

林木の生長過程を考慮した生産構造図の新たな解釈とその有用性

誌名	日本林學會誌 = Journal of the Japanese Forestry Society
ISSN	0021485X
著者	千葉, 幸弘 藤森, 隆郎 清野, 嘉之
巻/号	70巻6号
掲載ページ	p. 245-254
発行年月	1988年6月

Another Interpretation of the Profile Diagram and Its Availability with Consideration of the Growth Process of Forest Trees

Yukihiro CHIBA,* Takao FUJIMORI,* and Yoshiyuki KIYONO***

CHIBA, Yukihiro, FUJIMORI, Takao, and KIYONO, Yoshiyuki : **Another interpretation of the profile diagram and its availability with consideration of the growth process of forest trees** *J. Jpn. For. Soc.* 70 : 245~254, 1988 The plant form is well expressed by the pipe model theory led by the relationship between the amount of leaves on the surface of a stand to a certain depth z , $F(z)$, and the quantity of non-photosynthetic organs at that depth, $C(z)$. Although the profile diagram of the production structure represents a contrast of photosynthetic and non-photosynthetic organs at a given time, considering the growth process of plants, especially forest trees, $C(z)$ is considered as an accumulation of annual increments of non-photosynthetic organs. Premising that the leaf density of the crown (or canopy) of a closed stand would not vary during a definite period, $F(z)$ can be regarded as the amount of leaves, having been sustained at the z -horizon while the tree height increased z from that horizon. Also, it should be reasoned that the quantity of non-photosynthetic organs at the crown bottom, $W\sigma$, represents the last increment of non-photosynthetic organs, considering the accumulating process of $C(z)$. Then it would be indicated from this hypothesis that the specific pipe length L has a dimension of time and that the reciprocal of L seems to be equivalent to leaf efficiency. As a result of the examinations of individual trees, these hypotheses were ascertained; a stem's weight for 1 m of length at the crown bottom was nearly equal to the last increment of all non-photosynthetic organs. Using $W\sigma$, an estimation method of forest productivity can be improved more effectively.

千葉幸弘・藤森隆郎・清野嘉之：林木の生長過程を考慮した生産構造図の新たな解釈とその有用性 日林誌 70 : 245~254, 1988 パイプモデルは、林分表面からある深さ z までの積算葉量 $F(z)$ とその深さにおける非同化部量 $C(z)$ との直線関係から導かれたもので、それは植物形の特徴を端的に表現している。生産構造図はある時点における同化部と非同化部を対比して表すものであるが、植物とくに林木の生長過程を考慮すれば $C(z)$ は非同化部の毎年の生長量の蓄積とみなすべきである。樹冠（林冠）の葉量密度がある高さを通する間変化しなければ、 $F(z)$ は、樹高がある高さに達してから z だけ樹高生長する間に、その高さで支え続けてきた葉量の合計とみなすことができる。また樹冠直下の非同化部量 $W\sigma$ は、 $C(z)$ が生長量の蓄積であることから、非同化部の生長量に相当すると推論される。この推論から、 $F(z)$ と $C(z)$ の比である比パイプ長は時間の次元をもち、その逆数は葉の能率に等しいであろうと考えられる。スギとヒノキの単木について検討した結果、これを裏づける事実が確かめられ、樹冠直下 1m の長さの幹重は非同化部全体の 1 年間の生長量にほぼ等しかった。 $W\sigma$ を用いることによって森林生産力の推定法をより簡便で効果的なものに改善できるであろう。

I. Introduction

To analyze the stand structure of terrestrial plants, MONSI and SAEKI (1953) developed the concept of dry matter production from BOYSEN-JENSEN (1932) and proposed the stratified clip method. The profile diagram, a description of the stratified clip method, shows the contrast of the vertical distribution of the amount of leaves and non-photosynthetic organs within a plant community.

Noticing that the profile diagrams of various kinds of plant communities have similarities in spite of

* For. and Forest Prod. Res. Inst., Ibaraki 305 林業試験場

** Present address : Kansai Branch, For. and Forest Prod. Res. Inst., Kyoto 612 林業試験場関西支場

differences even in forest and weed communities, SHINOZAKI *et al.* (1964 a, b) explained one of the fundamental characteristics of plants by proposing the pipe model theory : that is, a unit quantity of leaves is supported by a unit pipe which has a constant cross-sectional area and which connects the leaves downward to the stem base. This model gives important information from the view point of exactly estimating the quantity of leaves, photosynthesis, and respiration of forest stands (NINOMIYA and HOZUMI, 1978 ; OOHATA *et al.*, 1971 ; YODA *et al.*, 1965). OOHATA and SHINOZAKI (1979) made a further analysis of the pipe model theory while static and pointed out that the tree form is made up so as to keep it reasonable, economical, and efficiently statical.

As the pipe model theory and the statical model are irrespective of plant sizes, species, and even herbs or woody plants, the results obtained by them have universal applications. However, a quantitative analysis in order to link up the two parts, above and under the crown (canopy), has not been made yet, and the meaning of the specific pipe length in the pipe model theory still remains vague.

In the growth process of plants, of all products assimilated by foliage some are consumed to maintain life activity, that is, respiration and other metabolism, and the remaining products are accumulated in non-photosynthetic organs, which may be recognized as growth. The growth process of plants has never been considered concretely in developing both of these theories.

In this paper, we propose another interpretation of the profile diagram by considering the growth process, and suggest the possibility of estimating forest productivity more easily than by other methods.

II. General Conception of the Pipe Model Theory

The profile diagram of a terrestrial plant community represents the vertical distribution of the quantity of leaves, $\Gamma(z)$, and of the non-photosynthetic tissues, $C(z)$, contained in a certain stratum of unit thickness, (Δz) (Fig. 1A), defining z as the depth from the surface of the community downward. There is a close relationship between the accumulated quantity of leaves, $F(z)$, and $C(z)$ (Fig. 1B) :

$$F(z) = \int_{TOP}^z \Gamma(z) dz. \tag{1}$$

Here we obtain a proportional relationship between the two as follows :

$$F(z) = L \cdot C(z) \tag{2}$$

where the constant of proportionality L is called "the specific pipe length" (SHINOZAKI *et al.*, 1964 a). Defining $S(z)$ and ρ as the total cross-sectional area of stems and branches in the z -horizon and as specific gravity, respectively, and presuming that ρ has a constant value, we obtain the following equation as shown by HOZUMI (1981) :

$$C(z) = A \cdot S(z) \cdot \rho \cdot \Delta z \tag{3}$$

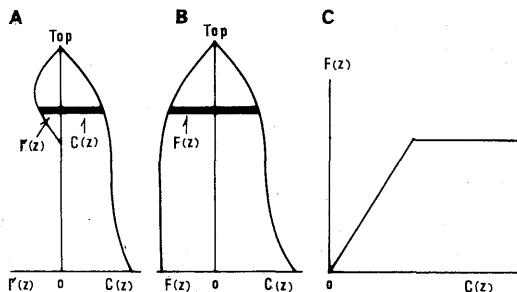


Fig. 1. Vertical distributions of Γ , C , and accumulated leaf quantity F , and their interrelation according to the Pipe Model Theory of Plant Form (SHINOZAKI *et al.*, 1964 a)

where A is a constant. From Eqs. (2) and (3), the leaf quantity is in proportion to the cross-sectional area of the non-photosynthetic organs sustaining it.

Based on this relationship, SHINOZAKI *et al.* (1964 a) constructed the concept of the unit pipe system, consisting of a unit quantity of leaves and a pipe sustaining it. They concluded that plant communities were made up from a number of unit pipes, and that the non-photosynthetic tissues of a plant were an assemblage of these unit pipes. The pipes serve both as vascular passages and as mechanical supports, running through all of the

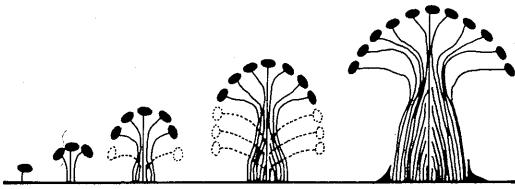


Fig. 2. Diagrammatic representation of the pipe model of tree form showing the successive accumulation of disused pipes in the trunk associated with the progress of tree growth (SHINOZAKI *et al.*, 1964 a)

intervening strata from the leaves to the stem bases.

However, we can find an increase of non-photosynthetic organs even in the lower strata of a community where no leaves exist, especially in woody plants (shown as a horizontal line in Fig. 1C). This phenomenon has been explained from the hypothesis that the disused pipes, which were once connected with living leaves which were shed as the tree grew, remain in the trunk as they are. This hypothesis is called "the pipe model theory of tree form." SHINOZAKI *et al.* (1964 a) diagrammatically showed this concept (Fig. 2).

III. Another Interpretation on the Profile Diagram

Some reports on the vertical distributions of stem increment have been made (SAITO *et al.*, 1968 ; SHIDEI and TADAKI, 1960 ; TADAKI, 1965 ; TADAKI, 1966 ; TADAKI and KAWASAKI, 1966). It is common in these reports that even in the lower range where leaves are absent, stems grow in thickness, and the increment at different heights in the forest is distributed equally (simplified model shown in Fig. 3A). Therefore, non-photosynthetic organs increase by accumulating assimilated products by means of translocation (Fig. 3B), and they continue to grow in thickness so as to maintain leaves and to be an individual tree.

Defining H^* as the height of a tree at the present time (t^*), we imagine the z -horizon which exists at a distance of z downward from the top of the tree. The z -horizon is standardized against the H^* so that it should be independent of time. $C(z)$ is the cumulative amount of annual increment of non-photosynthetic tissues at the present time which has accumulated since the tree height reached the z -horizon. Defining the increment density of non-photosynthetic tissues at the z -horizon at time $t(t \leq t^*)$ by $\Delta y(t, z)$, we can represent $C(z)$ as follows :

$$C(z) = \int_0^{t^*} \Delta y(t, z) dt \tag{4}$$

where $t=0$ indicates the time of germination of the seed which became the tree, and the dimensions of

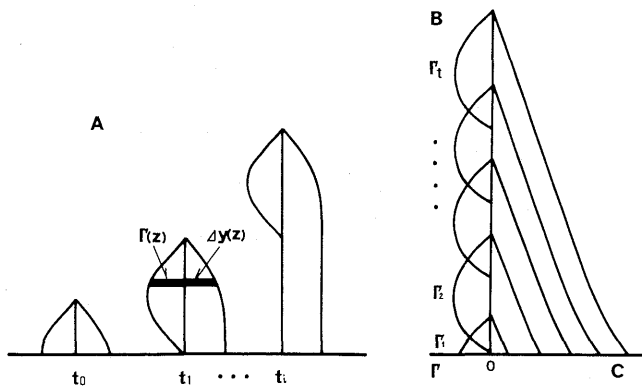


Fig. 3. Simplified model of an accumulating process of non-photosynthetic organs with height growth

A : Vertical distributions of Γ and Δw , B : Accumulation of Δw with height growth.

$\Delta y(t, z)$ and $C(z)$ are $[g \cdot m^{-1} \cdot yr^{-1} \cdot tree^{-1}]$ and $[g \cdot m^{-1} \cdot tree^{-1}]$, respectively.

Concerning leaf demography, once leaves emerge at a certain position, the quantity of leaves will increase as the plant grows. However, the position of the leaves will never move upward even if the plant increases in height. Therefore, the leaves at their initial position will eventually wither and others will not regenerate there again because of insufficient light intensity due to the shade of the living leaf-mass above them. The leaf density, as well as the increment density of non-photosynthetic tissues, can be defined as a function with respect not only to the depth z but also to the time t . Then, we propose another interpretation of the accumulated leaf quantity than that of SHINOZAKI *et al.* (1964 a).

Defining the leaf density in the z -horizon at time t ($t \leq t^*$) by $\Gamma(t, z)$, $F(z)$ at the present time t^* is given by

$$F(z) = \int_0^z \Gamma(t^*, z) dz \tag{5}$$

whose dimension is $[g \cdot tree^{-1}]$ (Fig. 4A), which is the same as that of SHINOZAKI *et al.* With consideration of the growth process, especially of leaf density in the crown, the leaf quantity $f(z)$, having been sustained at the z -horizon while the tree height increased z from that horizon (z -horizon), can be represented as follows (Fig. 4B) :

$$f(z) = \int_{t_z}^{t^*} \Gamma(t, z) dt \tag{6}$$

where t_z is the time when the tree height reached the z -horizon. The dimension of $f(z)$ is $[g \cdot yr \cdot m^{-1} \cdot tree^{-1}]$. The $f(z)$ should include the leaf amount which has died and fallen already. Here we must pay attention to the proposition that if the leaf density $\Gamma(t, z)$ should never vary, the following relationship can be obtained :

$$F(z) = f(z). \tag{7}$$

To judge the propriety of the proposition, the shift of leaf distribution in forest stands must be discussed.

There is a tendency for the leaf quantity of a closed stand to have a constant value in certain species (SATO *et al.*, 1955 ; MÖLLER, 1945) even if some conditions, for example, stand density, stand age, and so forth, are different. TADAKI (1966) pointed out that leaf-mass in a closed stand seems to be similar not only for the same species but also for related species, and furthermore for the same plant formations such as deciduous, evergreen, broadleaved, or needle-leaved forests. He also said that light is a limiting factor for increasing leaves, and the optimum leaf-mass seems to depend upon it.

Accordingly, unless the stand is very dense or conversely very sparse, or unless it is almost at climax, it

may be conceivable that the leaf density in a stand hardly varies except for a shift in the vertical direction during such a restricted time that the leaf density rises upward a distance equivalent to the crown (or canopy) depth with height growth, and the crown (or canopy) bottom rises in proportion to the increase in tree height. This hypothesis, however, should be on the premise of a period of time restriction because the distribution of leaf density would be different over so long a term.

With these assumptions, $f(z)$ should be equal to $F(z)$. Note that although the accumulated leaf quantity can be translated in a way (as shown above) other than as SHINOZAKI *et al.* (1964 a) did, these values of $F(z)$ and $f(z)$ are not different from each other. This relationship is an important

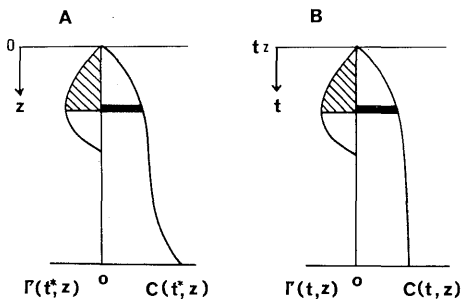


Fig. 4. Two interpretations of the profile diagram

A : The usual profile diagram represented the vertical distributions of Γ and C at the present time t^* . B : Another profile diagram represented the distributions of Γ and C with respect to time, at the z -horizon.

and available characteristic of the accumulated leaf quantity for developing derivative problems. Even this new interpretation of the accumulated leaf quantity also can make possible a reasonable explanation of the pipe model theory without any contradictions because of this equality.

IV. Discussion

1. Plant form

Reports on the vertical distribution of stem increment state that the distributions have differences among stands of different ages, sites, stand densities, and of course species. Concerning the quantitative analysis of stem form, OOHATA and SHINOZAKI (1979) proposed a statical model of plant form : namely, the $C(z)$ curve is represented as an exponential function of z . It is significant, for an explanation of the growth mechanism and for its application to silvicultural treatment, to analyze stem form in conformity with the theoretical and actual bases.

An upward movement in the distribution of the leaf density of the crown, increases the number of pipes passing through a given height, and the lower the z is, the more the amount of non-photosynthetic organs increases, because the pipes, which became useless after the leaves withered, still remain as they are (diagrammatically illustrated in Fig. 3).

Considering that the stem-wood increments in the last five years at different heights above the ground are more or less proportional to the corresponding values of $F(z)$ (SHIDEI and TADAKI, 1960), the following concept can be advanced on the relationship between the leaf density and the quantity of non-photosynthetic tissues. Regarding z as the parameter independent of time, as is the same as in the previous section, the relationship between $\Gamma(t, z)$ and $\Delta y(t, z)$ can be represented hypothetically as follows :

$$\Delta y(t, z) = \mu \int_0^z \Gamma(t, z) dz \quad (8)$$

where μ is a proportional constant. Because the amount of non-photosynthetic tissues in the z -horizon at the present time, $C(z)$, is an accumulation of the annual increment of them, it is represented as Eq. (4). From Eqs. (8) and (4), we obtain

$$C(z) = \mu \int_0^{t^*} \int_0^z \Gamma(t, z) dz \cdot dt. \quad (9)$$

Then the proportional constant μ must be regarded as the function with respect to time because the annual increment of the stem cross-sectional areas become smaller with tree growth (SHIRAISHI, 1986). Replacing μ with $\mu(t)$, we obtain

$$C(z) = \int_0^{t^*} \mu(t) \int_0^z \Gamma(t, z) dz \cdot dt. \quad (10)$$

It is possible to reduce the amount of accumulated annual increment in accordance with actual conditions by introducing $\mu(t)$ as shown in Eq. (10).

However, it is difficult at present to ensure that the relationship shown in Eq. (10) can be held because of the lack of data on the differentiation of leaf density with respect to time. Although we can not determine the trunk form because the vertical distribution of the stem increment is changeable under various conditions, there is no reason to doubt that non-photosynthetic tissues should be accumulated annually, and it can be inferred that the non-photosynthetic organs continue to grow while keeping their exponential shape in the leafless range as OOHATA and SHINOZAKI (1979) indicated.

2. Proportional constant L

The relationship of a simple linear-regression as shown in Eq. (2) is a fundamental concept of the pipe model theory. The gradient of the regression line, L , is an important parameter, and it is necessary to clarify its meaning although SHINOZAKI *et al.* (1964 a) referred to it.

The proportional constant L , the specific pipe length, has the dimension of length as shown by

$$[L] = \frac{[F(z)]}{[C(z)]} = \frac{[g \cdot ha^{-1}]}{[g \cdot m^{-1} \cdot ha^{-1}]} = [m]. \quad (11)$$

SHINOZAKI *et al.* (1964 a) also said that the L is not always constant but that considerable seasonal change occurs and that the L is changeable under various stand densities. The conceivable reason for this instability may be that the L should be calculated by measuring the actual leaf quantity. It is known that leaf quantity has seasonal changes (TADAKI, 1976).

Because the accumulated leaf quantity, $F(z)$, can be regarded as the $f(z)$ under the conditions previously stated, we can expect $f(z)$ and $C(z)$ to have different dimensions from those of SHINOZAKI *et al.* (1964 a). Because $f(z)$ and $C(z)$ can be represented as shown in Eqs. (6) and (4), respectively, considering the dimensions of $f(z)$ and $C(z)$ leads to

$$[\Lambda] = \frac{[f(z)]}{[C(z)]} = \frac{[g \cdot yr \cdot m^{-1} \cdot tree^{-1}]}{[g \cdot m^{-1} \cdot tree^{-1}]} = [yr]. \quad (12)$$

The difference in the dimensions of Eqs. (11) and (12) corresponds to that of the change of the meanings in the vertical axes of Fig. 4.

If the premise of the leaf density that should not change except for upward movement can hold, Λ ought to have the same ratio of the total leaf-mass $F(z^*)$ to $C(z^*)$:

$$\Lambda = L \quad (13)$$

Moreover, the value of Λ never should be influenced by the seasonal change of leaf quantity, and it should be the average ratio of a tree after the height of it reached at the z^* -horizon.

Now we should think about the product of a total leaf-mass $w_f (= F(z^*))$ and $1/\Lambda$ of a tree. The dimension of the product is

$$[w_f \cdot 1/\Lambda] = [g \cdot yr^{-1} \cdot tree^{-1}]. \quad (14)$$

Paying attention to the meaning of Λ ,

$$w_f \cdot \frac{1}{\Lambda} = w_f \cdot \frac{C(z)}{f(z)} \quad (15)$$

Specifically, it is suggested that the dimension of Eq. (14) is equivalent to that of the growth rate of the non-photosynthetic tissues. Under the condition that $f(z^*) = w_f$, we can find not only that the value of Eq. (15) is equal to the $C(z^*)$, but also that the quantity of the stem at the crown bottom will apparently correspond to the annual increment of the non-photosynthetic organs.

Figure 5 shows a simplified model to aid in understanding the meaning of $C(z)$. Considering the level at the base of the lowest living branch (z^*), $C(z_1)$ consists mainly of the accumulation of photosynthate by the leaves above the z_1 -horizon $F(z_1)$. However, $C(z_2)$ consists not only of the accumulation of photosynthate translocated from the leaves above $F(z^*)$, but it also contains the non-photosynthetic tissues which had been accumulated before the height of the lowest living branch reached the z^* -horizon. On the contrary, $C(z^*)$ consists merely of the non-photosynthetic tissues which had been accumulated since the tree height was just at the z^* -horizon. In other words, considering the equality of $F(z)$ and $f(z)$, it follows that $C(z^*)$ represents the increment of non-photosynthetic organs in the last year which consists of the photosynthate by the total quantity of leaves $F(z^*)$. This makes a good agreement with the conclusion induced by Eq. (15). If this concept is correct, the reciprocal of L nearly will represent the leaf efficiency of a stand which is the ratio of the increment of non-photosynthetic organs to the total leaf biomass.

Because the linear regressions of the $F(z)$ - $C(z)$ line can be recognized both in an individual tree and in a stand, another interpretation can be made for both cases. Thus, the dimensions of $F(z)$, $f(z)$, and $C(z)$ can be rewritten as replacing $[plant^{-1}]$ in them with $[ha^{-1}]$, and vice versa. Although it is apparent that the dimensions of L and Λ never change in either case, the reciprocal of Λ in a forest stand indicates the leaf

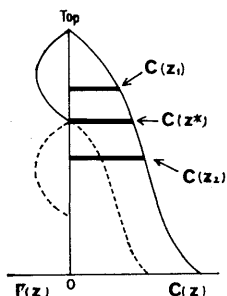


Fig. 5. The meaning of $C(z)$ depending upon the depth z

The solid line and the dashed line show $\Gamma(z)$ and $C(z)$ at the present time and at a time when the tree height corresponded to the height of the lowest living branch at present (z^* -horizon), respectively.

(FUJIMORI, 1970) were used for an analysis to clarify this point. Defining Δw , x , and H_b as the last increment of non-photosynthetic organs, height above the ground, and the height of the lowest living branch, respectively, Figs. 6 and 7 show an interesting relationship between the ratio of $C(z)$ to Δw (R_z) and the ratio of x to H_b (R_x) in individual trees. If $C(z) = \Delta w$, then $R_z = 1$; if $x = H_b$ then $R_x = 1$. According to the assumption stated above, the amount of non-photosynthetic tissues in the z^* -horizon will represent the value of the last increment of non-photosynthetic organs. This means that the R_z - R_x curve should pass through the point (1, 1) in Figs. 6 and 7.

The heights of sample trees ranged widely, approximately 5 to 13 m for *C. japonica* and 6 to 10 m for *C. obtusa*. In spite of this wide variance in tree sizes, the R_z - R_x curves pass around the point (1, 1), except for one of them of each species. These exceptions will, however, be dissolved when H_b is regarded not as the height of the actual lowest living branch, but as the height of the crown bottom considering the distribution of its crown; the living branches which cannot be regarded as being in the range of its crown must be ignored. The curves vary widely from each other, both in the lower range ($R_x < 1$) and in the upper range ($R_x > 1$), but around the point of the crown bottom ($R_x = 1$), variances of these curves become small and focus at this point ($R_x = 1$). This tendency is represented in the relationship between R_z' and R_x ; R_z' is the ratio of the density of stem weight $S(z)$ to Δw (Fig. 8).

Consequently, if a stem 1 m in length at the crown bottom would be cut off from a tree, its weight, defined as $W\sigma$, will represent the last increment of non-photosynthetic organs with a small error. This weight, $W\sigma$, would be equivalent to the accumulated amount of the non-photosynthetic organs increment in a year which is distributed over the outer side of a stem from the top to the stem base (Fig. 9). This fact is expected from the assumptions and interpretation stated before.

In the stratified clip method, the thickness of a stratum, Δz , can be decided at will according to the height of a community and the purpose of the study. It is apparent that the specific pipe lengths should not be compared with each other when they were decided only from the gradient of Eq. (2) because the value of $C(z)$ is changeable with the thickness of a stratum. SHINOZAKI *et al.* (1964 a), of course, defined and decided the specific pipe lengths of some species with consideration of this aspect in their original paper (1964 a).

Here we discuss the relationship between Δ and the specific pipe length decided at the different Δz s. Defining the gradients of Eq. (2) when $\Delta z = a$ and $\Delta z = b$ as L_a and L_b , respectively, we can find the relationship between them as follows:

$$\frac{L_a}{L_b} = \frac{b}{a} \tag{16}$$

efficiency of the stand.

3. Actual proof

Table 1 shows the specific pipe lengths L , the reciprocals of L , and the ratio of woody production to leaf weight: that is, leaf efficiency, for some tree species. Some leaf efficiencies are very close to the reciprocal of L , but some are relatively different. The reason for the variation is that the error for reading data arises because all data is for a forest stands, not for a tree. It is, therefore, impossible to determine which layer is suitable for the mean clear-length of a stand from only the profile diagram.

These difficulties may be disregarded for individual trees. The data on *Cryptomeria japonica* D.DON and *Chamaecyparis obtusa* S. and Z.

Table 1. Specific pipe length L , reciprocal of L , and leaf efficiency of some species

Species	Age	L	$1/L$	Leaf efficiency	Source
<i>Castanopsis cuspidata</i>	11	0.47	1.35	1.53	TADAKI, 1965
<i>Camellia japonica</i>	65	1.03	0.97	0.99	SAITO <i>et al.</i> , 1965
Mixed evergreen hardwoods	65	0.47	2.14	2.34	SAITO <i>et al.</i> , 1965
<i>Abies veichii</i>	23	2.45	0.41	0.51	TADAKI <i>et al.</i> , 1970
<i>Abies veichii</i>	25	1.78	0.56	0.51	TADAKI <i>et al.</i> , 1970
<i>Abies veichii</i>	60	1.72	0.58	0.36	TADAKI <i>et al.</i> , 1970
<i>Chamaecyparis obtusa</i>	45	1.38	0.72	0.80	TADAKI <i>et al.</i> , 1966
<i>Tsuga heterophylla</i>	19~32	0.97	1.03	1.17	FUJIMORI, 1971
<i>Cryptomeria japonica</i>	5	2.23	0.45	0.63	TADAKI and KAWASAKI, 1966
<i>Metasequoia glyptostroboides</i>	9	0.72	1.39	2.35	SAITO <i>et al.</i> , 1970

Unit of L is (m). All data are for forest stands.

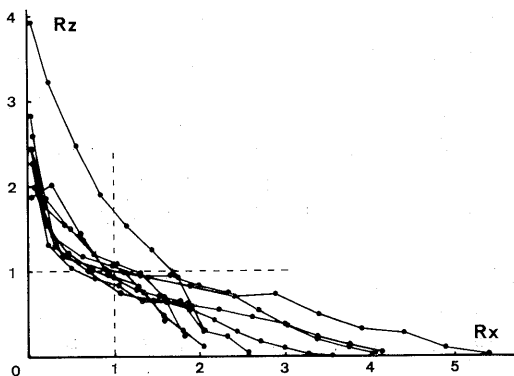


Fig. 6. Relationship between R_z and R_x of *Cryptomeria japonica* individual trees

$$R_z = C(z)/\Delta w, \quad R_x = x/H_B$$

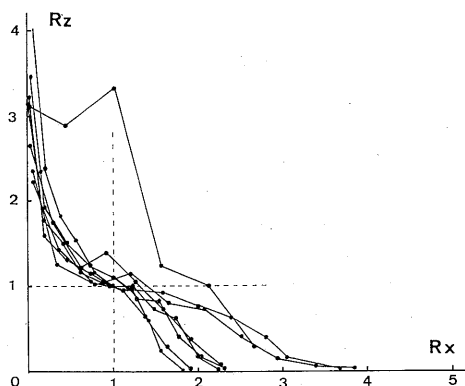


Fig. 7. Relationship between R_z and R_x of *Chamaecyparis obtusa* individual trees

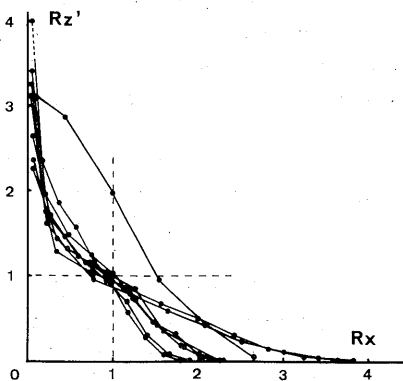


Fig. 8. Relationship between R_z' and R_x of *C. obtusa* individual trees

$$R_z' = S(z)/\Delta w, \quad S(z) : \text{density of stem quantity in the } z\text{-horizon.}$$

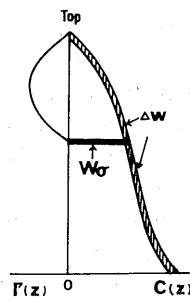


Fig. 9. Increment of non-photosynthetic organs in the last year, Δw , and stem weight for 1 m of length at the height of the crown bottom, W_σ

when $b=1$, we obtain

$$L_1 = a \cdot L_a \quad (17)$$

Accordingly, it can be said that the specific pipe length, L_1 , is a value converted into a 1 m depth of a stratum. Now we can expect the existence of the gradient, $L_n (\Delta z = n)$, which has a same value as L_1 . Using Eqs. (16) and (17), Δ can be presented as follows :

$$\Delta = L_n = \frac{a}{n} \cdot L_a = \frac{L_1}{n} \quad (18)$$

Thus we can obtain the equality of Δ and L_1 when $n=1$ [m].

In explaining why the stem weight of the 1 m length cut off should be adequate to represent Δw , the significance is in the stem weight just at the crown bottom which is, in other words, the stem density at that height. The stem length itself of $W\sigma$ seems to be merely a problem of appearance, and the cases of *C. japonica* and *C. obtusa* in this paper seem to be adequate for 1 m in stem length. To clarify the reason theoretically, more premises or conditions concerning the distributions of plant organs or other growth processes will be needed.

Our discussion has used data only of the conifers, *C. japonica* and *C. obtusa*. Broadleaved trees, however, differ from them in branch structure, and the differences of life forms among tree species should exert a great influence on the growth styles of trees. To generalize the interpretation in this paper, we need to ensure that the R_z-R_x curve will pass at point (1, 1) even in other forest species, and how to apply the $W\sigma$, which is observed in individual trees, to forest stands must be studied.

Nevertheless, there is the possibility of lessening difficulties in estimating forest productivity by using the $W\sigma$ in the cases of *C. japonica* and *C. obtusa*, and it can be shown that the reciprocal of the specific pipe length is approximately equivalent to leaf efficiency with the interpretation that the accumulated leaf quantity must be that of Eq. (6). This enables the lack of a relationship with the seasonal changes of L .

Acknowledgement

We thank Professor Kazuo HOZUMI and the members of the Laboratory of Silviculture, Nagoya University, for their helpful advice on this study.

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* In Japanese with English summary

** only in Japanese

The title in parentheses is a tentative translation from the original Japanese title by the authors of this paper.

(Received March 24, 1987)