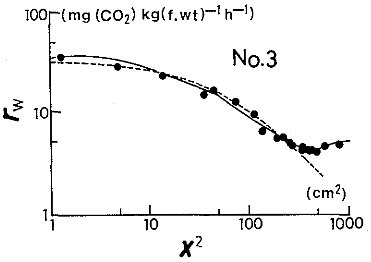

Fig. 5. An example of the relationship between the respiration rate per unit weight of stem segment, r_w (mg (CO$_2$) kg (fresh wt)$^{-1}$ h^{-1}), and its circumference squared, x^2 (cm^2)

The dashed line is an approximation by Eq.(7), where the data of the thicker part of the stem are omitted. The solid line corresponds to the r_w-x^2 relationship which is obtained from Eq.(1) by considering Eqs.(8) and (9).

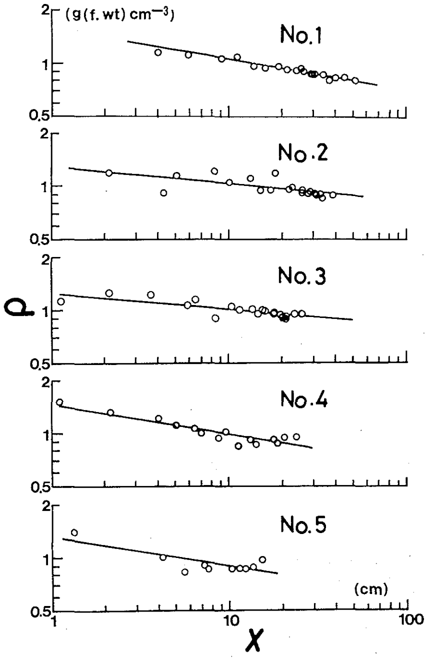

Fig. 6. Density of stem segment ρ (g (fresh wt) cm^{-3}) relating to its circumference x (cm)

The data are fitted to Eq.(9).

IV. Discussion

In this report, the effect of stem cutting on respiration rates (EVANS, 1972) was not examined. However, OOHATA and others (1967) and OGAWA and others (1985) have pointed out that the effect is not very serious in stems of hinoki trees.

The respiration rate of woody organs on a weight basis depends on their circumference (MÖLLER and others, 1954). YODA and others (1968) and YODA (1978) have formulated the relationship between the two quantities for stems using a hyperbolic equation,

$$1/r_w = ax^2 + b, \qquad (7)$$

where r_w and x are the respiration rate per unit weight and the circumference of stem segments, respectively, and a and b are coefficients characteristic of a sample tree. HAGIHARA and HOZUMI (1981) confirmed the above relationship in this plantation. However, the present results inadequately fit the data to Eq.(7) for the thicker part of stems, as shown in Fig.5.

Respiration rates on a length basis can be connected with respiration rates on a weight basis by the following equation:

$$r_w = r_l/w, \qquad (8)$$

where w is the fresh weight of a stem segment, one decimeter in length. Figure 6 indicates that the density ρ increases upward from about 0.8 at the bottom to about 1.4 g (f. wt) cm^{-3} at the top of stems. As a result, ρ was correlated closely with x as

$$\rho = \alpha x^{-\beta}, \qquad (9)$$

where α and β are coefficients specific to each sample tree. Considering Eqs.(1), (8), and (9) leads to the r_w-x^2 relationship.

The converted r_w-x^2 relationship fitted well the observed data over the entire range of stem circumfer-

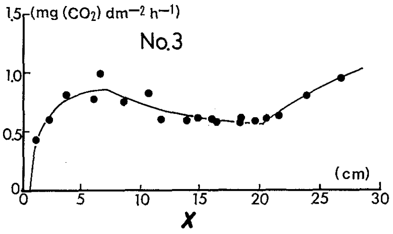

Fig. 7. An example of the relationship between the respiration rate on a surface area basis, r_a (mg(CO$_2$) dm^{-2}h^{-1}), and the circumference, x (cm), of a stem segment

The curve corresponds to the r_a-x relationship converted from Eq.(1) by considering Eq.(10).

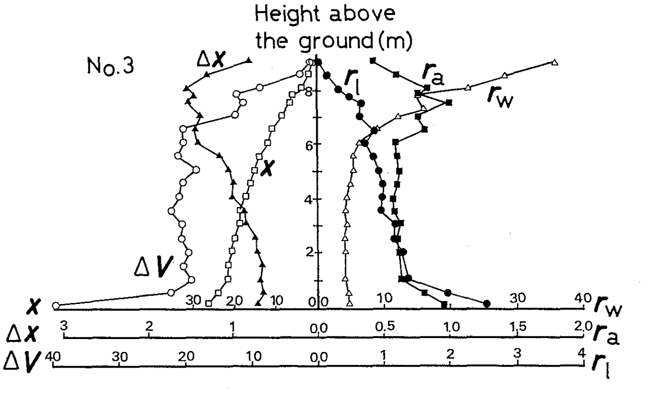

Fig. 8. Examples of vertical variations in different respiration rates, namely, r_l(●), r_w(△), and r_a(■), and stem volume growth Δv(○), circumference growth Δx(▲), and stem circumference x (□)

Units of respiration rates r_l, r_w, and r_a, and those of x, Δx, and Δv were as follows: r_l, mg (CO$_2$) dm^{-1}h^{-1}; r_w, mg(CO$_2$)kg(fresh wt)$^{-1}$ h^{-1}; r_a, mg(CO$_2$)dm^{-2}h^{-1}; x, cm; Δx, cm yr^{-1}; Δv, cm^{3}dm^{-1}yr^{-1}.

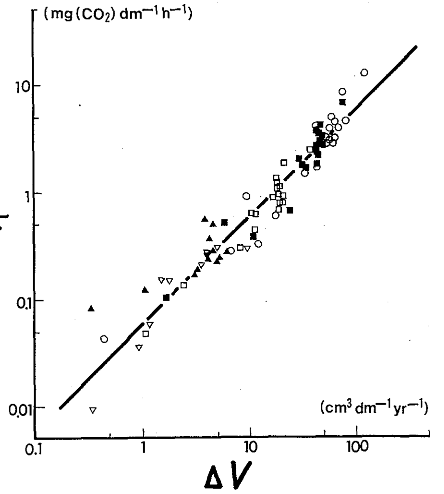

Fig. 9. Proportionality of the respiration rate on a length basis r_l (mg(CO$_2$) dm^{-1}h^{-1}) to the volume increment Δv (cm^{3}dm^{-1} yr^{-1})

The straight line shows the equation $r_l=0.058\Delta v$.
Legend: ○, Sample No. 1; ■, No. 2; □, No. 3; ▲, No. 4; ▽, No. 5.

ences, as exemplified in Fig.5. On the basis of Eq.(4), the respiration of Sample No.3 was estimated to be 5.6, 46, and 41 mg (CO$_2$) h^{-1}, respectively, for the upper, middle, and lower parts, totaling 93 mg (CO$_2$) tree^{-1}h^{-1}. The respiration of the lower part has a 44% share of the total stem respiration. Thus, it may be necessary to examine closely the respiration rate in the thicker part of stems for estimating the stem respiration of a tree.

Respiration rates on a length basis, r_l, also can be converted into those on a surface area basis, r_a, by the following equation:

$$r_a=r_l/u, \qquad (10)$$

where u is the surface area of a stem segment, one decimeter in length. Figure 7 shows an example of the r_a-x relationship where the respiration rate on a surface area basis in the lower and upper parts of a stem increases with increasing x, and the rate in the middle part decreases with increasing x. Similar tendencies in respiration rates have been reported for stems of *Fagus silvatica* L. (MÖLLER and others, 1954), *S. sebiferum* (NAKAI and YODA, 1968), and *P. densiflora, Cryptomeria japonica* D. DON, and *Chamaecyparis obtusa* (OOHATA and others, 1971). Therefore, these tendencies seem to be common for stems of woody species.

Figure 8 shows comparative compilations of three respiration rates of different dimensions together with stem circumferences, their increment, and stem volume increment. It seems that there is a closer correlation between r_l and the stem volume increment Δv.

Figure 9 indicates that r_l is approximately proportional to Δv, irrespective of both the position of sample segments and the size of mother trees. OOHATA and others (1971) found the proportional relationship in the three species listed above. The cause of proportionality is not sufficiently clear. However, GOODWIN and GODDARD (1940) pointed out that respiration in stems is concentrated mainly in the cambium and its adjacent tissues. Thus, the linearity between r_l and Δv seems to be reasonable.

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