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The Mechanism and Function of Tree Root in the Process of Forest Production II

Root biomass and distribution in stands

By

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Summary : In this issue, the root biomass of the model stands in the nursery, the part biomass per tree and per ha of each sample stand and those ratios in the ordinary planted stands, and the horizontal and vertical distribution of root biomass, were studied in relation to the environmental conditions such as the growth of stands, planting density, soil condition, and so on.

The root biomass per ha was 40 to 60 tons in the ordinary stands. That of fine root was the largest, 1 ton, for *Ch. obtusa* and 0.1 ton for *P. densiflora*. The fine root biomass, directly related to the root-function goes up in the young stands and down in the matured stands. This relation agreed to the change of growth in this period. These phenomena are very interesting.

P. densiflora and *L. leptolepis* were of dispersion-root type horizontally, *C. japonica* and *Ch. obtusa* of concentration-root type; and vertically, *L. leptolepis* and *Ch. obtusa* of flat-root type, *C. japonica* and *P. densiflora* of deep-root type. This result of inspection demands the semi-logarithmic formula and the GRAM-CHALIER's equation to be used in analysing a variation curve of the root density, horizontal and vertical.

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I. Introduction

The methods of investigation and estimation of the root biomass and the outline of the sample stands, have been reported already in the report of Gov. For. Exp. Sta. No. 259[4]. The interrelationship between the root biomass and the root density estimated on the investigation of the standing biomass of stand and the soil conditions in relation to them has been reported in this issue.

II. Sample stands

The stand 54 of *C. japonica*, the stand 8 of *Ch. obtusa*, the stand 12 of *P. densiflora*, and the stand 29 of *L. leptolepis* have been investigated with the purpose of the study and the methods reported in the previous issue[4]. The situations and site conditions of these stands are shown in the Appendix-Table 1, and the average standing biomass of the sample trees of those stands in the Appendix-Table 2 on the preceding No. 259[4]. The author actually drafted the detailed data concerned with the standing biomass and production of each sample tree, but partly for reasons of space finally decided not to include them. This issue, however, has been based on those data.

III. Representation of the structure of the underground part and the distribution of the root biomass in the model young forest by nursery experiment

The method of measuring each factor and its accuracy for analyzing the structure of the underground parts have been mentioned thus far. In the following chapters the structure of the underground parts in forests will be analysed according to the above-mentioned method and factors. Its relation to the growth of forest will be dealt with. The ordinary forests have such different nursing conditions as site conditions, stand densities, and the conditions growing with them. It is, therefore, difficult to examine the structure of the underground parts on a given condition. The horizontal distribution of the root biomass, for example, differs from one tree to another. As, however, the root systems intermingle with one another in the ordinary forests, it is difficult to know the properties of distribution of the root systems of each tree as an isolated tree. In addition, the different site conditions there, as before, cause the conditions of growth to vary extremely, making it is difficult to discern clearly the effects of density on the distribution of the root system.

So prior to the study of the structure of the underground parts in the ordinary stands, the model stands, dense and sparse, of the main species such as *C. japonica*, *Ch. obtusa*, *P. densiflora*, and *L. leptolepis*, were set up in the nurseries under the uniform soil conditions (*C. japonica* stands with 156 to 20, 400 trees per ha were picked out and *Ch. obtusa*, *L. leptolepis*, *P. densiflora* stands with 156 trees were done respectively). Then we tried to determine the distribution of the root system, horizontal and vertical, under the isolated conditions and the distribution of the root biomass in a sparse stand.

The investigation backs up that of the existing stands as will be mentioned afterwards. It is possible to know the properties of the distribution of the root biomass of every species, for all that was done in these immature stands.

In this chapter we try to make clear the distribution of root biomass divided into two groups, the stand under the isolated conditions and the formation group.

1. Isolated tree

Sample stand : Forests of 6-year-old *C. japonica*, *Ch. obtusa*, *P. densiflora*, and *L. leptolepis*

Location : Asakawa nursery

Soil condition : Moderately moist Kanto loam soil

Number of the sample trees : 5 per species

Growth condition of the sample trees : Moderate growth, their heights, part biomass of the under-and-aboveground parts, T/R ratios, and the maximum depths of the root system are shown in Fig. 20.

Density : 156 trees per ha and per species. The distance between the sample trees was 8 m wide and almost no intermingling roots were recognized.

Process : Horizontal divisions are from 1 to 8, divided by the concentric circles drawn at every 50 cm up to 4 m in radius as shown in Fig. 1. Vertically, soil horizons I and II were divided at every 15 cm in depth and the other lower soil horizons at every 30 cm in depth. The root biomass were measured at every horizontal and vertical sample division.

The sample divisions were far finer than those of the ordinary forests, but the methods of measurement were taken exactly in the same way as in the ordinary ones.

1) Horizontal distribution

The average root biomass at every sample division has been measured. Although the root density was high, the root biomass was small in horizontal division 1 near the root stock as the investigated area was narrow. In horizontal division 8 the root biomass was small, though the area was investigated widely. The distribution of the root biomass of all species reached to the maximum in horizontal division 2. This is shown in Table 1 on the fine roots of each species according to the detailed data.

This tendency is clear in the upper parts of soil horizons I and II. In the lower horizons

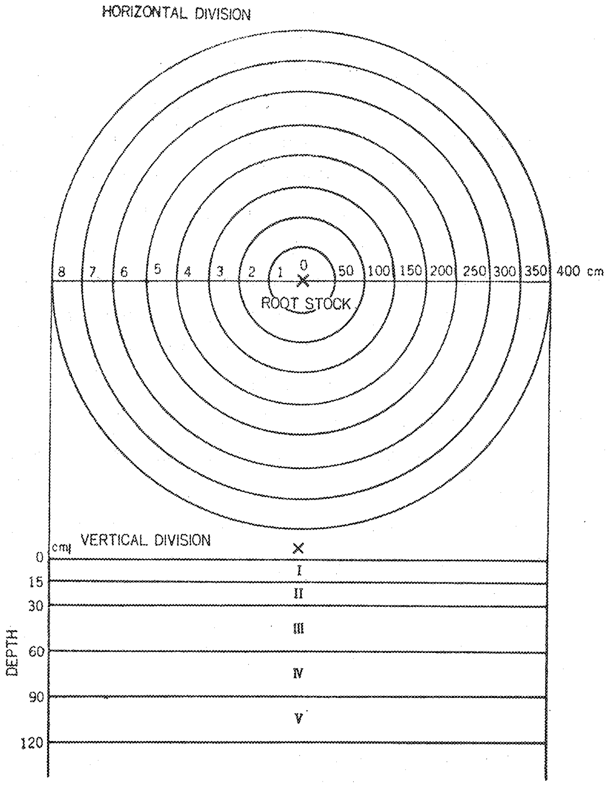

Fig. 1 Sampling unit to investigate the root biomass of an isolated tree.

the root biomass becomes larger in horizontal division 1, closest to the root stock. The biomass of the roots larger than a large root, are distributed there even in the surface soil layers as well as in the lower soil horizons. Each ratio is shown in Table 2 when the total biomass of the fine roots is to be 1. According to the table, in horizontal division 1 each biomass of the fine roots was distributed at 20% of the total root biomass for *C. japonica*, 18% for *Ch. obtusa*, 13% for *P. densiflora*, and 17% for *L. leptolepis*. Hence it is that the root biomass near the root stock is larger for *C. japonica* and smaller for *P. densiflora* than for other species.

As already mentioned, most of the root biomass was distributed to horizontal division 2. Each ratio of the distribution of root biomass was 24% of the total root biomass for *C. japonica*, 23% for *Ch. obtusa*, 22% for *L. leptolepis*, and 18% for *P. densiflora*. On the other hand, in horizontal division 8, farthest away from the root stock, each biomass of the fine roots was distributed at 4% of the total root biomass for *C. japonica*, 11% for *Ch. obtusa*, 16% for *P. densiflora*, and 13% for *L. leptolepis*.

This change occurred between horizontal divisions 5 and 6. The root biomass of *P. densiflora* were distributed to horizontal division 1 to 4 in a lower proportion than those of *C. japonica* and *Ch. obtusa*, whereas they were distributed to division 5 or 6 in the higher proportion of 4 to 5%. The change of those of *L. leptolepis* took place in horizontal division 6. The distribution ratios to horizontal divisions 1, 2, 3, and 4 were 77% for *C. japonica*, 68% for *Ch. obtusa*, 64% for *L. leptolepis*, 51% for *P. densiflora* showing the maximum of the

Table 1. Fine root biomass in each horizontal division (g)

Horizontal division Species	1	2	3	4	5	6	7	8	Total
C. japonica	26	32	28	14	10	8	7	5	130
Ch. obtusa	40	51	36	21	20	11	16	23	218
P. densiflora	1.3	2.0	1.0	1.0	1.2	0.9	1.2	1.8	10.4
L. leptolepis	7	9	6	4	2	3	4	5	40

Table 2. Ratio of the fine root biomass in each horizontal division to the total fine root biomass, when the total biomass is to be 1 (%)

Horizontal division Species	1	2	3	4	5	6	7	8
C. japonica	20	24	22	11	8	6	5	4
Ch. obtusa	18	23	17	10	9	5	7	11
P. densiflora	13	18	10	10	12	9	12	16
L. leptolepis	17	22	15	10	5	8	10	13

Table 3. Ratio of the fine root biomass of *C. japonica* in each horizontal division to the total fine root biomass in each soil horizon, when the total biomass is to be 1 (%)

Horizontal division Horizon	1	2	3	4	5	6	7	8
I	17	20	23	12	9	5	8	6
II	23	25	19	13	7	13	—	—
III	22	56	22	—	—	—	—	—
IV	50	50	—	—	—	—	—	—
V	50	50	—	—	—	—	—	—
Total	20	24	22	11	8	6	5	4

Table 4. Ratio of each root biomass in each horizontal division to the total root biomass (%)

Horizontal division Root class[4]	1	2	3	4	5	6	7	8
f	20	24	22	11	8	6	5	4
s	24	28	18	12	6	4	4	4
m	31	37	15	10	4	3	—	—
l	100	—	—	—	—	—	—	—

horizontal distribution.

The distribution ratios of the fine roots of *C. japonica* at every soil horizon are shown in Table 3.

As the soil horizons go down lower, the root biomass distribution decreases in the order of the horizontal divisions farther away from the root stock. It was only recognized within horizontal divisions 1 to 6 in horizon II, within those up to 3 in horizon III, and within those up to 2 in soil horizons IV and V. It showed a great horizontal change between soil horizons II and III. For the root biomass distribution changes suddenly according to the change of the soil properties at the depth of 40 to 50 cm. In soil horizons I to III, the root biomass goes up in horizontal division 2 at the depth of 50 to 100 cm as the soil horizons go lower. The distribution ratio was 20% in soil horizon I, but 56% in soil horizon III; it increased by 36% between them. There was no root distribution in horizontal divisions 4 to 8 of soil horizon III.

The distribution ratio increased by 50% in horizontal division 1 of soil horizons IV and V.

This relation is shown in Table 4 when applied to each root class of *C. japonica*. As it increases in size as shown there, the distribution of the root biomass becomes narrower from the farther horizontal divisions in the order. The medium roots were observed to distribute only within the divisions up to 6, and the large root to distribute only within the division up to 1. As shown in Table 4, the fine and the small roots made similar distribution, but the medium and the large roots made much different ones.

(1) Root density

Fig. 2 shows the root density (the root weight per soil of a cubic meter) calculated from the root biomass and the soil volume in each division.

In soil horizon I, the densities of the fine roots of *C. japonica* were 127 g/m^3*, the highest of all in horizontal division 1, 48 in division 2, and 34 in division 3. Hence it goes down rapidly as the divisions go farther away from the root stock.

A similar tendency holds true in the case of the fine roots in soil horizon II. And the tendency of decreasing horizontally becomes clearer as the soil horizons go lower. As concerns the fine roots of *C. japonica*, *Ch. obtusa*, *P. densiflora*, and *L. leptolepis*, Fig. 2 shows the changes in root density at soil horizons, and the ratio of root density in each horizontal division to that of 100 of horizontal division as the changing ratio of the root density. As is clear from Fig. 2, the root density of every species increases to the maximum in horizontal division 1 nearest the root stock and decreases, describing a slow-curved line in inverse proportion to the distance from the root stock. As the soil deepens, the gradient of this curve becomes steeper and the root density decreases in an almost straight line.

This tendency of decreasing horizontally differed from species to species. The root density in horizontal division 2, for example, of *C. japonica* decreased by 38% and that in division 3 by 27% of that in division 1. That of *Ch. obtusa* decreased by 47% in division 2 and by 24% in division 3, that of *P. densiflora* by 56% in division 2 and by 24% in division 3. In the case of *P. densiflora* it was by 56 % in division 2 and by 28 % in division 3. The root density near the root stock becomes lower in the order of *C. japonica*, *Ch. obtusa*, *L. leptolepis*, and *P. densiflora*. The gradient of the abovementioned slow-curved line becomes steeper in the same order in the change of the root density at the distance of 100 cm and farther than that from the root stock. Besides, it is observed that *P. densiflora* and *L. leptolepis* distribute the fine roots more widely to the divisions far from the root stock than *C. japonica* and *Ch. obtusa* do.

This tendency, however, has no relation to root density. For example, the maximum densities of fine root in soil horizons I were 127 for *C. japonica*, 212 for *Ch. obtusa*, 4 for *P. densiflora* and 25 for *L. leptolepis*. That for *Ch. obtusa* was more than 50 times as high as that for *P. densiflora*. *P. densiflora*, however, which has a lower root density, makes a rather gentle changing curve. Besides, the root density is high even at the parts far from the root stock. It is likely that the horizontal distribution of the root system indicates the character of species regardless of the biomass of the roots.

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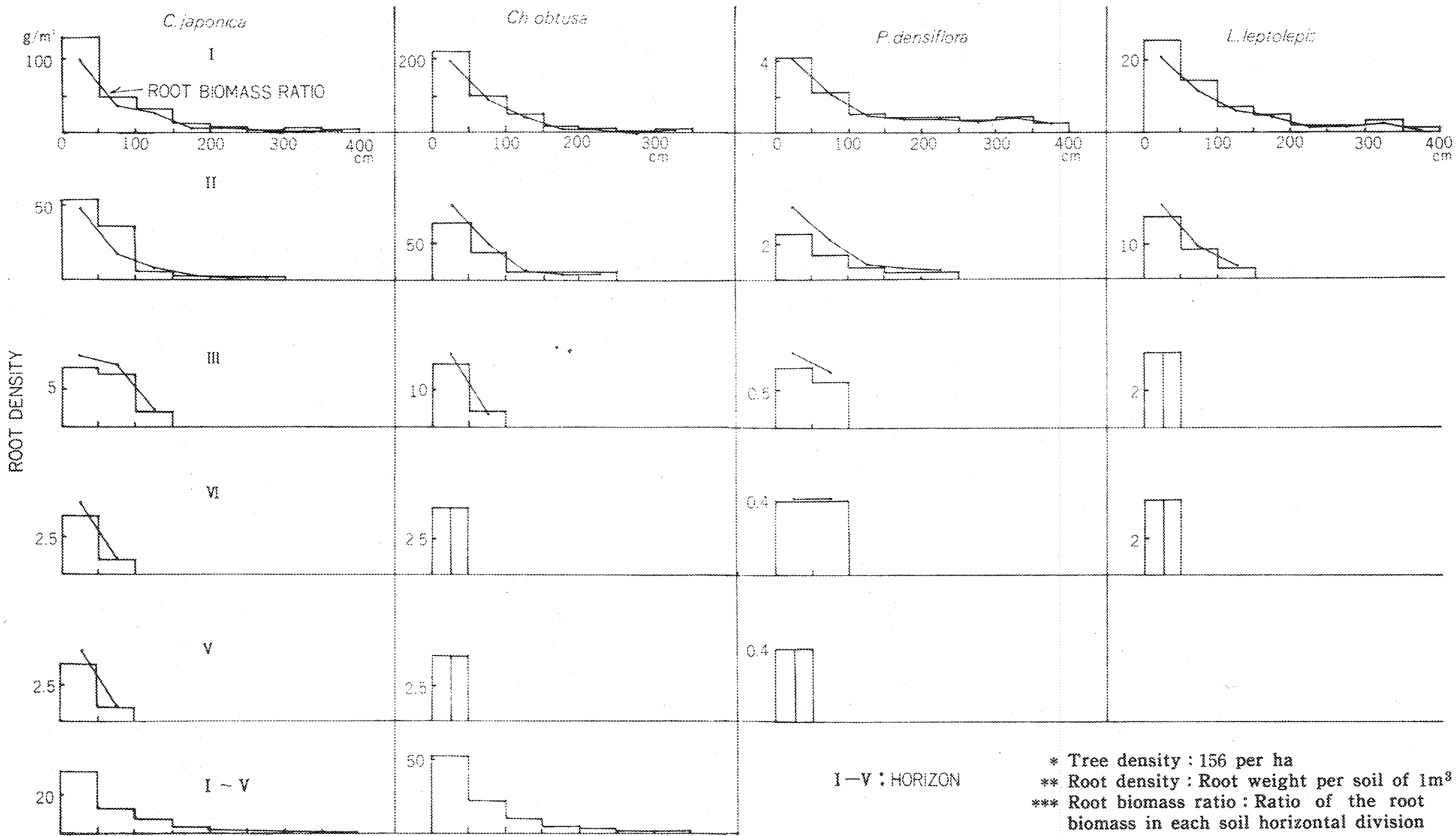
* g/m^{3}s are omitted hereinafter.



* Tree density : 156 per ha
** Root density : Root weight per soil of 1m³
*** Root biomass ratio : Ratio of the root biomass in each soil horizontal division to that in horizontal division 1.

Fig. 2 Fine root density and horizontal distribution ratio by distance from the root stock of the main species.

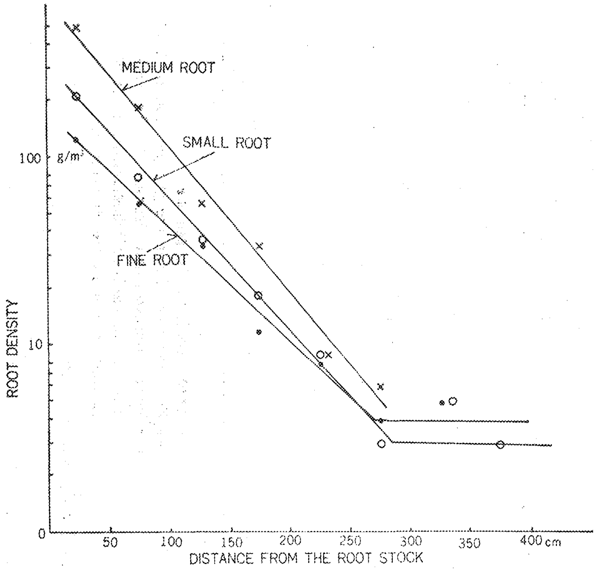
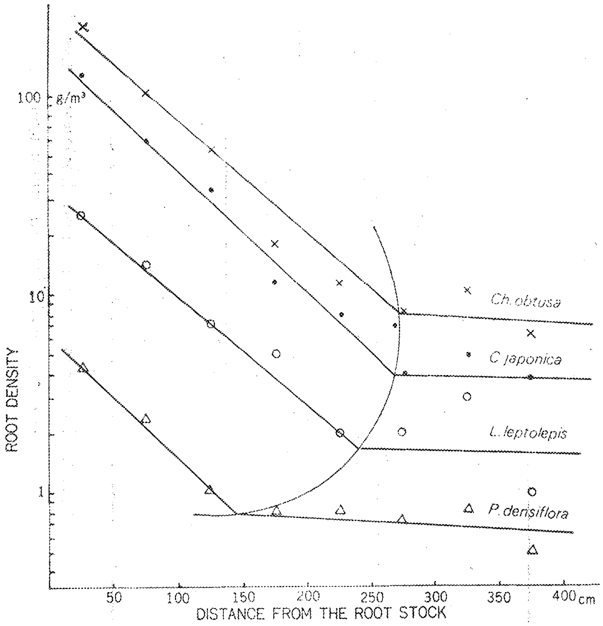


Fig. 3 Horizontal change in root density of each root class (*C. japonica*, horizon I).



There are many roots growing far from the root stock. The more extensive root-typed the tree is, the nearer to the root stock the critical point is.

Fig. 4 Horizontal change in fine root density of the typical species in horizon I.

Table 5. Horizontal

Root class	f s m
Species	*C. japonica* *Ch. obtusa* *P. densiflora* *L. leptolepis*
Horison	I II III IV

To sum up : *C. japonica* and *Ch. obtusa* belong to the so-called intensive-root type with high root density and comparatively many fine roots near the root stock; *P. densiflora* and *L. leptolepis* belong to the extensive-root type with few and widely spread fine roots.

The change of the density of the small, medium and large roots was observed in the same way. The small root showed similar distribution with that of the fine root; the difference among the species was clear. The medium and large roots, however, were mostly distributed around the root stock; the difference among the species was vague. Hence it is that the characters of the distribution of the root biomass are easier and clearer to observe in the fine and the small roots than in the large roots.

(2) Representation of the decreasing curve of the root density

Things can go well for analysis of the root biomass distribution if such changing curves of root density as shown in Fig. 2 be expressed by a given equation. A few methods are taken here to express this curve.

change in root density expressed by the semi-logarithmic equation

Sx^2	Sy^2	Sxy	a	b	Standard deviation	Variation coefficient	Correlation coefficient	
105,000	3.316435	−574.4287	2.153561	−0.005471	0.170166	0.1606	0.9476	*C. japonica*, Horizon I
105,000	3.805988	−606.5189	2.319487	−0.005776	0.224621	0.1929	0.9205	
25,000	1.790811	−210.4392	0.790546	−0.008417	0.043790	0.0438	0.9892	
105,000	3.316435	−574.4287	2.153561	−0.005471	0.170166	0.1606	0.9476	Fine root, Horizon I
105,000	2.246006	−461.0698	2.254131	−0.004391	0.192094	0.1396	0.9014	
105,000	0.642650	−228.8649	1.085140	−0.002180	0.158200	5.5509	0.7762	
105,000	1.541833	−379.0190	1.367915	−0.003610	0.170000	0.2632	0.8874	
105,000	3.316435	−574.4287	2.153561	−0.005471	0.170166	0.1606	0.9476	*C. japonica*, Fine root.
43,750	1.552252	−248.7945	1.788000	−0.005687	0.354000	0.1981	0.9115	
5,000	2.220617	− 30.6914	1.134573	−0.006020	1.428000	2.0906	0.0816	
1,250	0.181238	− 15.0515	0.903030	−0.012041	—	—	—	

a. Semi-logarithmic equation

Great effort was made to express the horizontal change of the density of the fine roots of every species in soil horizon I by a logarithmic diagram or a semi-logarithmic one. After due deliberation it was concluded that the former was of no use. When the distance from the root stock is drawn as the horizontal axis (the *X*-axis) in an even scale and the root density as the vertical axis (the *Y*-axis) in a logarithmic scale, the change is to be expressed by a nearly straight line. From this it is to be supposed that its regression coefficients show the tendency of the change. But as is clear from Fig. 3 and 4, the semi-logarithmic diagram works well within the horizontal distance, 50 to 200 cm far from the root stock where the change is great, but not in the area outside this, where the change is very slow. It follows from these facts that this semi-logarithmic equation holds true in expressing any part but the slow-curving parts coming up to over 200 cm.

b. Representation of the changing curve of root density in every root class

Let us apply the distribution curve of the root density of the fine, small and medium roots of *C. japonica* to the semi-logarithmic graph. The result is shown in Fig. 3. It is evident from this figure that the regression line tends to become steeper downward as the root becomes larger.

This fact, as already mentioned, verifies that the biomass of the thick roots are larger than the fine roots near the root stock, decreasing rapidly as they go farther away from it.

This relation is to be expressed as follows:

$$\log y = a + bx$$

y : Root density (g/m^3), x : Distance from the root stock (cm)

Table 5 shows the constant coefficients and errors calculated by this regression. According to the table, the difference between the coefficients of the fine and small roots was extremely small; whereas the difference between those of the small and the medium roots was large.

Every coefficient of correlation of this equation gets up to over 90%. The errors, however, were rather large, 10 to 20%, because not many samples were measured.

c. Difference of the changing curves according to species

Table 5 shows the density of the fine root of each species in soil horizon I calculated by the same method. The gradient of the regression line got gentler in the order of *C. japonica, Ch. obtusa, L. leptolepis*, and *P. densiflora*. The coefficients of regression were −0.0055 for *C. japonica*, −0.0044 for *Ch. obtusa*, −0.0036 for *L. leptolepis* and −0.0022 for *P. densiflora*. The coefficients of variation ranged from 14 to 26% and the coefficients of correlation ranged from 77 to 95%.

d. Horizontal change in root density according to every soil horizon

The horizontal changing curve of the root density goes up gently in soil horizon I and down steeply near the root stock in the lower horizons. This is shown in Fig. 5, the semi-logarithmic graph.

The coefficients, as shown in Table 5 are −0.0055 in soil horizon I, −0.0057 in II, −0.0061 in III, and −0.0020 in IV. That is to say, the coefficients of regression become gentler and the gradient of the regression lines becomes steeper as the soil horizons go lower; and besides, the root density becomes higher in horizontal division 1 as the soil horizons become lower. Little difference is recognized between the regression coefficients in soil horizons I and II. In the soil horizons below them, however, the difference shows a rapid rate of increase.

In addition, the pattern of the horizontal distribution of the root system changes greatly at the depth of 40 to 50 cm. The coefficients of variation of this regression are 16% in soil horizon I, 20% in II, and 26% in III. In brief, they increase hand in hand with the lowering soil horizons. A great change was here also recognized between soil horizons II and III.

The regression line of the semi-logarithmic diagram is divided into two lines, one with a gentle incline and the other with a steep incline, bending at the slow-curved part.

This bending point in the horizontal change of each fine root in soil horizon I, as shown in Fig. 4, was about 250 cm away from the root stock of *C. japonica* and *Ch. obtusa*, 200 cm away from that of *L. leptolepis*, and 150 cm away from that of *P. densiflora*. To sum up, the semi-logarithmic lines of *L. leptolepis* and *P. densiflora* go down with the steeper gradient within the distance up to 100 cm from the root stock, but with the gentler one beyond that.

The farther the bending point is away from the root stock, the wider the root biomass is distributed near it. The closer it is to the root stock, the wider the root biomass is distributed far away from it. It is, therefore, possible to know the character of the root distribution from the position of the bending point of the semi-logarithmic diagram.

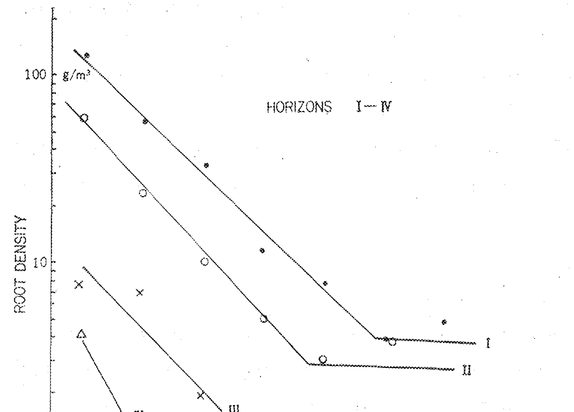


Fig. 5 Horizontal change in fine root density of *C. japonica* in each soil horizon.

Let us examine the horizontal changes of the root density of *C. japonica* in every soil horizon. We find out thereby the bending points in soil horizons I and II but not in III and below. Furthermore, it is evident from the figure that the slow-curving parts exist in the former and not in the latter when the root density decreases horizontally. Briefly, in the latter, the root density decreases rapidly farther

Table 6. Vertical distribution of fine root biomass

Horizon \ Species	*C. japonica*		*Ch. obtusa*		*P. densiflora*		*L. leptolepis*	
I	86*	(65)**	167	(76)	7.4	(71)	30	(74)
II	31	(24)	42	(19)	1.9	(18)	7	(18)
III	9	(7)	7	(3)	0.6	(6)	2	(5)
IV	2	(2)	1	(1)	0.4	(4)	1	(3)
V	2	(2)	1	(1)	0.1	(1)	—	
Total	130	(100)	218	(100)	10.4	(100)	40	(100)

* g, ** %

from the root stock.

This is clear even from the locational change of the bending points according to the root class of *C. japonica* in soil horizon I.

There are the slow-curved parts in the fine and the small roots but not in the medium roots. This makes clear the characteristic difference between the distributions of the root density of the former two and those of the latter one.

From the analysis of the horizontal distribution of the root biomass and the root density, it is clear that the root system distributes broad when it is far off from the root stock in the case of *P. densiflora* of *L. leptolepis*, while it distributes broad when it is near it in the case of *C. japonica* or *Ch. obtusa*. This explains a clear difference in the character of the horizontal distribution between them. Particularly, the root system of *P. densiflora* has the character of absorbing nutriment or water even in the area far away from the root stock owing to the horizontal extention.

The horizontal extension of the root system decreased as the soil horizons became deeper, and rapidly so below 30 cm in depth. It was also found that the root biomass of the large and the very large roots was closely concentrated around the root stock.

2) Vertical distribution

Table 6 shows the vertical distribution of the root biomass of all the species and every part of the isolated trees as above-mentioned. This table shows the distibution and the ratio of the fine roots of each species in every soil horizon as shown in Table 6.

It is clear from this that *P. densiflora* and *C. japonica* are of the deep-root type with the root biomass much distributed to the lower soils, while *Ch. obtusa* and *P. densiflora* are of the shallow-rooted type with the root biomass maldistributed to the surface soils.

(1) Representation by the semi-logarithmic diagram

a. Species

Table 6 is drawn as Fig. 6. According to the figure, the root biomass decreases rapidly down to a given depth and then slowly in the lower soils. For this reason it is very difficult to comprehend such decreasing curves systematically. So here again as in the study of the horizontal distribution, these curves are put into a semi-logarithmic graph (Fig. 7). According to the figure, they become straight lines to certain depths where they bend into straight lines with less acute inclines.

This relation to the biomass of the fine roots of every species is shown in Fig. 7. As is clear from the figure, every species has this point where the gradient changes at the depth of 60 to 80 cm. The coefficients of regression became smaller in the order of the increasing ratio of root biomass to depth, that is, in the order of *Ch. obtusa*, *L. leptolepis*, *P. densiflora*

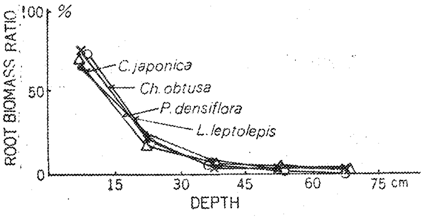


Fig. 6　Vertical distribution of root biomass.

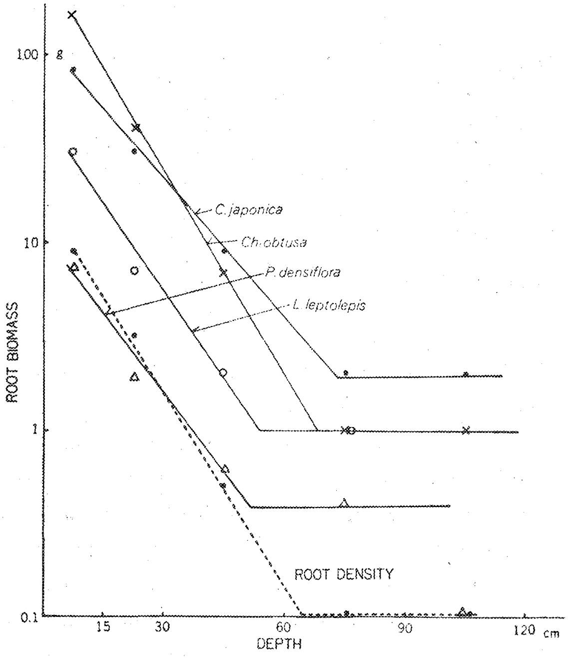


Fig. 7　Vertical distribution of the fine root biomass and root density of each species.

and *C japonica*. The same tendency was recognized in the change in root density.

The gradient of regression of small root becomes steep, as shown in Fig. 8. The tendency is remarkable in the case of the flat-rooted trees as *L. leptolepis* and *Ch. obtusa* and not in the case of the deep-rooted *C. japonica* and *P. densiflora*. This holds good in the case of the fine root.

This tendency is vague in the case of the medium and the large roots. The regression line of the large root bends downward in the soil horizon II in contrast with that of the fine root (Fig. 9 and 10).

b.　Root class

Fig. 11 shows the distribution of the root biomass according to every root class by depth. The gradient of the semi-logarithmic graph became less acute as the root system became larger in diameter from a fine root to a medium root. The lines of the fine and the small root bent upward at certain points around the depth of 60～80 cm, while that of the medium root bent downward.

The line of the large root also bent downward at the depth of about 20 cm. And at the same time, it was found that every root-size has its own way of distribution.

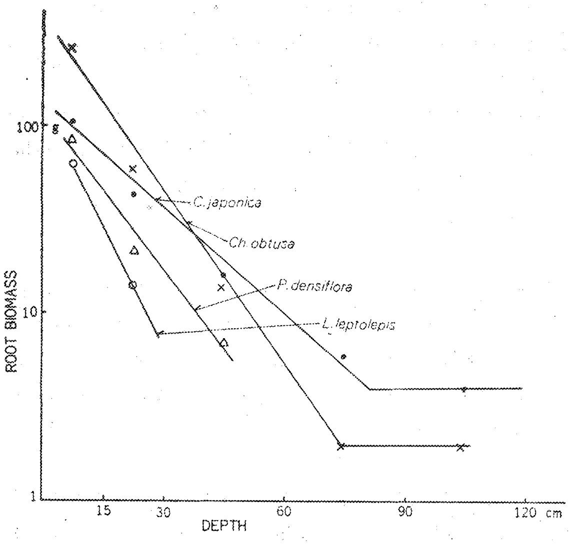
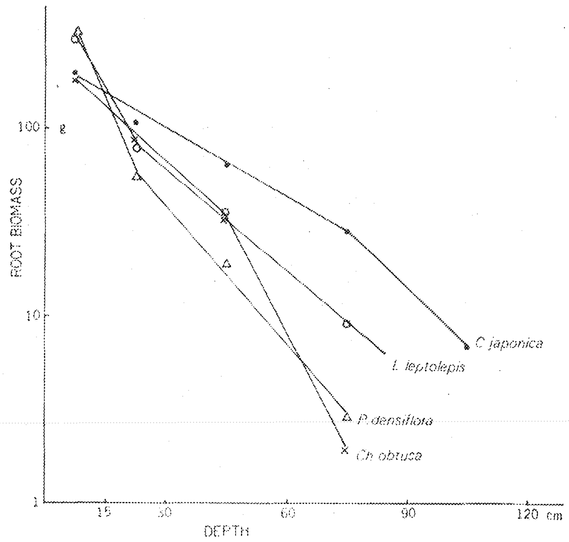


Fig. 8　Vertical distribution of the small root biomass.

c.　The vertical distribution of the root biomass in each horizontal division

The tendencies of the horizontal distribution, as already described in



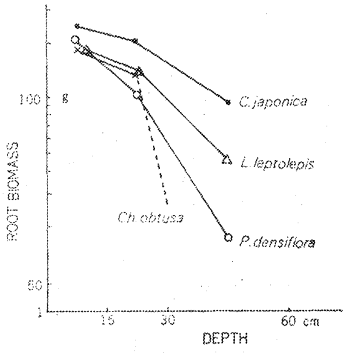


Fig. 10 Vertical distribution of the large root biomass.

Fig. 9 Vertical distribution of the medium root biomass.

the section dealing with the horizontal distribution, are different in each soil horizon. Similarly, the vertical distributions of the root biomass are different in each horizontal division.

The vertical change of the biomass of the small roots in every horizontal division is shown in Fig. 12, a semi-logarithmic graph. As shown there, the gradients of the graph of the root stock in horizontal divisions 1 and 2 near the root stock are not so steep, and the root biomass has a tendency to decrease slowly. In horizontal divisions 3 and 4, however, the gradients become steeper. Hence it is that the root weight decreases rapidly as the soil horizons go lower.

In horizontal divisions 1 and 2, where the roots are distributed to the deeper soils, the regression line bends at a depth of 40 to 50 cm. In other words, the character of the distribution of the root biomass changes here. The above-mentioned relation was also expressed on root density by a semi-logarithmic graph. The reader may refer to Fig. 13.

2. Distribution of the root biomass in a community

The question dealt with so far has been how a tree makes the root biomass distributing on an isolating condition. Here, we go into the argument how a tree distributes the root biomass horizontally and vertically, when the root system of it inter-

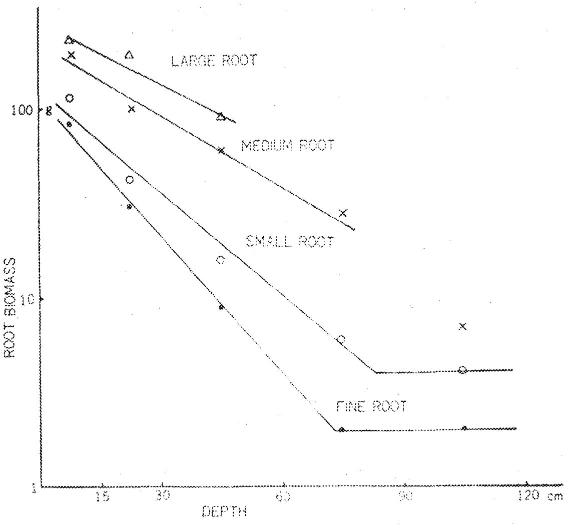


Fig. 11 Vertical distribution of each root biomass.

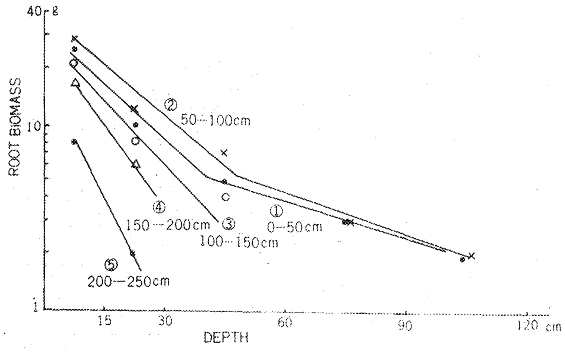


Fig. 12 Vertical distribution of the small root biomass of *C. japonica* in each horizontal division.

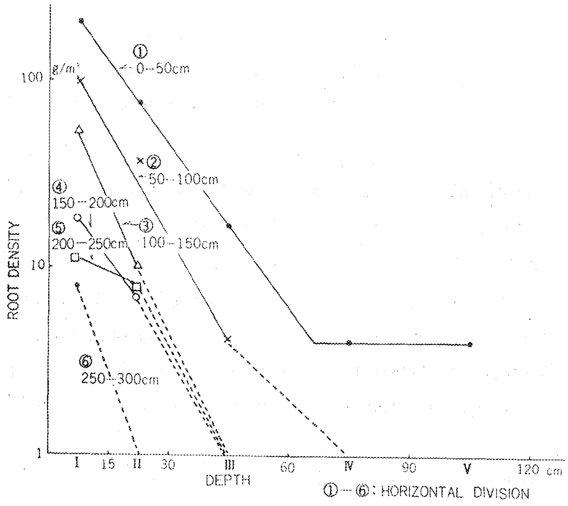


Fig. 13 Root density of each horizontal division in each soil horizon.

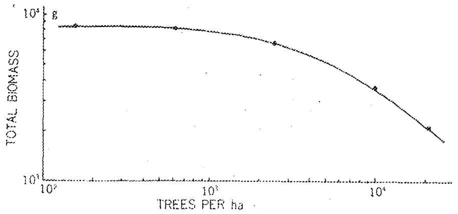


Fig. 14 Total biomass and tree density.

mingles with that of another.

When a tree is in a position of isolation, the root density goes down rapidly as it goes farther from the root stock. The root density of a tree growing in a dense community has, however, a tendency to be equalized at each part of the forest floor due to intermingling between root systems. Hence it is that the root density of the tree growing in high density decreases vertically more rapidly than that of an isolated tree, as the root systems intermingle with one another remarkably in the surface soil horizon.

An experiment was carried out on these relations as to the changes in root biomass by tree density. The result is shown in Fig. 20.

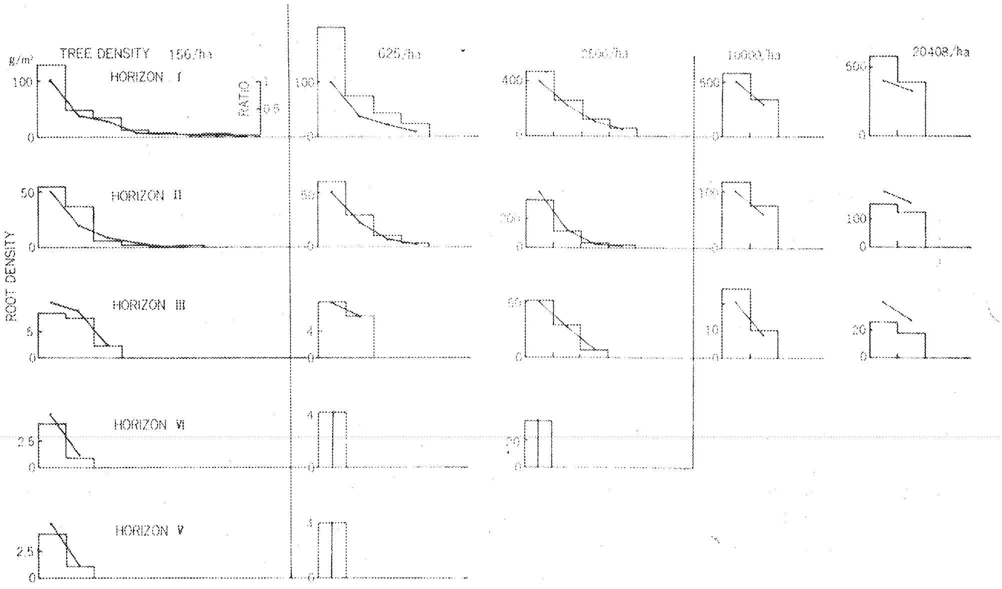
(1) Establishment of the sample blocs

Along with the investigation of the root system of the isolated trees in Asakawa nursery, the investigation of distribution of the root biomass was carried out as to the young trees, 6-year-old *C. japonica*, where 5 blocs with 156, 625, 2,500, 10,000 and 20,000 trees per ha were established. Each factor measurement of the investigated trees is shown in Fig. 20. Density effect by competition was recognized between the root density and the total root biomass as shown in Fig. 14.

The sample bloc was horizontally divided at every 50 cm width

Table 7. Design of the sample bloc for the study of relationship between root biomass and tree density

Tree density : Trees per ha	156	625	2,500	10,000		20,408	
Horizontal division	1～8	1～4	1～4	1	2	1	2
Width of division (cm)	50	50	25	25	5	20	15



Ratio : Ratio of the root density in each horizontal division to that in horizontal division 1.

Fig. 15 Root density in each horizon, and tree density.

as in the isolated trees. In the stands with higher density, the distance between the horizontal divisions was narrowed as shown in Table 7. Vertically, the sample bloc was divided at every 15 cm width into soil horizons I to V.

(2) Horizontal change of the root biomass

Fig. 15 shows the vertical and horizontal distributions of the density of the fine roots at every tree density. When a tree is in a position of isolation, the root density goes down, describing a slow-curved line at the farther distance from the root stock. That of the tree in a dense stand, however, is high as a whole, because the intermingling between the root systems takes place more and more remarkably as the tree density goes up. Particularly halfway between two trees, the root density tends to increase and to be equalized.

This tendency was perceived at all the soil horizons. As the tree density became higher, for example, difference decreased between the root densities around the root stock and halfway between the sample tree and its neighboring tree. This difference tended to increase gradually as the soil horizon went lower. In the blocs with over 10,000 trees, no root distribution could be observed in soil horizons IV and V, because the trees grew smaller and most of the roots grew unbalancedly in the surface soil horizon.

When the horizontal distribution of the fine root in soil horizon I is to be expressed in a semi-logarithmic graph, the gradient of the regression line becomes steeper as the root density becomes higher except for the bloc with 20,000 trees (Fig. 16).

This relation was also recognized in the small and the medium roots. The gradient of the regression line became steeper here again as the root system became larger and the density higher (See Fig. 17).

Let us calculate this relation by a semi-logarithmic equation. A result is shown in Table 8.

According to the table, the coefficients of regression became larger as the tree density

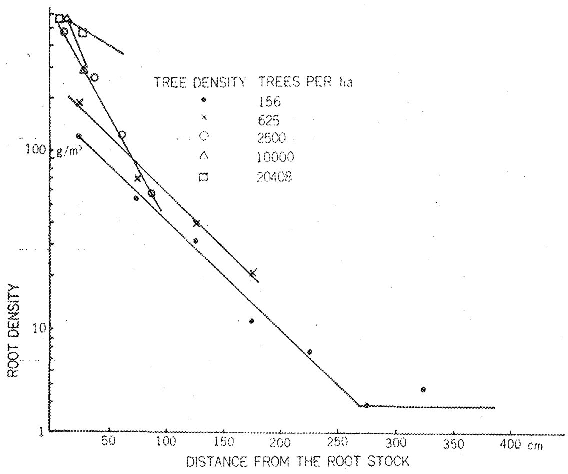


Fig. 16 Tree density and horizontal change in root density (Fine root, Horizon I, *C. japonica*).

became higher concerning the fine, small and medium roots. In the sparse stands, the coefficients of correlation became smaller instead, and the coefficients of variation became larger. For the slow-curved part is included in this calculation.

(3) Vertical change of the root biomass

As can be seen from the vertical distribution of the fine root biomass by tree density (Table 9 and Fig. 18), the distribution ratio by root biomass tends to go down in soil horizons I and II as tree density goes up. For example, in the bloc with 156 trees, 89% of the total biomass of the fine roots was distributed to the soil 30 cm deep from the surface soil, whereas 94% of that was distributed in the bloc with 20,000 trees.

This is mainly due to the difference in size between individuals. In the sparse planting blocs, the root system grows in the deeper soils as each individual is large. Inversely, in the dense planting blocs, it grows remarkably in the surface soil as each individual is small.

It is evident from another experiment that the root system of the tree in a dense-planting stand tends to grow in the lower soil horizons, because growth is checked in the surface soil by root competition[8]. This relation also differs according to soil conditions. It was observed in Asakawa nursery with black volcanic ash soil, that the content of water contained in the

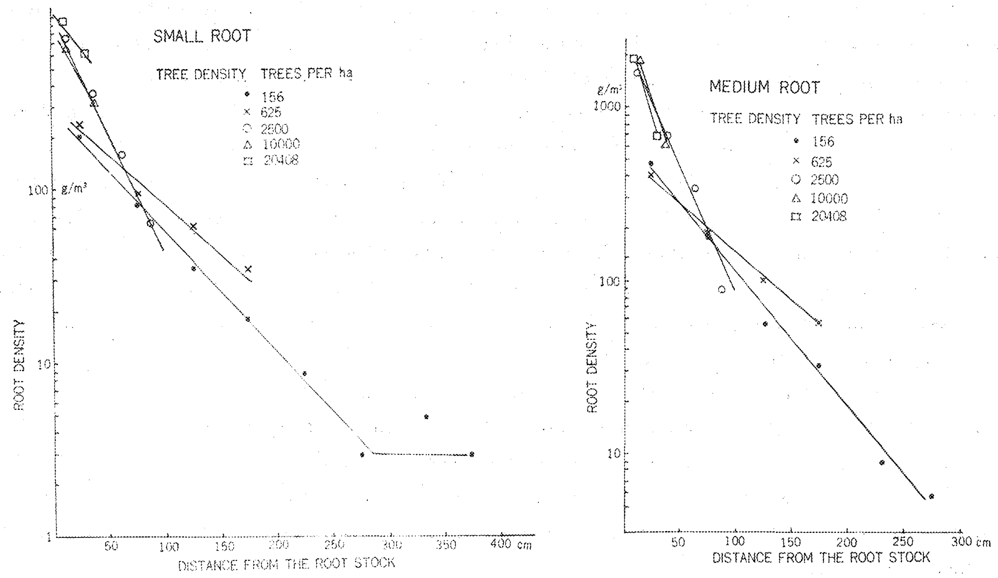


Fig. 17 Tree density and horizontal change in root density (Horizon I, *C. japonica*).

Table 8. Horizontal change in root biomass and tree density

Trees per ha			156	625	2,500	10,000	20,408
Root class	f	*a*	2.153561	2.398697	2.843895	2.997707	2.805302
		b	−0.005471	−0.006200	−0.012097	−0.018983	−0.004018
		$S_{xy/\bar{y}}$	0.1606	0.0340	0.0096	—	—
		r	0.9476	0.9851	0.9980	—	—
	s	*a*	2.319487	2.479192	3.071995	3.082655	3.092127
		b	−0.005776	−0.005502	−0.014024	−0.020055	−0.011292
		$S_{xy/\bar{y}}$	0.1929	0.0333	0.0118	—	—
		r	0.9892	0.9786	0.9975	—	—
	m	*a*	0.790546	2.743974	3.20111	3.662861	3.505384
		b	−0.008417	−0.005733	−0.016644	−0.032014	−0.023655
		$S_{xy/\bar{y}}$	0.0438	0.0163	0.0147	—	—
		r	0.9892	0.9939	0.9967	—	—

Table 9. Vertical distribution of fine roots and tree density

Trees per ha / Horizon	156		625		2,500		10,000		20,408	
I	86*	(65)**	91	(72)	75	(63)	53	(75)	38	(74)
II	31	(24)	26	(21)	30	(26)	13	(19)	10	(20)
III	9	(7)	6	(5)	10	(9)	4	(6)	3	(6)
IV	2	(2)	1	(1)	2	(2)	—		—	
V	2	(2)	1	(1)	—		—		—	
Total	130	(100)	125	(100)	117	(100)	70	(100)	51	(100)

* g, ** (%)

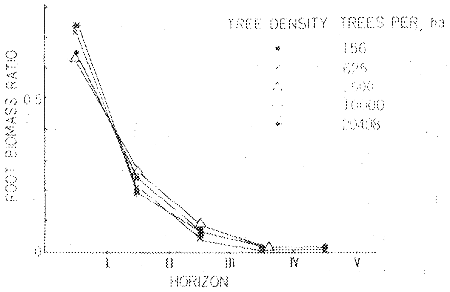


Fig. 18 Tree density and ratio of the root biomass in each soil horizon to the total biomass.

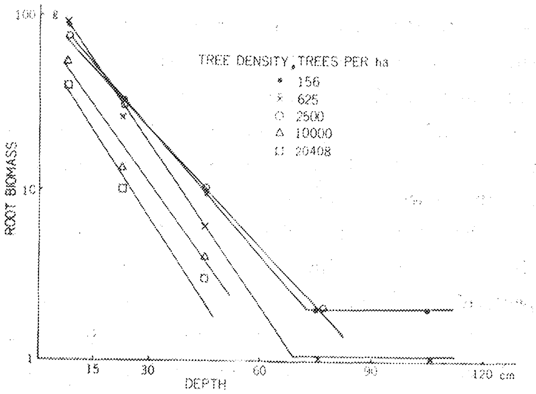


Fig. 19 Tree density and vertical distribution of the fine root biomass of *C. japonica*.

surface soil increased as the tree density increased, and the fine roots grew dense there.

The relation between the tree density and the vertical distribution of the root biomass is shown in Fig. 19, a semi-logarithmic graph. According to the figure, the slow-curving parts tended to disappear and the gradient of the regression lines tended to become steeper with the increasing tree density.

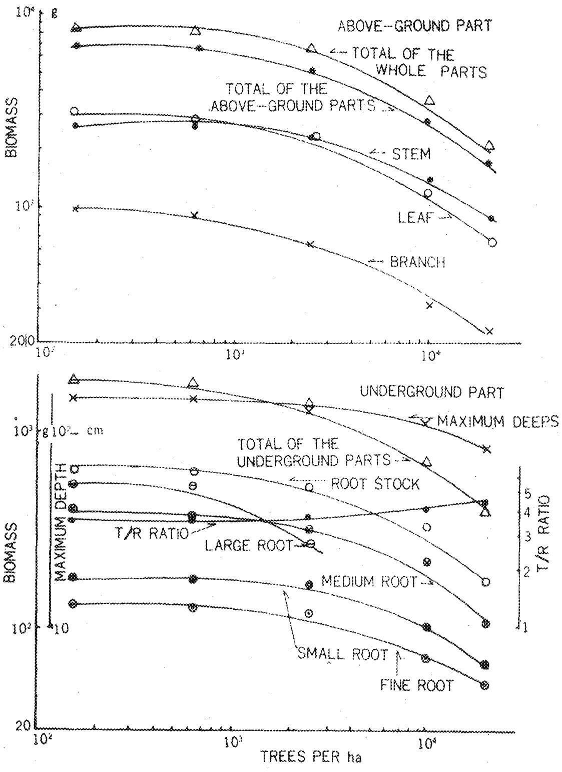


Fig. 20 Tree density and average part biomass per tree.

(4) Tree density and the part biomass of a tree

The relation between the tree density and the partical biomass of a tree is shown in Fig. 20. As is evident from it, each partial biomass of the above-and-under ground parts shows a rapid rate of increase as the tree density reaches about 2,000 to 2,500. This is due to the effect of tree density. The phenomenon does not take place so remarkably at the above-ground part as at the underground part. The relation between the tree density and the T/R ratio is shown in Fig. 20. With decrease of the partial biomass by the effect of tree density, the T/R ratios increased in a slightly concave curve upwards. They came up to about 3.5 in the most sparse planting bloc, 3.8 in the bloc with 3,000 trees, and 4.4 in the bloc with 20,000 trees.

The influence by tree density occurs greatly in the underground part rather than in the above-ground part; that is to say, the biomass of the underground part decreases more remarkably than that of the above-ground part along with the increasing tree density. It has not been made clear yet why the biomass of the underground part is easily affected by tree density. It is likely that the external forces inflicted on the above-ground parts affect the growth of the root system to enhance the supporting power of the root.

The effect of tree density on the above-ground part is remarkable at the leaves rather than at a stem. The biomass of the stem and the leaf in the bloc with 20,000 trees are respectively 34% and 22% of those in the bloc with 156 trees.

As concerns the underground part, the biomass of the fine root and the root stock in the bloc with 20,000 trees are 40% and 28% of those in the bloc with 156 trees respectively. The increase of tree density puts a limitation on the growth of root stocks rather than that of fine roots. The same tendency is also recognized among the other roots. It means that as the root becomes larger, the root biomass is affected more easily by tree density. For the ratios of the fine and the small roots increase rather than those of the large root and the root stock do, when the individual tree becomes smaller by the competitive density effect.

Thus, the supporting power of the root system decreases in the dense planting stands as the roots larger than the large root supporting the above-ground parts, grow poor.

The maximum depth of the root system is not much affected by tree density. This factor of the root system in the full density stand was about 60% of that in the sparse planting stands.

3. Representation of the root biomass distribution curve by GRAM-CHARLIER's expansion

As already pointed out, it is difficult to express the change of the slow-curved parts accurately by the above-mentioned semi-logarithmic equation. It is also impossible to estimate the root biomass at the slow-curved part by this equation. Therefore, its representation by GRAM-CHARLIER's expansion was applied in order to express the change in root biomass accurately.

The equations to be used in calculation are as follows:

GRAM-CHARLIER's expansion

$$\begin{aligned} f(x) &= \sum Cm\phi m(x) \\ &= C_0\phi_0(x) + C_1\phi_1(x) + C_2\phi_2(x) \cdots\cdots \end{aligned} \qquad \begin{aligned} \phi m(x) &= Pm(x)\phi_o(x) \\ \phi_o(x) &= \frac{a^x}{x!}e^{-a} \end{aligned}$$

$$\begin{aligned} f(x) = \Big[1 &+ C_2\left(\frac{x(x-1)}{a^2} - 2\frac{x}{a} + 1\right) \\ &+ C_3\left(\frac{x(x-1)(x-2)}{a^3} - \frac{3x(x-1)}{a^2} + \frac{3x}{a} - 1\right) \\ &+ C_4\left(\frac{x(x-1)(x-2)(x-3)}{a^4} - \frac{4x(x-1)(x-2)}{a^3} + \frac{6x(x-1)}{a^2} - \frac{4x}{a} + 1\right)\Big]\phi_o(x) \end{aligned}$$

$$\left.\begin{aligned} \mu_1' &= \textstyle\sum_{x=o}^{\infty} xf(x) \\ \mu_2' &= \textstyle\sum x^2 f(x) \\ \mu_3' &= \textstyle\sum x^3 f(x) \\ \mu_4' &= \textstyle\sum x^4 f(x) \end{aligned}\right\} \rightarrow \left.\begin{aligned} \lambda_1 &= \mu_1' = M \\ \lambda_2 &= \mu_2' - \mu_1'^2 = \sigma \\ \lambda_3 &= \mu_3' - 3\mu_2'\mu_1' + 2\mu_1'^3 \\ \lambda_4 &= \mu_4' - 4\mu_3'\mu_1' - 3\mu_2'^2 + 12\mu_2'\mu_1'^2 - 6\mu_1'^4 \end{aligned}\right\} \rightarrow$$

$$\begin{aligned} C_o &= 1 \\ C_1 &= 0 \\ \rightarrow \quad C_2 &= \frac{\lambda_2 - \lambda_1}{2} \\ C_3 &= \frac{2\lambda_1 - 3\lambda_2 + \lambda_3}{2} \\ C_4 &= \frac{-6\lambda_1 + 11\lambda_2 - 6\lambda_3 + \lambda_4 + 3(\lambda_2 - \lambda_1)^2}{24} \end{aligned}$$

1) Horizontal change in root density (extensive-root type and intensive-root type)

Calculation was carried out on the density of the fine roots of *C. japonica*, *Ch. obtusa*, *P. densiflora*, and *L. leptolepis*, at each horizontal division of soil horizon I. For the sake of convenient comparison among species, the ratios of the root density at each horizontal division were calculated first (Table 10). Then, calculation by the above-mentioned equations was done with these ratios as the independent variable and distance from the root stock as dependent variable (0 for 0 to 50 cm, 1 for 50 to 100 cm, 2 for 100 to 150 cm……).

From these calculations, the figures in Table 11 were obtained. The equation was made up to represent the ratios of the root density of every species at each horizontal division.

The ratio of the root density at each depth calculated by this equation is shown in Table 10 and Fig. 21. When it is used, the slow-curved part which was not well calculated by the semi-logarithmic equation is obtained, although each species has small errors.

Such coefficients of the items as x^4, x^3 and x^2 used in this equation were small for *P. densiflora* and *L. leptolepis* with the widely distributed root systems and many slow-curved parts. And yet they were large for *C. japonica* and *Ch. obtusa* with much root biomass around the root stock. The difference by the property of species was found out in the latter.

The trees with the large coefficients of the items, e. g., x^4, x^3 and x^2, may be called of the extensive-root type, and those with the small coefficients, of the intensive-root type.

Table 10. Calculated and measured values when

Horizontal division (cm)	*C. japonica*			*Ch. obtusa*		
	Measured value (M)	Calculated value (C)	C/M	Measured value (M)	Calculated value (C)	C/M
0～ 50	0.533*	0.525	0.98	0.511	0.502	0.98
50～100	0.202	0.229	1.13	0.239	0.321	1.34
100～150	0.142	0.114	0.80	0.123	0.077	0.63
150～200	0.050	0.053	1.06	0.043	0.025	0.58
200～250	0.034	0.038	1.12	0.027	0.053	1.96
250～300	0.013	0.025	1.92	0.019	0.045	2.37
300～350	0.021	0.011	0.52	0.024	0.021	0.88
350～400	0.004	0.004	1.00	0.014	0.007	0.50
Total	1.000			1.000		

* **Ratio of root density at each horizontal division to that of the total.**

Table 11. Independent variables, dependent variables, measured values and calculated values used in calculation

Species		*C. japonica*		*Ch. obtusa*		*P. densiflora*	
Horizontal division (cm)	x	Root density	Ratio (y_1)	Root density	Ratio (y_2)	Root density	Ratio (y_3)
0～ 50	0	127	0.533	212	0.511	4.1	0.372
50～100	1	48	0.202	99	0.239	2.3	0.209
100～150	2	34	0.142	51	0.123	1.0	0.091
150～200	3	12	0.050	18	0.043	0.8	0.073
200～250	4	8	0.034	11	0.027	0.8	0.073
250～300	5	3	0.013	8	0.019	0.7	0.064
300～350	6	5	0.021	10	0.024	0.8	0.073
350～400	7	1	0.004	6	0.014	0.5	0.045
Total			1.000		1.000		1.000

Species	Calculated values									
	μ_1'	μ_2'	μ_3'	μ_4'	λ_1	λ_2	λ_3	λ_4	C_0	C_1
C. japonica	0.993	3.045	12.405	60.189	0.993	2.0590	5.2922	13.2954	1	0
Ch. obtusa	1.017	3.495	16.473	89.195	1.017	2.4607	7.9135	22.4973	1	0
P. densiflora	1.975	8.831	46.783	268.919	1.975	4.9300	9.8668	−12.5762	1	0
L. leptolepis	1.461	5.541	26.757	145.893	1.461	3.4065	8.7079	12.0086	1	0

Species		Equations showing the changes in root density
C. japonica	Intensive-root type	$f(x)=(0.070401x^4-0.514561x^3+1.449537x^2-$
Ch. obtusa	Intensive-root type	$f(x)=(0.087025x^4-0.459503x^3+0.797208x^2-$
P. densiflora	Extensive-root type	$f(x)=(-0.008764x^4+0.100778x^3+0.057366x^2-$
L. leptolepis	Extensive-root type	$f(x)=(-0.001735x^4+0.095988x^3-0.173161x^2-$

the Gram-Charlier's expansion is used

P. densiflora			*L. leptolepis*		
Measured value (M)	Calculated value (C)	C/M	Measured value (M)	Calculated value (C)	C/M
0.372	0.348	0.94	0.423	0.405	0.96
0.209	0.283	1.35	0.237	0.311	1.31
0.091	0.043	0.47	0.119	0.074	0.62
0.073	0.030	0.41	0.085	0.048	0.56
0.073	0.101	1.38	0.034	0.074	2.18
0.064	0.103	1.61	0.034	0.059	1.74
0.073	0.060	0.82	0.051	0.030	0.59
0.045	0.024	0.53	0.017	0.011	0.65
1.000			1.000		

L. leptolepis	
Root density	Ratio (y_4)
25	0.423
14	0.237
7	0.119
5	0.085
2	0.034
2	0.034
3	0.051
1	0.017
	1.000

C_2	C_3	C_4
0.5330	0.1835	0.0684
0.7219	0.4276	0.0931
1.4775	−0.1622	−0.1334
0.9725	0.2353	−0.0079

$1.800161x+1.4179)\phi_0(a:x)$

$0.939280x+1.3874)\phi_0(a:x)$

$1.621842x+2.5063)\phi_0(a:x)$

$0.747571x+1.7451)\phi_0(a:x)$

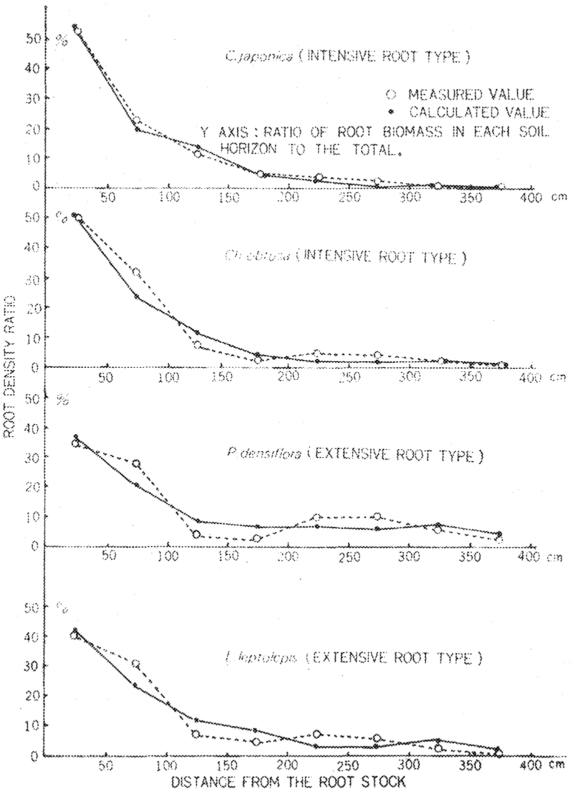


Fig. 21 Values measured and calculated by using Gram-Charier's expansion.

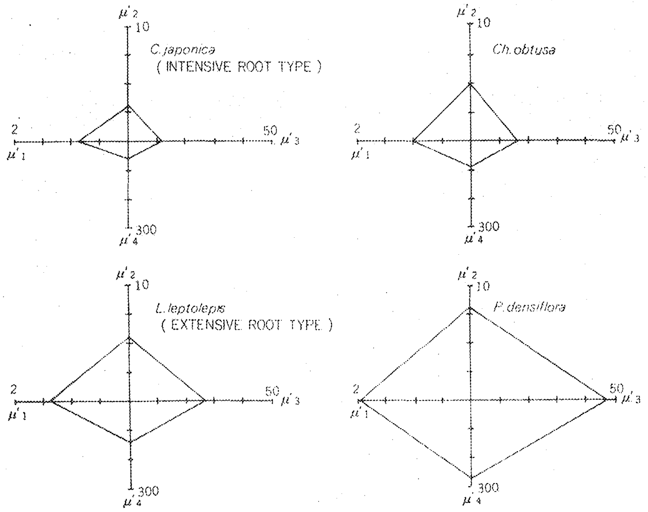


Fig. 22 Moment (μ') figured by a GRAM-CHARLIER's expansion. Horizontal change in root density.

Table 12. Independent variables, dependent variables, measured values, and calculated values used in calculation

Depth (cm)	X	*L. leptolepis* (Shallow-rooted)		*C. japonica* (Deep-rooted)		*L. leptolepis* (Shallow-rooted)		
		Root weight	Ratio y_1	Root weight	Ratio y_2	Measured value (M)	Calculated value (C)	C/M
0～ 10	0	233	51.3	118	27.0	0.513	0.502	0.98
10～ 20	1	72	15.8	87	20.0	0.158	0.193	1.22
20～ 30	2	47	10.3	66	15.0	0.103	0.077	0.75
30～ 40	3	28	6.2	52	12.0	0.062	0.052	0.84
40～ 50	4	22	4.8	44	10.0	0.048	0.055	1.15
50～ 60	5	21	4.6	31	7.0	0.046	0.055	1.20
60～ 70	6	16	3.5	17	4.0	0.035	0.038	1.09
70～ 80	7	12	2.6	9	2.0	0.026	0.019	0.73
80～ 90	8	3	0.7	4	1.0	0.007	0.007	1.00
90～100	9	1	0.2	4	1.0	0.002	0.002	1.00
100～110	10	0	0.0	0	0.0	—	—	—
Total		445	100.0	432	100.0			

Species	Calculated values									
	μ_1'	μ_2'	μ_3'	μ_4'	λ_1	λ_2	λ_3	λ_4	C_0	C_1
L. leptolepis (Shallow-rooted)	1.438	6.190	32.998	197.446	1.438	4.1222	12.2414	20.6367	1	0
C. japonica (Deep-rooted)	2.260	10.100	57.700	388.100	2.260	4.9924	12.3084	22.9776	1	0

Species	Equations showing the changes in root density
L. leptolepis (Shallow-rooted)	$f(x)=(0.053718x^4-0.477049x^3+1.705218x^2-$
C. japonica (Deep-rooted)	$f(x)=(0.020550x^4-0.282387x^3+1.419382x^2-$

It is better to examine the items μ_1', μ_2', μ_3' and μ_4' used in the above-mentioned equation for mere comparison of the difference among the changing tendencies. The correlation among these numerical values of every species obtained from the above-mentioned materials is shown in Fig. 22. According to the figure, the root density is comparatively high at the part far from the root stock. The value of μ' became smaller in the order of *P. densiflora*, *L. leptolepis*, *Ch. obtusa*, and *C. japonica*. Particularly, the value of μ_3' of *P. densiflora* was large. The difference was clearly recognized among the figures of these species.

Also here the tree with the large value of μ' can be called to be of extensive-root type and the tree with small value of it of intensive-root type.

2) **Vertical distribution of the root density (deep-rooted type and shallow-rooted type)**

The Gram-Charlier's expansion can express not only the horizontal change of the root density but the vertical change of it.

Let us calculate according to the above-mentioned equation the vertical change of the root densities of *C. japonica* and *L. leptolepis*, two years old, in Meguro nursery. A result is shown in Table 12 and Fig. 23. Clearly, the equation is very accurate. The calculated values agree quite closely with the measured ones.

As concerns the vertical change as well as the horizontal change in root density, the coefficients of the items x^2, x^3 and x^4 were large for the shallow-rooted *L. leptolepis* which root density went down rapidly in the lower soil horizons and small for the deep-rooted *C. japonica*.

C. japonica (Deep-rooted)		
Measured value (M)	Calculated value (C)	C/M
0.270	0.271	1.00
0.200	0.199	1.00
0.150	0.141	0.93
0.120	0.139	1.16
0.100	0.098	0.98
0.070	0.056	0.80
0.040	0.037	0.93
0.020	0.027	1.35
0.010	0.016	1.60
0.010	0.009	0.90
……	……	……

C_2	C_3	C_4
1.3420	0.4586	0.2297
1.3660	0.3087	0.5363

$2.830565x+2.1131)\phi_0(a:x)$

$2.905820x+2.5936)\phi_0(a:x)$

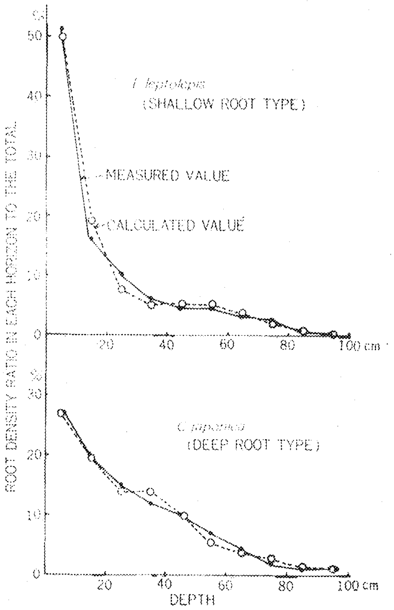


Fig. 23 The measured values and the calculated values by Gram-Chalier's expansion (Vertical change in root density).

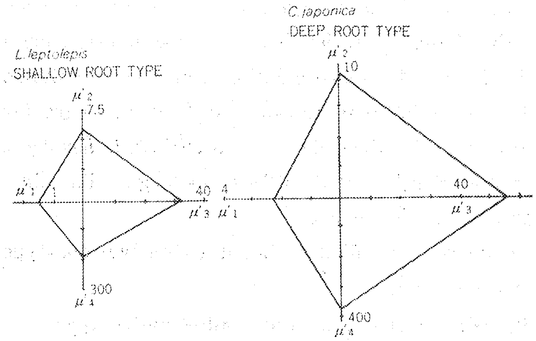


Fig. 24 Moment (μ') figured by a GRAM-CHARIER's expansion: (Vertical change in root density.)

This relation is shown in Fig. 24 when it is to be expressed by the values of μ'. The value of μ' is small for the shallow-rooted *L. leptolepis*, the root biomass of which is maldistributed to the surface soil, and large for the deep-rooted *C. japonica* whose root biomass was distributed to the deep soils. A remarkable difference was perceived between them.

In this way, the root distribution changes horizontally and vertically according to a slow-curved line. Particularly, this tendency is remarkable in the fine root. From the studies which have been dealt with so far, it is clear that this curve could not be fully expressed by any semi-logarithmic or logarithmic equation, and that the curve, inclusive of the slow-curving parts, could be calculated very accurately by GRAM-CHARLIER's expansion.

IV. Analysis of the structure of the underground part in the stand investigation

1. Process for analysing the structure of the underground part

The factors indicating the structure of the underground parts in stands, such as the biomass length, surface area or volume of the root system, were obtained according to such a process as shown in Fig. 25.

At the first stage, the average diameter and bulk density were measured, from which the root length and volume per unit root weight were calculated. The root length and volume per gram were then multiplied by the average root weight to obtain the average root weight and root volume of a tree from which factors of the root system per ha were calculated, making use of the relation between the sample trees of stands and the basal area.

2. Part biomass

As concerns the sample trees in the stands, the average values of a tree and the proportion to each part were first calculated from the sample trees which were already measured according

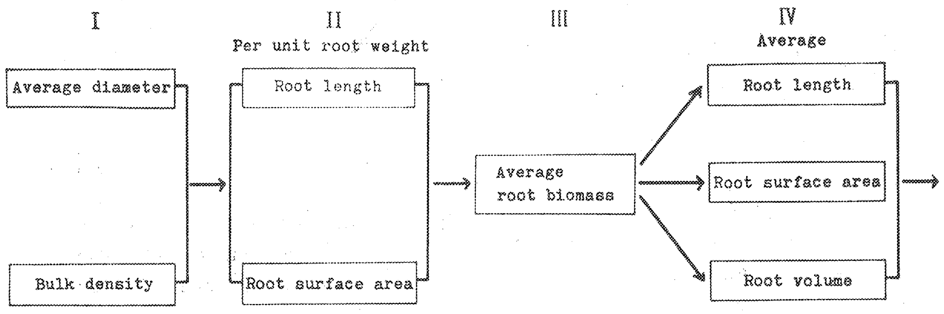


Fig. 25 A procedure for the calculating of the factors of the underground

to such methods as have been already dealt with in the preceding number⁴⁾. The part biomass per ha were then calculated from them and by a ratio estimate method of basal area. And in addition, to get the total production at full density, the partial weights were calculated from the density indices.

The root biomass and the ratios of them to each soil horizon and to each horizontal division were calculated.

The structure of a stand, above-and-under ground, will be explained henceforth dealing mainly with these part biomass and their ratio.

1) **Average value of sample tree in a stand**

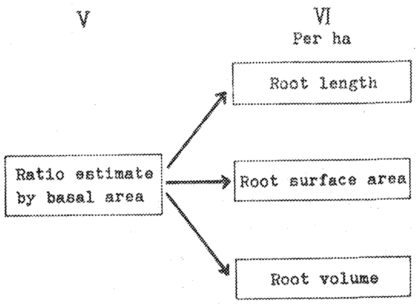
The average values of the sample trees in each sample stand are shown in Appendix-Table 2 on the preceeding number⁴⁾.

Let us examine the relation between the average values and the basal areas in each sample stand. A result is shown in Fig. 26. As clear from it, the unique regression curves were obtained for each part, such as stem, branch, leaf, root, etc.

Of all the parts, the accumulating parts, such as a stem, branch, large root, very large root, and root stock, drew a slightly concave increasing curve upward, whereas the working parts, such as a leaf, fine root, small root, and medium root, produced a straight increasing line or a parabolic increasing curve. Thus, it is because the above-ground parts are highly related to the underground parts from the standpoint of function that they both have an almost similarity in variation. Furthermore, from the increasing curve of the leaves and fine to medium roots, it is apparent that the root biomass shows a great rate of increase rather than the leaf biomass. A comparatively earlier time is when the current annual increment of a tree comes up to its maximum. It is in line with the changing time of the biomass of fine to medium roots. Therefore, it is not unreasonable to say that there exists a high interrelation between them. Hence it is that the increasing biomass of fine to medium roots and the consequently increasing absorption of nutriment and water are both connected with the tree growth more closely than the leaf biomass.

The unworking parts* have a greater portion of the total biomass and biomass of the above-and-under ground parts; and therefore, their change is to be expressed by a slightly concave curve upwards similar to these curves.

As explained above and in Fig. 25-1, each part and each species have their own increasing curve, so it is quite difficult to express those relations by a certain equation. For this reason the coefficients of the measured individuals, all run together in the normal stands of all the sample stands, were calculated according to the equations from ① to ⑦. A result is shown in Table 42 on the preceeding number⁴⁾. Specifically, the coefficients of regression selected from it as an indication of growth and calculated by equation ⑤ are shown in Table 13. There we see that the accumulating parts, such as a stem, above-ground part, and the underground part, got the large coefficients of 0.8 to 1.0, whereas the working parts, such as a leaf, branch, fine root, and small root, got the remarkably small coefficients of 0.2 to 0.4. These are characteristic of part in a stand.



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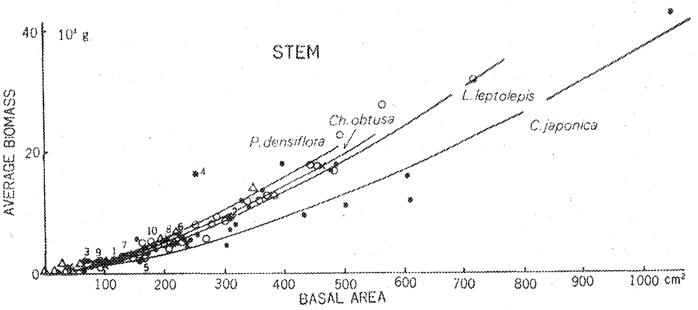
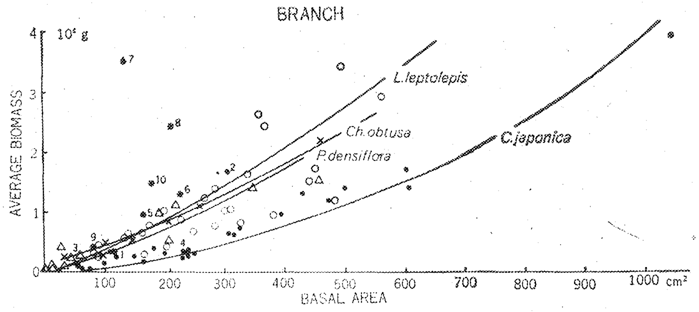
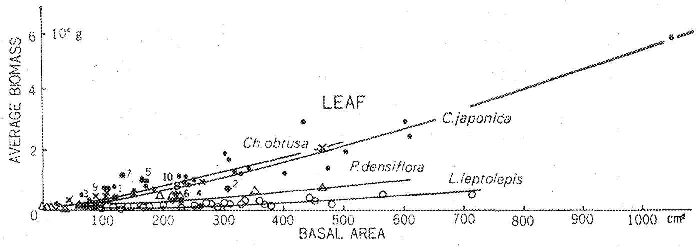
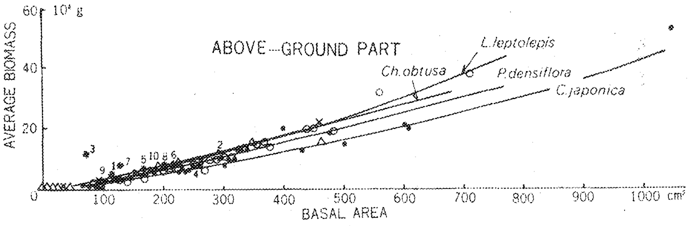
* The working parts are the leaf and the fine root which are related to absorption and assimilation, and the unworking parts the others.









The sign * indicates the other species except for *C. japonica*, *Ch. obtusa*, *P. densiflora*, and *L. leptolepis*. This is applied to the tables which have been used hereafter. See M 1 to M 10 on the Bulletin No. 259 of For. Exp. Sta. The other species here are *Ch. pisifera* (*1, 2), *Eucalyptus globulus* (*3), *Zelkova serrata* (*4), *Abies firma* (*5), *Tsuga canadensis* (*6), *Quercus mongolica* v. *grosseserrata* (*8), *Betula platyphylla* v. *japonica* (*9), and *B. davurica* (*10).

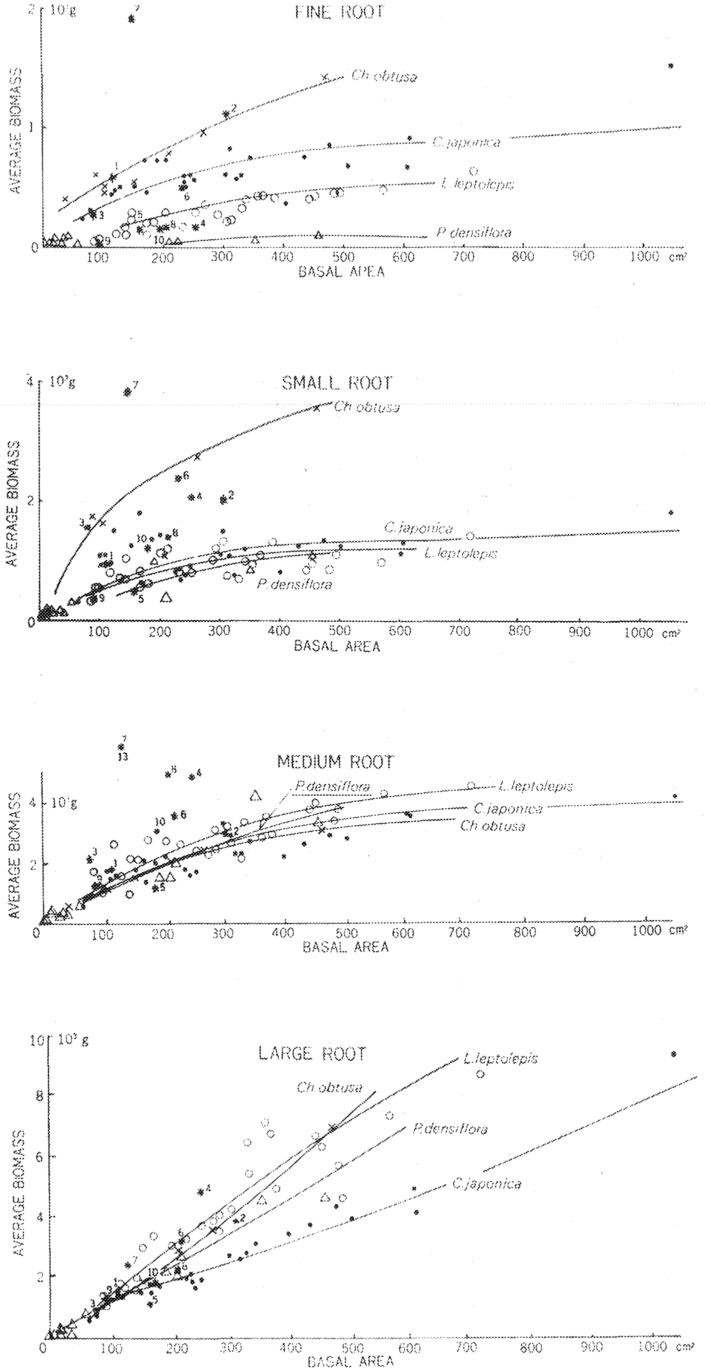


Fig. 26 Average biomass of each part a tree.

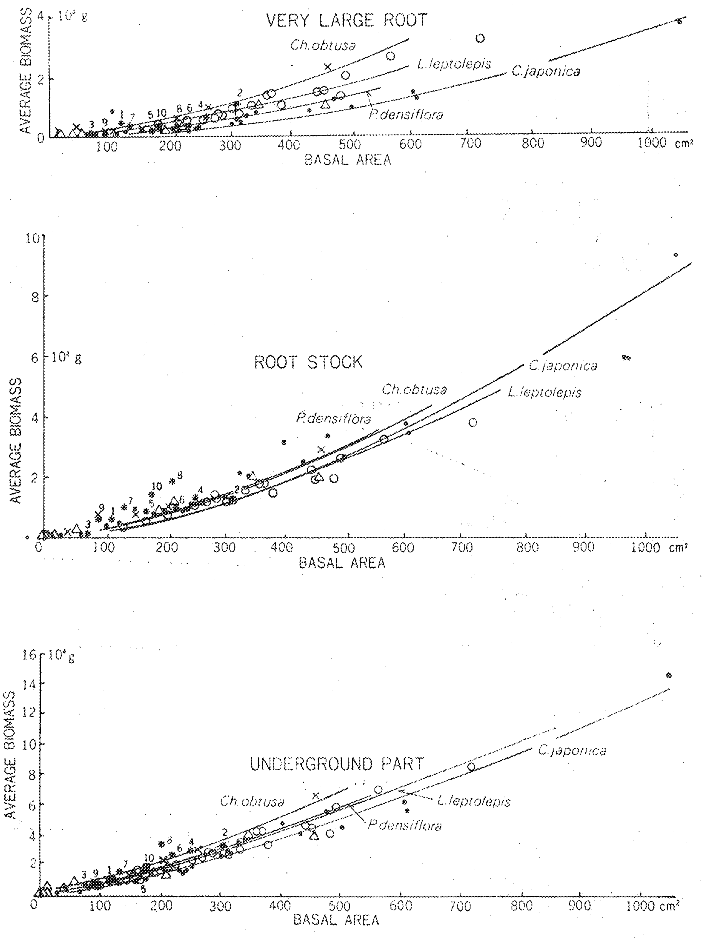


Fig. 26 (Continued)

them. These coefficients also differ with species. They were, for example, 0.24 for the fine root of *P. densiflora* with a low rate of increase, and 0.44 for that of *C. japonica* with a high rate of increase.

Each species's root biomass is shown in Table 14 when it is estimated from Fig. 26 at the basal area of 500 cm². There, each part is clearly characteristic of each species. The biomass of the stem and the branches of *C. japonica* were much smaller than those of the other species.

Table 13. Regression coefficients in each part biomass of trees calculated by equation No. 5 (%)

Species \ Part (y)	1*	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
C. japonica	95	80	57	84	44	42	50	69	—	94	82	84	58	63	67	93	43	87	90	52	23
Ch. obtusa	95	60	41	79	37	51	43	69	38	80	77	79	49	27	42	87	46	83	85	38	19
P. densiflora	91	75	64	85	24	45	61	—	—	88	82	85	58	61	45	88	41	87	86	54	20
L. leptolepis	88	105	77	90	38	26	50	63	116	79	80	88	107	77	107	90	30	82	88	95	33

* Equation No. 5 : $\log y = a + b \log (D^2H)$

Table 14. Estimated part biomass of each species, 500 cm² in basal area (kg)

Part \ Species	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
Stem	130	200	210	195
Branch	12	22	22	28
Leaf	22	23	8	4
Above-ground part	164	245	240	227
f	0. 8	1. 3	0. 1	0. 5
s	1. 3	1. 7	1. 0	1. 1
m	3. 4	3. 2	3. 8	4. 0
l	3. 8	7. 4	5. 7	7. 0
L	11	24	13	17
St	27	32	32	27
Underground part	47. 3	69. 6	55. 6	56. 6

The main reasons for this are the following two. First, their part biomass are small. Second, they hold many young tissues and high water content, due to favorable growth. The part biomass of the fine roots were 0. 8 kg for *C. japonica*, 1. 3 kg for *Ch. obtusa*, 0. 1 kg for *P. densiflora*, and 0. 5 kg for *L. leptolepis*. Clearly, those of *C. japonica* and *Ch. obtusa* were much larger than those of *P. densiflora* and *L. leptolepis*.

2) Part biomass per ha

The part biomass per ha was calculated from the average values in relation to basal area. They are shown in Fig. 27.

The curves of Fig. 27 can be classified into two types, the one describing a parabolic curve of the part biomass increasing, which answers to the increasing basal areas, and the other showing the part biomass increasing temporarily in the prematured stands at the basal area of 150～200 cm² and then their decreasing with the growing stands.

The former is the curve of the accumulating parts, such as the stem, branch, large root, very large root, root stock, biomass of the above-and-underground parts, and the total biomass, occupied preponderantly by those parts. The latter is the curve of the working parts, such as the leaf, fine, small and medium roots, and parts relating to them. It has a clear and direct relation to the form of the curves showing the average values of a tree. This is proved by the curves describing the average values of a tree.

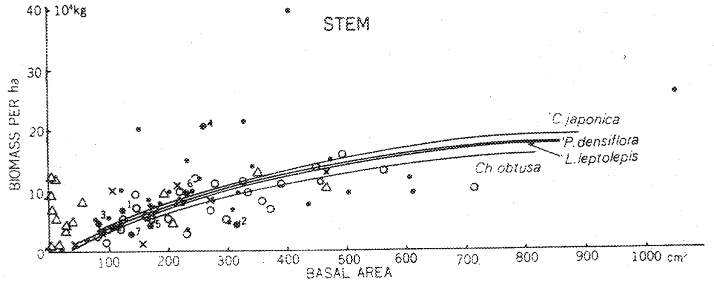
The part biomass per ha varies with stands due to their number of trees. Generally speaking, the change of this calculation is much greater than that of the average value of a tree.

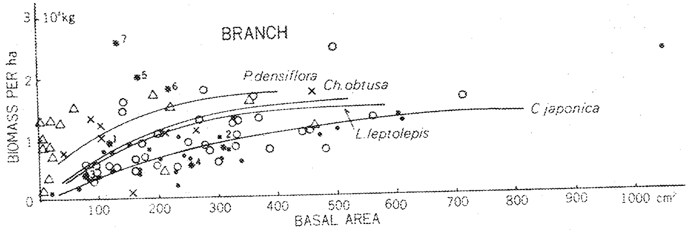
(1) Above-ground parts

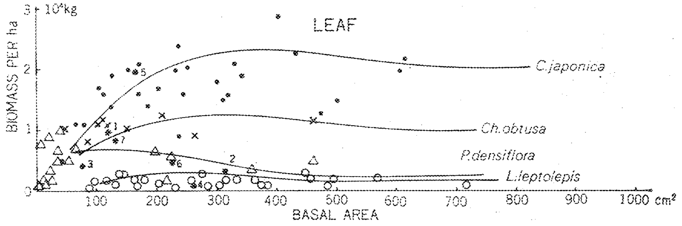
Stem : The stem biomass per ha at the basal area of 500 cm² were 100～120 tons for *C. japonica*, *Ch. obtusa*, *P. densiflora*, and *L. leptolepis*. Particularly in the stand of S 22 with a high density index, it got up to 400 tons. The stands which show a comparatively large stem biomass in Fig. 27, say, S 23, S 16, etc., are all the stands of which density indices are large.

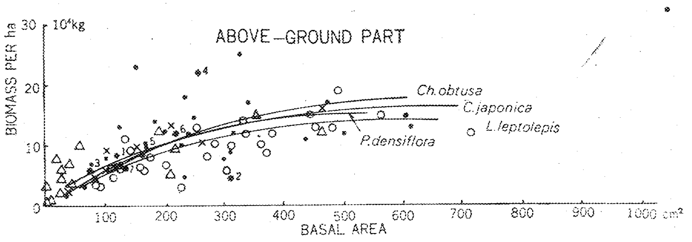
Branch : The species do not make so great a difference in branch biomass as in the average values of a tree. And yet *P. densiflora*, *L. leptolepis*, and *Ch. obtusa* tend to get larger values than *C. japonica*. The standing branch biomass, for example, of the former three were almost 15 tons, but that of *C. japonica* about 10 tons a stand at the basal area of about 500 cm².

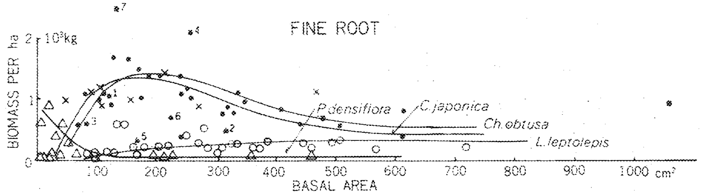
The basal area-branch biomass curve goes up at a rapid rate of increase before the basal area comes up to 200 or 300 cm². After that, it goes gentler. This, however, is dominant

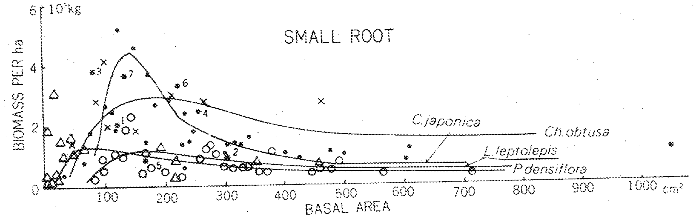

STEM
40 10⁴kg
30
20
10
0
BIOMASS PER ha
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA
C.japonica
P.densiflora
L.leptolepis
Ch.obtusa


BRANCH
3 10⁴kg
2
1
0
BIOMASS PER ha
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA
P.densiflora
Ch.obtusa
C.japonica
L.leptolepis


LEAF
3 10⁴kg
2
1
0
BIOMASS PER ha
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA
C.japonica
Ch.obtusa
P.densiflora
L.leptolepis


ABOVE-GROUND PART
30 10⁴kg
20
10
0
BIOMASS PER ha
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA
Ch.obtusa
C.japonica
L.leptolepis
P.densiflora


FINE ROOT
2 10³kg
1
0
BIOMASS PER ha
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA
P.densiflora
C.japonica
Ch.obtusa
L.leptolepis


SMALL ROOT
6 10³kg
4
2
0
BIOMASS PER ha
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA
C.japonica
Ch.obtusa
L.leptolepis
P.densiflora

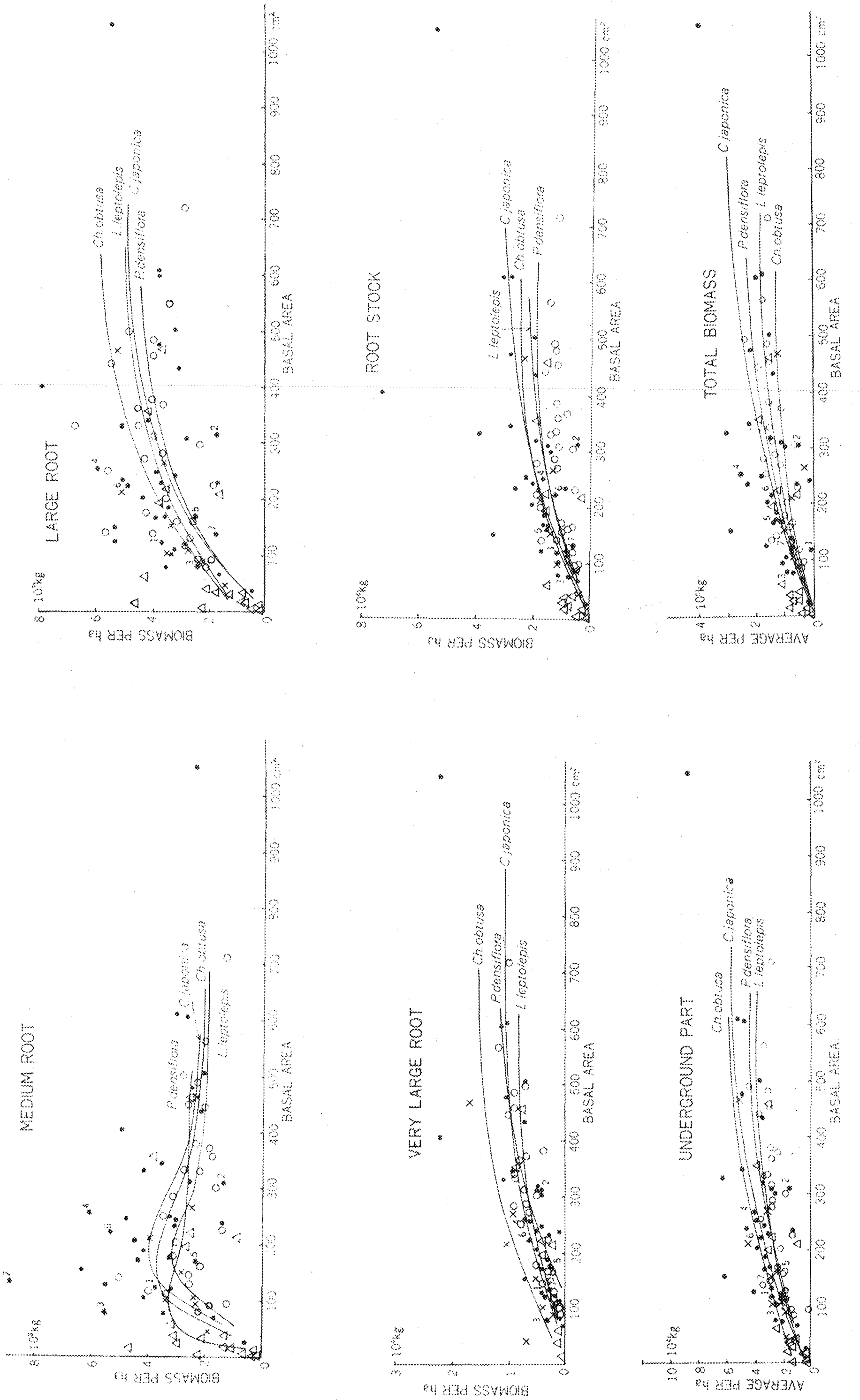


Fig. 27 Biomass of each part of trees per ha.

in the cace of the large diameter trees. That is to say, the branch biomass per ha shows a very low rate of increase in the stands with them. For branches are, though one of the accumulating parts, regenerated with growth after dying and falling.

Leaf : As already mentioned, the leaf biomass per ha of a small diameter tree goes up to the maximum point at the younger stage, and then down slightly to a given point regardless of species. The tendency is particularly clear for *P. densiflora* but not for *L. leptolepis.* We must leave it for a future study to make clear why *L. leptolepis* does not show the same change in branch biomass per ha as the other species. Its little shade tolerance or defoliation may, however, be among the reasons.

P. densiflora gets the branch biomass to increase to the peak at the basal area of about 50 cm^2 when its density is high enough. It may be partly owing to the temporary increase of tree density at an earlier time. Young trees, however, have much larger leaf biomass even at the same density. Judged from this fact, that may reveal one of the phenomena in the growing process of stands. To sum up, that may cause trees to grow vigorously at an earlier time, along with growth of the working parts of the underground parts, such as fine or small roots, corresponding to that change.

Of all the four kinds of species, *C. japonica* had the largest branch biomass. The branch biomass increased, for example, to the maximum of 22～25 tons at the younger stage at the basal area of about 150～200 m^2. After that, it decreased slightly by 20 tons at the basal area of 600 cm^2. And in addition, it was 29 tons in the S 22 stand with high tree density (tree density index 1. 2), and 34 tons in the S 17 stand with high tree density and sufficient growth.

Ch. obtusa had a standing leaf biomass per ha smaller than *C. japonica*, owing to the low tree density of the investigated stand. The biomass was 12 tons, sixty per cent of that of *C. japonica*, at the basal area of 500 cm^2. That of the younger stands was large enough to reach 10 tons in the H 1 stand, 10 years old. The density was about 0. 3 in this stand. In spite of this rarity, decay of under branches got slower and the leaves were distributed corn-like from down to upper stem, making the biomass as large as in the close planting stand.

At an earlier time the leaf biomass of *P. densiflora* increase temporarily up to 10 tons, mainly because of high density. The mature stand, say, the A 8 stand (35 years old and 361 cm^2 in basal area) had 5. 8 tons, owing to the tree density decreasing.

L. leptolepis did not make the distinctive change in leaf biomass as the other three kinds of species at an earlier time. At the basal area of 150 cm^2 that biomass increased, for example, slightly by 3. 5 tons, say, in the stands of K 23 and K 26. The variation was little scattered. Most of all stands had only about two or three tons. The widest stand of the investigated ones, the K 28 stand, had only 1. 9 tons.

The leaf biomass of each species, about 200 cm^2 in basal area, which was obtained from

Table 15. Leaf biomass per ha of each species

	C. japonica	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*	*Ch. pisifera*	*E. globulus*
Stand	S 10	H 3	A 3	K 29	M 2	M 3
Basal area (cm^2)	208	254	198	200	238	177
Density index	0. 59	0. 57	0. 75	0. 57	0. 22	*
Leaf biomass	17. 0	13. 0	7. 0	1. 7	3. 4	4. 0

Appendix-Table 2 on the preceeding number⁴⁾, is shown in Table 15. According to the table, it becomes smaller in the order of *C. japonica*, *Ch. obtusa*, *Acacia decurrens*, *P. densiflora*, *Tsuga canadensis*, *Eucalyptus globulus*, *Ch. pisifera*, *Abies firma*, and *Zelkova serrata*, or *L. leptolepis* (These biomass depend partly upon the density index). Hence it is that the evergreen coniferous trees have all the large leaf biomass, whereas the deciduous trees, broad-leaved and coniferous, such as *Zelkova serrata*, *L. leptolepis*, etc., have the small leaf biomass.

As concerns the biomass of the above-ground parts, all the species as shown in Fig. 27 are affected by the change in stem biomass, which has a greater part of the total biomass of a tree. They drew a parabolic increasing curve upward, where it is observed they made constant the biomass of the aboveground parts when the basal area increased from 400 to 500 cm². At the basal area of 500 cm², they all had the branch biomass of 100 to 200 tons in average. And that biomass became smaller in the order of *Ch. obtusa*, *C. japonica*, *P. densiflora* and *L. leptolepis*.

(2) Underground parts

Fine root : The fine root biomass of *C. japonica* and *Ch. obtusa* increases to the largest, 1～1.5 tons, within the range of the basal area of 150～200 cm². After that, it decreases gradually to be constant. That of *Ch. obtusa*, for example, was 1 ton and that of *C. japonica* 0.7 ton. That of *P. densiflora* shows a different change from those of *C. japonica* and *Ch. obtusa*. That biomass is largest for the small diameter tree, about 500 cm² in basal area, as is the leaf biomass. It reached, for example, 0.7～1.0 ton in the stands of A 6, A 10 and A 11 and rapidly decreased to about 100 kg in the case of a tree, 100 cm² in basal area. And further, it decreased to 89 kg in the A 8 stand, 361 cm² in basal area.

The fine root biomass of *L. leptolepis* does not show a distinctive peak ; it tends to increase gradually, answering the increasing basal area. As shown in Fig. 27, it was 200～500 kg regardless of the small or large trees. But the fine root biomass of the K 23, K 25, and K 26 stands were 4～5 times as large as those of the other stands. They are all on the highly dense and dry sites (The density indices and soil types of the K 23, K 26 stands are 1.03, B*l*ᴅ(d), and 1.27, B*l*c respectively). The same is true of *C. japonica*, *Ch. obtusa* and *P. densiflora*. Their fine root biomass showed a remarkably larger value than the averages of each species. The S 23, S 24, A 6, A 10 and A 11 stands are all on the close planting or dry site.

That the fine root biomass show their own change corresponding to basal area thus is related to the pattern of root systems spreading or the property of root biomass *C. japonica* and *Ch. obtusa* had a similar tendency. *P. densiflora* and *L. leptolepis* had a different one from the former, though.

This changing type in Fig. 27 is contrasted clearly with the changing types of leaf biomass in the same figure. *C. japonica* and *Ch. obtusa* both had the largest fine root biomass just as the leaf biomass went up to the peak within the range of the basal area of 150～200 cm². *P. densiflora* had their largest biomass of the leaves and the fine roots at the basal area of about 50 cm². *L. leptolepis* drew their gentle parabolic increasing curves upward.

It is quite an important fact in analysing tree growth that a leaf, a working part of the above-ground parts, has a similar

(tons)

Z. serrata	*Abies firma*	*Tsuga canadensis*	*Acacia decurrens* v. *dealbata*
M 4	M 5	M 6	M 7
188	156	211	135
*	*	*	*
1.7	2.1	5.7	8.4

Table 16. Fine root biomass per ha of each species (kg)

	C. japonica	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*	*Ch. pisifera*	*E. globulus*
Stand	S 10	H 3	A 3	K 29	M 2	M 3
Basal area (cm²)	208	254	198	200	238	177
Density index	0.59	0.57	0.75	0.57	0.22	*
Fine root biomass	1,438	1,453	104	350	562	671

Table 17. Small root biomass per ha (tons)

Species	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
Maximum value in a young stand age	3.0	3.7	1.4	1.2
Root biomass at the basal area of 500 cm²	1.0	2.0	0.7	0.7

Table 18. Root biomass per ha at the average basal area of 500 cm² (tons)

Species		*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
Root class	I	5.0	5.7	4.5	5.0
	L	10	16	11	9
	St	25	22	20	18

tendency in the changes in biomass to a fine root, a working part of the underground parts. Their increasing biomass reveal their growing vigorously at an earlier time, and it is noteworthy that this is the time when a tree picks up speed to the peak of growth.

Let us compare the change of the leaf biomass in Fig. 27 with that of the fine root biomass in Fig. 27. There we find that the latter is recognized clearer than the former, from which it follows that it is greatly concerned with the growth of the above-ground parts.

The fine root biomass per ha is shown in Table 16. As is clear from this table, *Zelkova serrata*, *C. japonica*, *Ch. obtusa*, and *Acacia decurrens* have the large fine root biomass.

Small root : The small root has the maximum growing point at the younger stage. Table 17 shows the small root biomass both at the maximum growing point and the basal area of 500 cm². At an earlier time, the small root biomass, as shown there, became smaller in the order of *Ch. obtusa*, *C. japonica*, *P. densiflora*, and *L. leptolepis*. In the mature stand, however, difference was little observed among *C. japonica*, *P. densiflora*, and *L. leptolepis*. Only *Ch. obtusa* had the large biomass of the small roots regardless of tree size.

Medium root : As shown in Fig. 27, the medium root biomass got smaller at an earlier time than the fine and the small roots. And the difference became smaller among species. At the basal area of 500 cm², all the species had as much as 2 to 3 tons.

The reason why its difference gets smaller with the root system growing is that the characters each species shows of its fine root biomass, rooting, and branching are clear in the smaller parts and not so in the larger parts.

The biomass of the fine and the small roots are affected mainly by the soil conditions. Their biomass were observed not to be large even in the stands with high density indices, S 22 and S 23. On the other hand, the biomass of the large root and above are not so easily affected by the soil conditions as by tree density. The difference in root biomass between the

Z. serrata	*A. firma*	*T. canadensis*	*Acacia decurrens* v. *dealbata*
M 4	M 5	M 6	M 7
188	156	211	135
*	*	*	*
2, 158	337	706	2, 564

stand with high density and the stand with low density was recognized to become much larger. For instance, the medium root biomass is 2 tons in the S 26 stand in which density is 0. 45. Yet it is 5 tons in the S 22 stand in which density is 1. 2. To sum up, the biomass of the working parts, above-and-under ground, per ha tends to be constant regardless of tree density in the like manner with the leaf biomass. But the biomass of the branch, stem, large root, very large root, and root stock are likely to be affected by tree density.

Large and very large roots, and root stock : The biomass of these parts increase, describing a parabolic curve upward answering the basal area, and they become almost constant when a tree is grown up. That curve is getting gentler as the root system is growing. The biomass of the root stock showed an almost straight increasing line.

For the growth rate differs from part to part. That of thinner roots slows down and that of thicker roots speeds up as a tree grows.

The large root, very large root, and root stock biomass at the basal area of 500 cm^2 are given in Table 18. As shown there, the large root biomass becomes smaller in the order of *Ch. obtusa, C. japonica, L. leptolepis,* and *P. densiflora*; the very large root biomass in the order of *Ch. obtusa, P. densiflora, C. japonica,* and *L. leptolepis*; the root stock biomass in the order of *C. japonica, Ch. obtusa, P. densiflora,* and *L. leptolepis.* Hence it is that those species get each root system to make each development.

Underground part : A greater part of the underground part biomass consists of the accumulating parts, larger than the large root. The changing curve corresponds to the change of those parts and thereby describes either a gentle parabolic curve upward or an almost straight line. The biomass of the underground parts became smaller in the order of *Ch. obtusa, C. japonica, P. densiflora,* and *L. leptolepis.*

Total biomass : Similarly, the total biomass describes a parabolic curve upward corresponding to the changing biomass of the accumulating parts, such as the stem, thick root, etc. The large diameter trees described a very gentle increasing curve, due to the decrease of both growth rate and tree density.

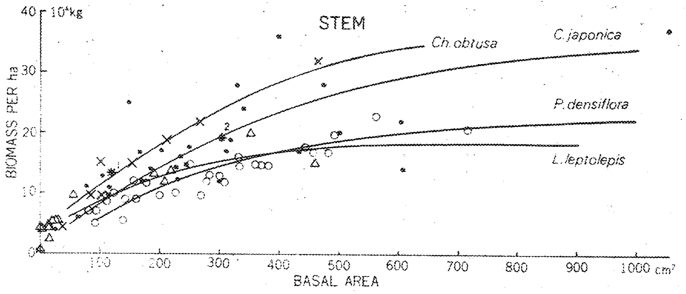
The total accumulated biomass of a stand per ha estimated from Fig. 27 at the basal area of 500 cm^2 is 200/(150-250) tons.

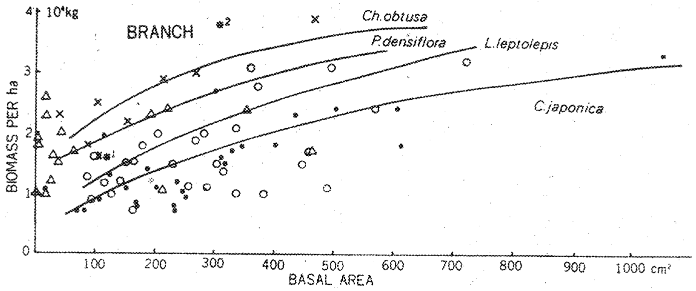
3) **Part biomass per ha at full density**

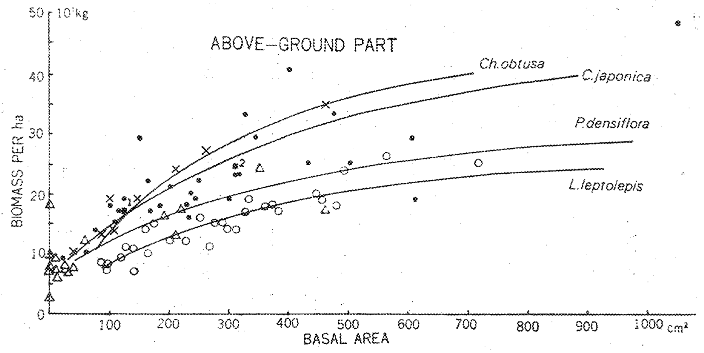
The standing biomass of a stand per ha differs greatly according to tree density, and for this reason it is not easy to determine the growth of a stand from its standing biomass. So the part biomass at full density was estimated from its density index. Its relation to basal area is shown in Fig. 28.

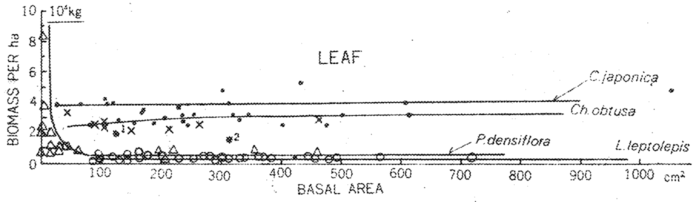
The actual accumulated volume of a stand at full density, even if converted into the tree number at full density as it is, is not the standing biomass at full density, because of the various kinds of growth rates of a tree caused by density. It is advantageous, however, to examine either the difference in part biomass by density or the standing accumulation at full density.

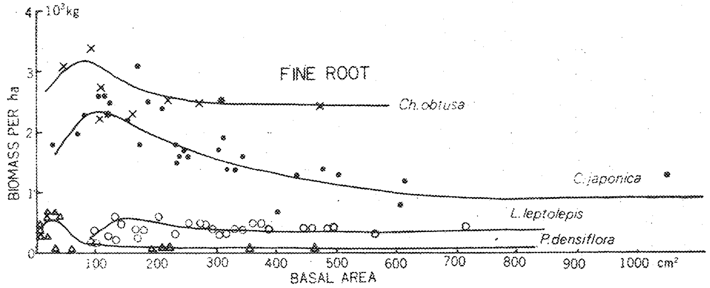
A comparison between Fig. 28 and Fig. 27 showing the part biomass per ha proves that

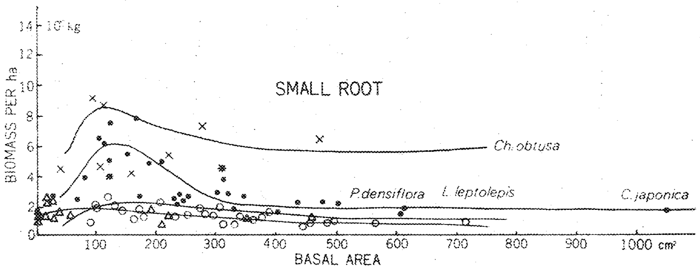

STEM
BIOMASS PER ha
10⁴kg
0
10
20
30
40
Ch.obtusa
C.japonica
P.densiflora
L.leptolepis
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA


BRANCH
BIOMASS PER ha
10⁴kg
0
1
2
3
4
Ch.obtusa
P.densiflora
L.leptolepis
C.japonica
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA


ABOVE-GROUND PART
BIOMASS PER ha
10⁴kg
0
10
20
30
40
50
Ch.obtusa
C.japonica
P.densiflora
L.leptolepis
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA


LEAF
BIOMASS PER ha
10⁴kg
0
2
4
6
8
10
C.japonica
Ch.obtusa
P.densiflora
L.leptolepis
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA


FINE ROOT
BIOMASS PER ha
10³kg
0
1
2
3
4
Ch.obtusa
C.japonica
L.leptolepis
P.densiflora
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA


SMALL ROOT
BIOMASS PER ha
10³kg
0
2
4
6
8
10
12
14
Ch.obtusa
P.densiflora
L.leptolepis
C.japonica
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA

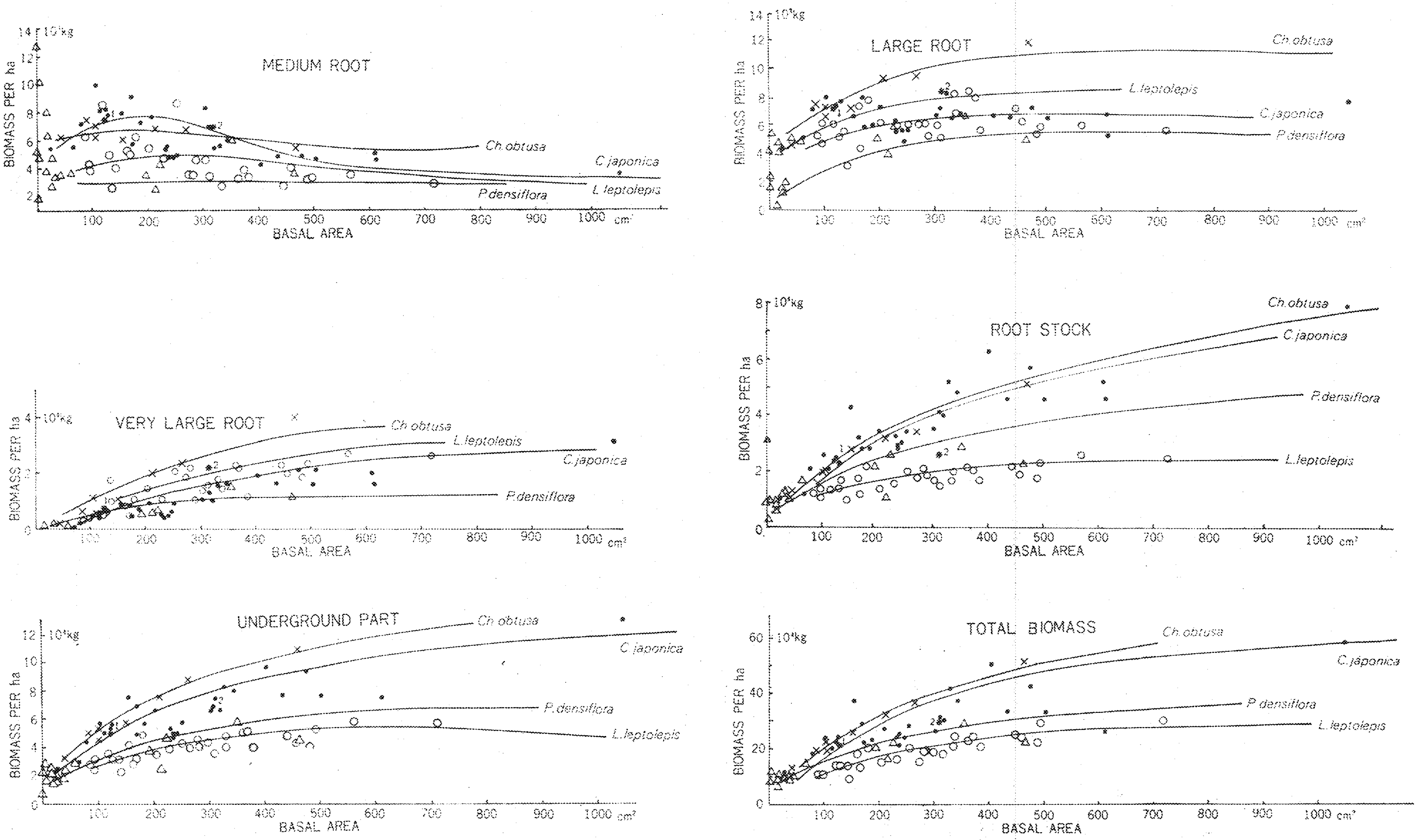


Fig. 28 Biomass of each part of a tree per ha in full density.

the calculated accumulation at full density is not scattered so much as the standing biomass per ha.

In brief, the formative influence on it is not the difference in formation by density, but the difference in density among stands.

(1) Above-ground part

Stem : The calculated biomass per ha at full density increases in such a parabolic curve upward as Fig. 28 and the species show very small variance. The accumulated biomass at the basal area of 500 cm² were 330 tons for *Ch. obtusa*, 250 tons for *C. japonica*, and 200 tons for *P. densiflora* or *L. leptolepis*. *P. densiflora* and *L. leptolepis* with intolerance had the biomass smaller by 80 to 130 tons than *Ch. obtusa* and *C. japonica* with tolerance.

Calculation results in the above-mentioned. The true value, however, is expected to be larger. Let us examine it on the stand of S 22 beyond full density and the stand of S 26, almost the same in basal area, with the density index of 0.4. This done, it was found that the standing biomass of S 22 and S 26 were 400 tons and 75 tons respectively. There was, that is, a difference by 325 tons. The calculated values of them at full density were still 360 tons and 170 tons respectively. There was a difference by 190 tons, which was nearly half that of the former. This difference is due to a difference in the stem formation caused by the difference in density between both stands. In other words, the stem formation is cylindrical in a close planting stand and conic in a sparse planting stand even at the same basal area.

The calculated average stem biomass was 220 tons at the same basal area as of S 22. There was a difference by 140 tons. And its rate of increase is 64% of the average value.

Branch : The calculated values are large in the sparse planting stand with many branches spreading rather than in the tree stand of full density. The actual biomass were, for example, 22 tons and 16 tons in the stand of S 22 and S 26 respectively. There was, that is, a difference by 6 tons between them, while the calculated biomass were 18 tons and 24 tons for the former and latter respectively. From this it is very clear that the sparse planting stand of S 26 gains a branch biomass larger by 4 tons than the close-planting stand of S 22. This difference, as with the stem biomass, is due to the difference of branching pattern by tree density. The calculated branch biomass at full density at the basal area of 500 cm² is shown in Table 19.

Leaf : The leaf biomass, as shown in Fig. 28, is almost constant, although the small diameter trees shows a slight increase. In *L. leptolepis* there was no change in the leaf biomass of its small and large trees. The average leaf biomass is shown in Table 20.

That the actual leaf biomass per ha at full density showed a slight increase at an earlier time means that an increase of branch biomass during that period was not caused so much by tree density as by the leaving pattern.

The calculated leaf biomass, as with the calculated branch biomass, at full density is larger than the actual leaf biomass at the near full density. For example, the stand of S 22 had the difference by two to three tons between the calculated values and true ones. This difference may not be, as with the difference in branch biomass, due to density but due to the leaving pattern; however, it is much smaller than that in branch biomass.

But the actual stand, if very close-planted, is induced to make it increase. In proof of this, there was a difference by 27 tons between the S 26 stand at the density of 0.4 and the S 22 stand at full density.

Biomass of the above-ground parts : The calculated values at full density are shown in Fig. 28. They increased parabolically, becoming smaller in the order of *Ch. obtusa*, *C. japonica*,

Table 19. Branch biomass at the average basal area 500 cm^2 and at full tree density (tons)

Species	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
Branch biomass	21	40	31	26

Table 20. Leaf biomass at full tree density (tons)

Species Basal area (cm^2)	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
100	35	25	10	5
500	30	20	7	5

Table 21. Root biomass per ha at the average basal area 500 cm^2 and at full tree density (tons)

Species Root class	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
f	1.4	2.5	0.1	0.4
s	2.0	6.0	1.0	1.0
m	5.0	5.5	3.0	3.0
l	6.0	12.0	5.0	7.0
L	20.0	40.0	3.6	23.0
St	51.0	52.0	36.0	21.0
Total	85.4	118.0	48.7	55.4

P. densiflora, and *L. leptolepis*. The above-ground parts cancels one another among stems, branches, and leaves the differences between the calculated values and the actual biomass at full density. But since the stem had the greater portion of the above-ground parts, the calculated values at full density were appreciably smaller than the actual biomass at full density. S 22 and the line of average values proves this relation.

(2) Underground part

Fine to medium roots : The underground part has a tendency towards similarity of the above-ground part. As shown in Fig. 28, the fine to medium root biomass made a somewhat increasing step at an earlier time, just as the leaf biomass, and then decreased gradually along with the increase of basal area.

Table 21 shows the root biomass of each species at full density in the mature stands extracted from Fig. 28. According to the table, *Ch. obtusa* had the larger biomass at every root classification on the whole. It also had the fine root biomass of 2.5 tons, the small root biomass of 6.0 tons, and the medium root biomass of 5.5 tons. Judged from the position of the S 22 stand in Fig. 28, the values in Table 21 are larger than the actual biomass at full dentity. This difference is big in the fine roots, and small in the small and the medium roots, evidencing that the small and the medium roots are not so much influenced by density as by the fine roots.

Large and very large roots : Their root biomass trend gradually to not change so rapidly with roots thickening. In fact those of large roots trend to go up parabolically, with the basal area increasing. The tendency is to be more distinguishable from a very large root to a root stock. Considered generally, it seems very similar to the tendency of root biomass per ha. Their variance, however, is much smaller owing to their decreasing variation by tree density.

Table 21 shows the biomass of large roots to underground parts at full density at the basal area of 500 cm^2 in Fig. 28.

Fig. 28 shows on the S 22 stand the difference between the values calculated at full density and the actual values at quasi-full density. It is evident from this figure that there is almost no difference in root biomass between large roots and very large ones. The calculated values were just in line with the actual root biomass at full density, which verifies that these part biomass are not greatly influenced by density effect.

The root stock had the biomass of 63 tons and the average of 45 tons corresponding to those in the S 22 stand. In other words, there was a difference by 18 tons between them. This is because a close-planting stand has a larger biomass of root stock than a sparse-planting stand at the same basal area.

The biomass of underground parts : The underground part biomass including all fine to very large roots make a parabolic increase with comparatively small variance, as shown in Fig. 28. According to Table 21, *Ch. obtusa* has an extremely large biomass of 118 tons. And *C. japonica*, *P. densiflora*, and *L. leptolepis* have the biomass of 85, 49, and 55 tons respectively. The species with possibility of close planting, such as *Ch. obtusa* or *C. japonica*, has over two times as large a biomass as *P. densiflora* and *L. leptolepis*.

The close-planting stand of S 22 had a slightly larger biomass than the average *C. japonica* had. This is due to a great difference in biomass at root stock between them.

Total biomass : A stem, large root and root stock account for a great part of the total biomass of a tree, and influence that biomass accordingly. The values draw a parabolic increasing curve upward as shown in Fig. 28.

Estimating the total biomass of each species at the basal area of 500 cm^2 in Fig. 28, we get the results shown in Table 22. According to the table, the total biomass of each species at full density becomes smaller in the order of *Ch. obtusa*, *C. japonica*, *P. densiflora*, and *L. leptolepis*. *Ch. obtusa* had the largest accumulation and *L. leptolepis* the smallest one. There was almost twice the difference in accumulation between them. That is to say, *Ch. obtusa* came in first, and *L. leptolepis* came at the other end. It is the proportion of the total accumulated biomass each species had when the tree density gets to the maximum.

The total biomass per ha at full density is always smaller than the true biomass at full density. At the same basal area, for example, the former was 380 tons when that of the S 22 stand was 500 tons, showing a difference of 120 tons between them, equivalent to 24% of 500 tons. This percentage explains the different degree of growth by density between the above-ground and the underground parts.

The average density index of *C. japonica* ranges from 0.6 to 0.7 in general. That of the S 22 stand, however, is the one converted into the density index of 1. The ordinary stand can

Table 22. Total tree biomass per ha in full tree density and at the basal area 500 cm^2 (tons)

Species	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
Tatal biomass	410	520	350	270

be estimated to have the above-mentioned difference by 24% between the calculated values and the values the actual stand had at full density.

For the calculated biomass of the stem, large to very large roots, root stock, the accumulating parts which have the greater portion of the total biomass of a tree, are smaller than the standing biomass of the densest stand.

4) **Part biomass ratio**

When the total biomass is to be 1, the ratio of each part biomass to the total biomass is calculated, and the Fig. 29 shows it in relation to basal area.

(1) Above-ground part

Stem : The ratio of the stem biomass to the total biomass is the highest of all, 65～75%, after grown up. It differs to tree size. Those ratio of the small diameter trees of each species were, for example, 20～30% as shown in Fig. 29. They increased rapidly in a parabola as they grew up to the basal area of 150～200 cm², and then became almost constant when the basal area got to 300 cm². When the basal area went beyond it, they showed almost no increase.

The increasing tendency stems make at an earlier time is related to the growth rate of stems during that period. All parts of a tree grow vigorously then. Both the annual increment and the ratios increase greatly. This is also characteristic of the accumulated parts. As the growth multiplies every year, it increases gradually. It is peculiar in a young stage of small diameter trees; large diameter trees show constant accumulation, instead.

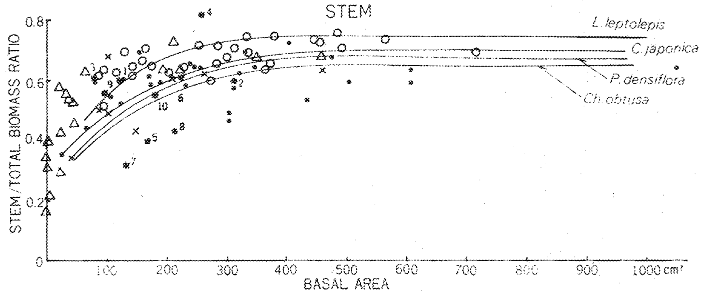
The proportion of stems changes according to stand size, and its change and ratio are different to species. The ratio of each part biomass to the total biomass of a tree at the basal area of 500 cm², in which all the ratios become almost constant, is shown in Table 23. According to the table, it becomes lower in the order of *L. leptolepis*, *P. densiflora*, *C. japonica*, and *Ch. obtusa*.

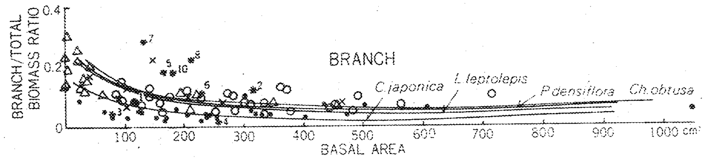
In this table, the proportion of the stem of *L. leptolepis* is higher than that of *C. japonica* and *Ch. obtusa*, because the proportion of the leaf of *L. leptolepis* is comparatively lower.

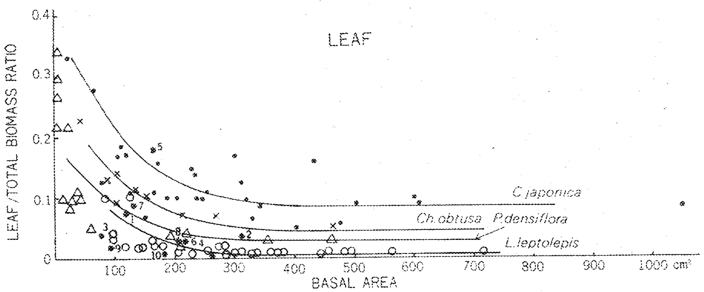
The other species involved in the proportion of the part biomass of each species at the basal area of 200 cm² or thereabouts is shown in Table 24. As is clear from it, *Zelkova serrata*, *Eucalyptus globulus*, *Ch. pisifera*, etc., show the high percentage; whereas *Acacia decurrens*, *Quercus mongolica*, etc., show the low percentage. For there are distinctively observed to exist the main stems in the former case; and instead, the branches have the high percentage in

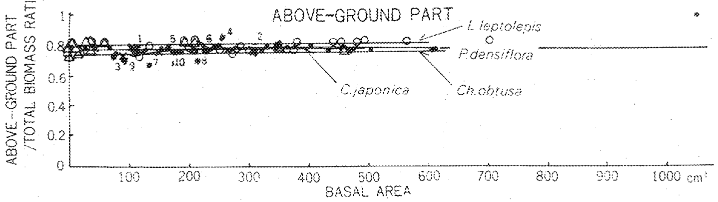
Table 23. Part biomass ratio of the trees in the mature stands (%)

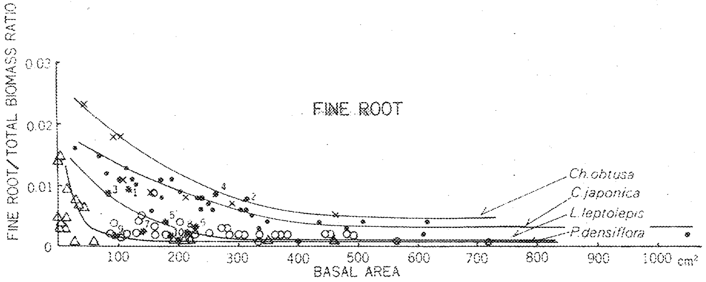
Species	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
Stand No.	S 5	H 5	A 8	K 19
Stem	67.3	63.5	68.2	73.4
Branch	4.7	7.7	7.9	6.1
Leaf	5.9	5.6	3.7	1.6
Above-ground part	78.1	76.8	79.8	81.1
f	0.3	0.5	0.1	0.2
s	0.5	1.2	0.5	0.3
m	1.2	1.1	1.7	1.1
l	1.7	2.4	2.3	2.8
L	4.9	7.9	5.2	5.7
St	13.3	10.1	10.4	8.8
Underground part	21.9	23.2	20.2	18.9

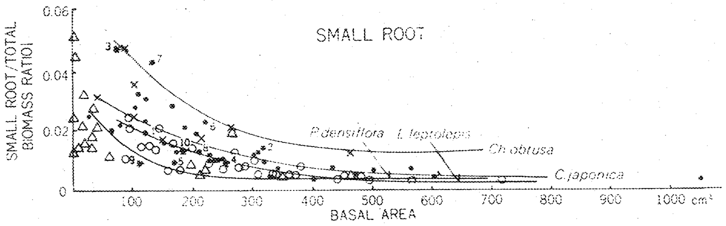

STEM
STEM/TOTAL BIOMASS RATIO
0
0.2
0.4
0.6
0.8
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA
L. leptolepis
C. japonica
P. densiflora
Ch. obtusa


BRANCH
BRANCH/TOTAL BIOMASS RATIO
0
0.2
0.4
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA
C. japonica
L. leptolepis
P. densiflora
Ch. obtusa


LEAF
LEAF/TOTAL BIOMASS RATIO
0
0.1
0.2
0.3
0.4
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA
C. japonica
Ch. obtusa
P. densiflora
L. leptolepis


ABOVE-GROUND PART
ABOVE-GROUND PART /TOTAL BIOMASS RATIO
0
0.2
0.4
0.6
0.8
1
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA
L. leptolepis
P. densiflora
C. japonica
Ch. obtusa


FINE ROOT
FINE ROOT/TOTAL BIOMASS RATIO
0
0.01
0.02
0.03
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA
Ch. obtusa
C. japonica
L. leptolepis
P. densiflora


SMALL ROOT
SMALL ROOT/TOTAL BIOMASS RATIO
0
0.02
0.04
0.06
100
200
300
400
500
600
700
800
900
1000 cm²
BASAL AREA
P. densiflora
L. leptolepis
Ch. obtusa
C. japonica

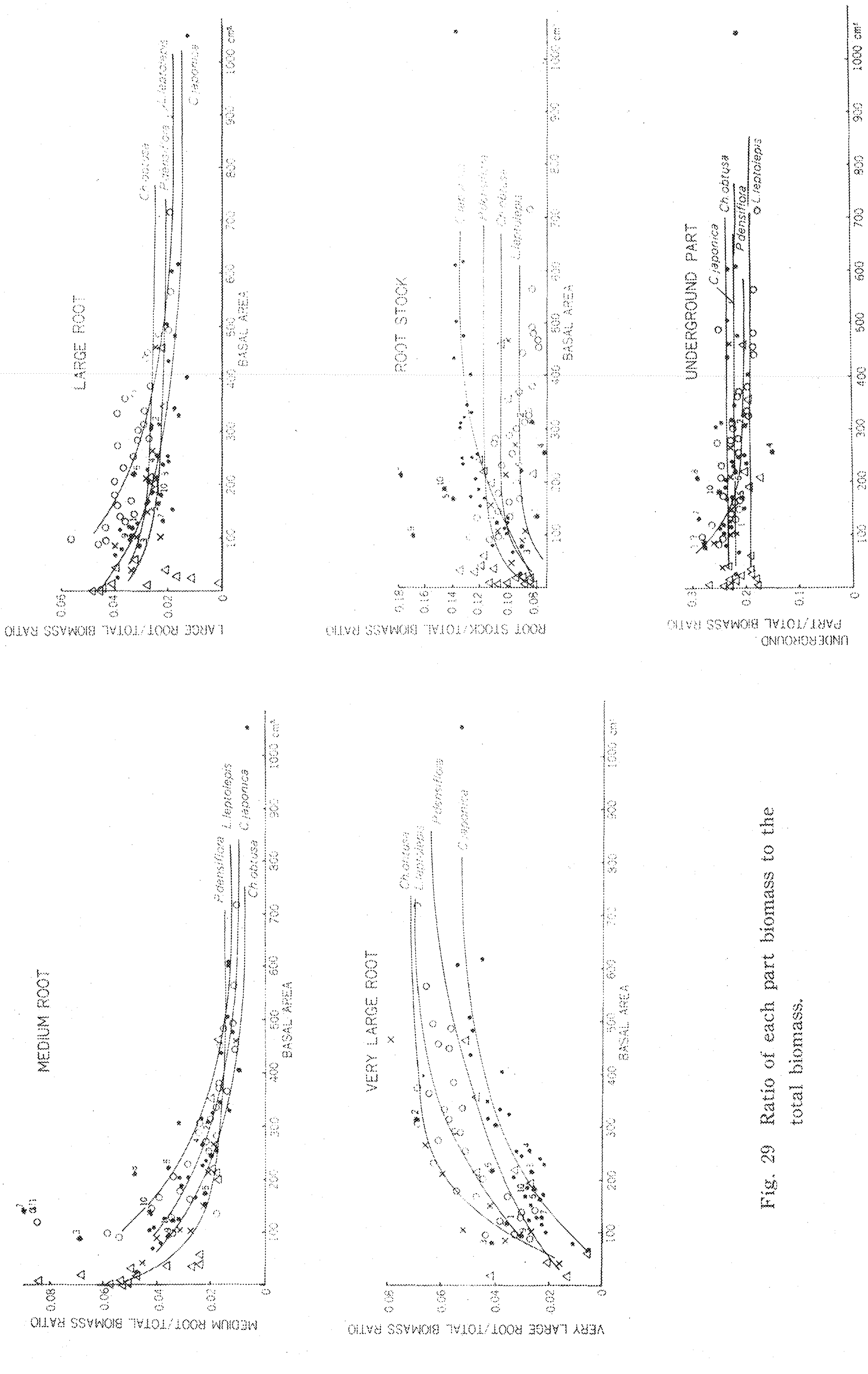


Fig. 29 Ratio of each part biomass to the total biomass.

Table 24. Part biomass ratio of each species at the

Species	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*	*Ch. pisifera*
Stand	S 10	H 3	A 3	K 29	M 2
Stem	61.2	60.4	64.9	62.2	60.6
Branch	4.3	9.0	11.5	12.9	12.1
Leaf	10.7	7.0	4.6	1.9	4.9
Above-ground part	76.2	76.4	81.0	77.0	77.6
f	0.9	0.8	0.1	0.4	0.8
s	1.8	1.7	0.9	1.4	1.4
m	2.8	2.1	1.8	3.4	2.1
l	2.7	2.8	2.5	4.0	2.7
L	3.3	6.0	2.7	4.5	7.0
St	12.3	10.2	11.0	9.3	8.4
Underground part	23.8	23.6	19.0	23.0	22.4

Table 25. Tree density and part biomass ratio (%)

	C. japonica				*P. densiflora*		*L. leptolepis*	
Stand	S 23	S 13	S 22	S 26	A 10	A 11	K 18	K 24
Basal area	152	196	419	425	18	32	346	410
Density index	0.798*	0.598**	1.158*	0.449**	1.243*	0.884**	0.811*	0.538**
Stem	69.4	58.2	72.2	53.4	58.3	53.1	74.3	63.2
Branch	3.2	3.5	3.8	7.2	13.5	15.9	4.8	13.4
Leaf	7.0	16.1	5.0	16.0	10.1	11.7	1.5	1.7
Above-ground part	79.6	77.8	80.9	76.6	81.9	80.7	80.6	78.3
f	0.6	0.8	0.1	0.4	1.0	0.7	0.2	0.2
s	1.5	1.2	0.3	0.7	3.2	1.8	0.4	0.5
m	2.2	2.6	0.9	1.5	4.8	3.7	1.3	1.4
l	1.8	2.7	1.3	2.0	0.1	2.1	3.9	3.6
L	2.7	2.2	3.8	4.9	—	—	5.2	6.5
St	11.6	12.7	12.7	13.9	9.0	11.0	8.4	9.5
Underground part	20.4	22.2	19.1	23.4	18.1	19.3	19.4	21.7

* Close planting stand. ** Sparse planting stand.

the latter case. That is to say, it is caused by the difference in formation between the stem and the branch.

The proportion of stems are easy to go up and down by tree density. For example, they increase in a highly dense stand. To clarify the relation, examinations as shown in Table 25 were carried out between the stands of S 23 and S 13, the stands of S 22 and S 26, the stands of *P. densiflora* A 10 and A 11, and the stands of *L. leptolepis* K 18 and K 24, which stands are all almost equal in tree size. It was found that the differences in stem portion for species are as follows : 11% between S 23 and S 13; 19% between S 22 and S 26; 5% for *P. densiflora*; and 11% for *L. leptolepis*.

The main reasons for it are as follows : First, the stem formation is caused to change by close planting. Second, the branches and the leaves are caused to decrease their percentage in a close-planting stand. And finally, the underground parts to decrease their percentage along with them.

To sum up, when production per area proceeds constantly, a close-planting stand causes the deposition of products to the stems to be larger than a sparse-planting stand, and thereby average basal area of about 200 cm² (%)

Eucalyptus globulus	*Zelkova serrata*	*Abies firme*	*Tsuga canadensis*	*Acacia decurrens* v. *dealbata*	*Quercus mongolica* v. *grosseserrata*	*Betula platyphylla* v. *japonica*	*Betula davurica*
M 3	M 4	M 5	M 6	M 7	M 8	M 9	M10
61.7	82.0	41.7	61.7	32.0	44.9	56.4	35.2
4.6	2.1	1.8	11.8	28.9	22.6	13.0	18.6
4.9	0.6	18.6	3.7	9.2	3.1	2.0	1.5
71.2	84.7	78.8	77.2	70.1	70.6	71.4	75.3
0.8	0.8	0.3	0.5	2.8	0.2	0.2	0.2
4.8	1.0	0.8	2.3	4.2	1.3	1.1	1.4
6.9	2.3	2.2	3.6	10.9	4.9	3.6	3.6
3.0	2.2	2.3	3.3	2.6	2.3	3.3	2.2
4.1	2.7	2.0	4.1	2.3	2.9	3.1	2.6
9.2	6.3	14.1	9.0	7.7	17.8	17.3	14.7
28.8	15.3	21.7	22.8	29.9	29.4	28.6	24.7

the proportion of the stem to be higher relatively. Thus, it is not unreasonable to conclude that close planting is more effective for stem productivity than sparse planting.

Branch : The proportion of branches decreases gradually in contrast with the case of stems, when the basal area increases. It decreases as a tree grows up to the basal areas of 50～200 cm², where the rate of increase goes almost constant. After that, it becomes almost constant (Fig. 29).

Three reasons account for this : First, branches grow vigorously at an earlier time and at the stage of small trees. Second, underbranches begin to decay gradually as trees grow up, although the amount of accumulation becomes larger because of the small amount of dead branches. Third, the amount of accumulation does not increase greatly because branches fall at a given rate every year.

Branches are quite different from stems, an accumulating part, in this respect. In short, their quantitative change makes clear a property as a working part.

The proportion of branches differs from one species to another. According to Table 23, the proportion of the branches the main species have in the matured stands are 7.9% for *P. densiflora*, 7.7% for *Ch. obtusa*, 6.1% for *L. leptolepis*, and 4.7% for *C. japonica*.

C. japonica has a lower percentage than any other species. Although it has a large amount of branches, *L. leptolepis* has a lower percentage than *Ch. obtusa*, because the species's stem has a greater part.

The relation between the tree density and the proportion of branches is shown in Table 25. As is clear from this table, the proportion is all low in the dense stand. There was, for example, a difference of 0.3% between S 23 and S 13, and of 3.4% between S 22 and S 26. *L. leptolepis* still had as large a difference as 8.6%. This explains that high density hinders branches' growth very remarkably for that species with intolerance.

Leaf : The ratio of the leaf biomass to the total biomass, as shown in Fig. 29, decreased gradually as trees grew up. It is quite in contrast to that of stems. As already mentioned on the leaf biomass, it is partly because leaves do not make so much accumulation as stems, as they are regenerated every year, and partly because they slow down growing speed when trees are grown up. The decrease of the ratio of the leaf biomass and the increase of accumulated parts with tree growth are the decrease of production and the increase of consumptive parts. As a result, the growth rate of large diameter trees decreases.

The ratio of the leaf biomass differs from one species to another. At the basal area of 500 cm², for example, they were 7% for *C. japonica*, 5% for *Ch. obtusa*, 2.5% for *P. densiflora*, and 1% for *L. leptolepis*. *P. densiflora* and *L. leptolepis* with intolerance had a lower ratio of leaf biomass than *C. japonica* and *Ch. obtusa*. The reader may refer to Table 23 on the ratios of leaf biomass of S 5 to K 19.

The ratios of the leaf biomass, inclusive of the other species, are shown in Table 24, and *Abies firma* had the highest ratio of 19%. According to the table, they became lower in the order of *Abies firma*, *C. japonica*, *Acacia decurrens*, *Ch. obtusa*, and *Ch. pisifera*. Hence it is that all these evergreen trees have high percentages, whereas the deciduous trees, such as *L. leptolepis*, *Zelkova serrata*, *Betula platyphylla*, *Betula davurica*, *Quercus mongolica*, etc., have much lower percentages.

In relation to tree density, the ratio of the leaf biomass of a dense stand was always lower than that of a sparse stand, as shown in Table 25. It tended to decrease by competitive density effect. *C. japonica* had a difference of 9% between either S 23 and S 13 or between S 22 and S 26. *P. densiflora* and *L. leptolepis* had both that by 2%.

(2) Above-and-under ground parts ratios (T/R ratio)

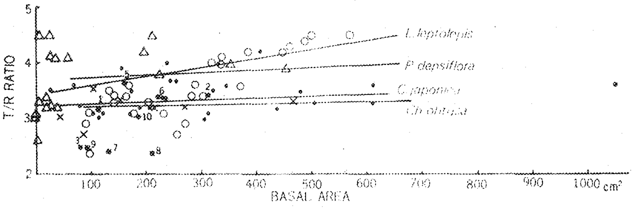
Fig. 29 shows the ratios of the above-ground parts, inclusive of the stems, branches and leaves altogether, to the total biomass, relating to basal area. This ratio also indicates the relation between the above-ground and the underground parts.

The ratios of the stem, branch, and leaf differ from stand to stand, and they vary greatly. Their differences are, however, offset if the biomass of the above-ground parts are run together, and consequently the variance becomes small. Hence it is that a high correlation exists between the above-and-under ground parts.

According to Fig. 29, the ratios of the above-ground part biomass to the total biomass are 75～80%, and they go almost constant for both large and small trees. And yet, those ratios of the underground part biomass range from 20 to 25%. It is, as shown in Fig. 29, quite in contrast with those of the above-ground part biomass.

Those ratios of the above-ground parts of the matured stands from S 5 to K 19, as shown in Table 23, are 78% for *C. japonica*, 77% for *Ch. obtusa*, 80% for *P. densiflora*, and 81% for *L. leptolepis*. They become lower in the order of *L. leptolepis*, *P. densiflora*, *C. japonica*, and *Ch. obtusa*. The other species counted in, those in Table 24, are 85% (the highest) for *Zelkova serrata*, 70～71% for *Acacia decurrens* or *Quercus mongolica* var. *grosseserrata*, and almost 75～80% for the other species. Indeed, it is true here that *P. densiflora* and *L. leptolepis* have a slightly higher percentage than *C. japonica* and *Ch. obtusa*, but the difference between them is low.

Calculation of the T/R ratio resulted in the following correlative changes of the biomass of the above-and-under ground parts. The variance of regression between T/R ratio and basal



* T/R ratio : Ratio of the above-ground part biomass to the underground part biomass.

Fig. 30 T/R ratio* and basal area.

Table 26. Basal area and T/R ratio

Basal area (cm^2) Species	100	200	300	500	800	1,000
C. japonica	3.1	3.1	3.2	3.3	3.5	3.6
Ch. obtusa	3.1	3.1	3.1	3.2	3.3	3.4
P. densiflora	3.6	3.6	3.7	3.8	3.9	4.0
L. leptolepis	3.3	3.5	3.8	4.3	4.5	4.6

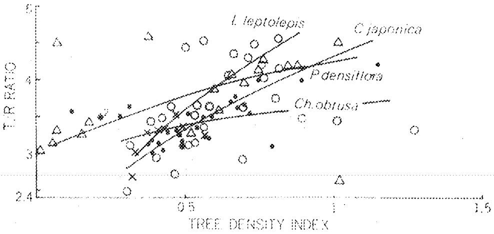


Fig. 31 Tree density index and T/R ratio.

Table 27. Tree density index and T/R ratio

Density index Species	0.5	1.0
C. japonica	3.2	4.3
Ch. obtusa	3.2	3.6
P. densiflora	3.7	4.4
L. leptolepis	3.5	4.8

area, as shown in Fig. 30, was large regardless of species. The other species included, the distribution of T/R ratio ranged from 2.5 to 4.5, due to tree density and site condition.

It is evident from this figure that the T/R ratios increase slightly as a tree grows up. *L. leptolepis* had, for example, a slightly higher percentage than *C. japonica*, *Ch. obtusa* and *P. densiflora*.

a. T/R ratio and tree growth

The relation between T/R ratio and basal area draws an almost straight increasing line or an extremely gentle parabolic increasing curve upwards. *C. japonica*, *Ch. obtusa* and *P. densiflora* drew, for example, a nearly straight line. *L. leptolepis* made a gentle curve upward for the large diameter tree and a rapid rate of increase of T/R ratio for the small diameter tree.

Table 26 shows the average changes in T/R ratios each species makes, based on these changing curves. When the basal area increased from 100 cm^2 to 1,000 cm^2, the T/R ratios of *C. japonica*, *Ch. obtusa*, *P. densiflora*, and *L. leptolepis* increased by 0.5, 0.3, 0.4, and 1.3 respectively. That of *L. leptolepis* was a little higher. Those ratios of the small diameter trees became lower in the order of *P. densiflora*, *L. leptolepis*, and *C. japonica* or *Ch. obtusa*. Those of the large diameter trees, however, became lower in the order of *L. leptolepis*, *P. densiflora*, and *C. japonica* or *Ch. obtusa*.

b. T/R ratio and tree density

The ratios of above-ground part biomass in both a dense stand and a sparse stand were calculated. *C. japonica*, *P. densiflora* and *L. leptolepis* had, as shown there, a higher percentage in a close planting stand. Examples are : a difference of 1.8% between S 23 and S 13, and of 4.5% between S 22 and S 26. *P. densiflora* differed by 1.2%, and *L. leptolepis* by 2.3%. Hence it is that all these species tend to increase the T/R ratios, corresponding to the increase of the density indices. If we convert this relation into the T/R ratios concerning the whole sample stands, we get the result shown in Fig. 31. According to the figure, the rates of increase of the T/R ratios become lower in the order of *L. leptolepis*, *C. japonica*, *P. densiflora*, and *Ch. obtusa*. *Ch. obtusa* had a difference of only 0.4 between the density indices of 0.5 and 1.0, because the species with great tolerance was given almost no influence by density (See Table 27).

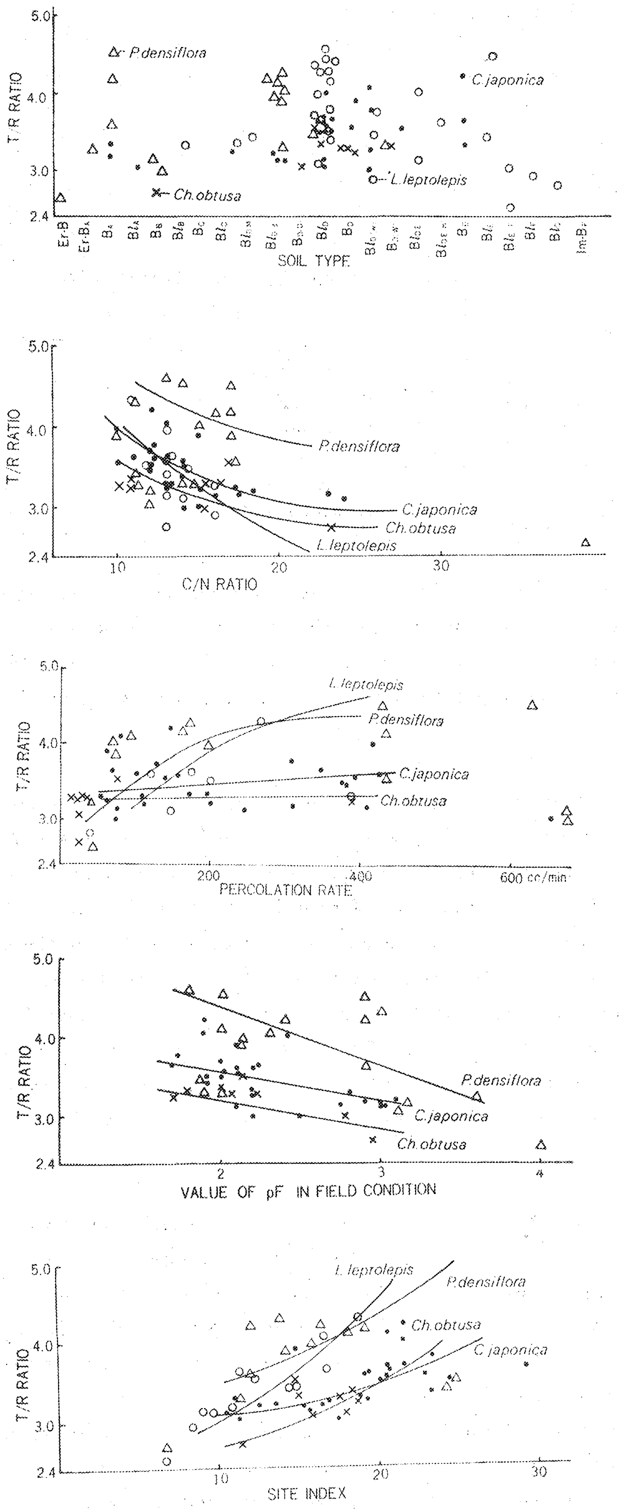


Fig. 32　Various soil properties and T/R ratio.

c.　T/R ratio and soil condition

The root system owes its growth to soil conditions, so it is likely that the T/R ratio depends strongly upon soil conditions.

Soil type : The relation between soil types and T/R ratios is shown in Fig. 32.

As can be seen there, the T/R ratios have a tendency to go lower in the dry-typed soils, such as E_R, B_A, Bl_C, and Bl_D(m), but to go higher in the Bl_D(w), Bl_E and E_E type soils.

But the T/R ratios have a tendency to go lower in the heavy wet soils, such as Bl_{EF}, Bl_F and Bl_G either due to the easy decay of absorption and production structures or due to the remarkable drop-off of the biomass of leaves and branches. It is evident from these that *L. leptolepis*, as shown in Fig. 32, has the low T/R ratios in the stands, such as K 4, K 5, K 6, and K 7. This explains the decay of absorption and production structures of the above-and-under ground parts, and besides, this leads to the natural decay of tree.

It changes by species. The following provide good examples : *C. japonica* and *Ch. obtusa* with the high water content are seldom affected by them, but *L. leptolepis* with the low water content responds easily to such an influence.

In the dry B_A typed soil, which causes T/R ratios to be low in general, that ratio of the stands of *P. densiflora*, A 10 and A 11, gave the indications of

Table 28. Typical soil types and T/R ratios

Species	Dry soil type	Moderately moist soil type	Moist soil type	Wet soil type
C. japonica	3.0	3.5	3.5	—
Ch. obtusa	2.5	3.4	3.4	—
P. densiflora	3.2	4.0	3.5	—
L. leptolepis	3.3	4.5	4.0	2.7

Table 29. C/N ratio and T/R ratio

Species \ C/N ratio	10	15	20	25
C. japonica	4.0	3.4	3.0	2.9
Ch. obtusa	3.4	3.3	2.8	2.7
P. densiflora	4.5	4.3	3.8	3.6
L. leptolepis	4.0	3.3	3.0	2.9

being high. This is due to the high density index of the two stands.

Judged from Fig. 32, the relation of the T/R ratios to the main soil types is shown in Table 28. According to the table, the T/R ratio is lower in the dry-typed soils than in the moderately moist soils.

The differences each species has in T/R ratio between both soils are as follows : *L. leptolepis* differs by 1.2; *Ch. obtusa* by 0.9; *P. densiflora* by 0.8; *C. japonica* by 0.5. Hence it is that *L. leptolepis* is much more influenced by dryness than *Ch. obtusa* and *P. densiflora.*

On the other hand, the difference in T/R ratio between the moderately moist soils and the moist soils is as follows : *L. leptolepis* and *P. densiflora* differed by 0.5 in the moist soils; *C. japonica* and *Ch. obtusa* had no difference. The T/R ratios of *L. leptolepis* and *P. densiflora* decreased a bit when in the more moist soil, but those of *C. japonica* and *Ch. obtusa* showed almost no change. In the excessively moist soil, *L. leptolepis* made the T/R ratio of 2.7, which difference was 1.8 in the moderately moist soil. These differences were caused by the decrease of the aboveground part biomass according to the decay of branches and leaves.

The soil factors of every species are highly related to the soil types. When we examine the relation to them, we can anticipate the relation of these factors to them as a whole. A few examples for this relation are explained henceforth.

C/N ratio : The C/N ratio is one of the factors that indicates the chemical property of soil in general. The relation between C/N ratio and T/R ratio is shown in Fig. 32, verifying that the soil of the high C/N ratio has a low T/R ratio. This explains why poorly nutritive location of the high C/N ratio is generally dry soil-typed.

The T/R ratio decreases rapidly, as shown in Fig. 32, when the C/N ratio ranges from 10 to 15. Table 29 proves that there exists such a correlation as will make the T/R ratio constant when the C/N ratio goes cross 20.

The influence of the T/R ratio on the C/N ratio is greater for *C. japonica* and *L. leptolepis* than for *P. densiflora* and *Ch. obtusa.* It follows from this that those ratios of the latter are less affected by soil chemical property than the former. It can be related to the property that *P. densiflora* and *Ch. obtusa* grow well in the soils with a meager supply of nutriment.

Percolation rate : The percolation rate and the T/R ratio have the tendency to go up together. This does not necessarily prove that all the species cause them to change at the same rate. The rate of change of their T/R ratios by percolation rate, for example, became lower in the order of *L. leptolepis*, *P. densiflora*, *C. japonica*, and *Ch. obtusa*. That is to say, the former two are caused to make their T/R ratios more changeable by percolation rate.

In the sites with high percolation rates can be found much moderately moist soils with well-developed crumbled structure, but in the sites with low percolation rate, lots of heavy wet soils with wall-like structure or dry soils are present. In the latter case, the T/R ratios have a tendency to go higher in general in the heavy wet soil although the percolation rates get lower. (Here, we do not take into account the decay of productive structures.) It is in marked contrast with the general tendency in Fig. 32. On the other hand, the T/R ratio becomes low in the dry soils. So such a tendency as shown in Fig. 32 is presumed to result from the dry soil as the sample soil.

Even when the percolation rate slows down, the T/R ratio, as already described, does not always go down, due to the extremely different soil conditions. The ratio is subjected to change by the conditions that make the percolation rate low.

pF values in field condition : The above-mentioned explanation may lead the reader to conclude that moisture condition gives the greatest influence to the T/R ratio. The following, however, makes it clearer. Fig. 32 shows the relationship between the T/R ratios and the pF values in field condition, which indicate directly the moisture condition of soil. According to the figure, the T/R ratios of each species get lower as soils become drier, and the pF values get larger. These factors have a closer relativity than any other factor; they both have a close connection.

The relation between the pF values and T/R ratios, obtained from Fig. 32, is shown in Table 30. According to the table, the T/R ratio of *P. densiflora* is higher than that of *Ch. obtusa*, as that of *P. densiflora* is 4.4, that of *C. japonica* 3.6 and that of *Ch. obtusa* 3.2, in the moderately moist soil with the pF value of 2.0. The differences among species, however, decrease in the dry soil with a pF value of 3.5; the T/R ratio of *P. densiflora* is 3.2, that of *C. japonica* 3.1 and that of *Ch. obtusa* 2.7.

As concerns the rate of decrease of the T/R ratio which answers the increase of the pF value, *P. densiflora* shows a higher percentage. That rate with the range of the pF value from 2.0 to 3.5, for example, was 0.5 for *C. japonica* and *Ch. obtusa*, but 1.2 for *P. densiflora*. The latter species showed over twice as high a rate of decrease as the former two.

This explains that *P. densiflora* has a tendency to make changeable the quantitative balance between the above-and-under ground parts on the dry condition, as against *C. japonica* and *Ch. obtusa*. Accordingly, it is not necessarily unreasonable to conclude that it is related to the strong adaptability of that species to drought.

Site index : Fig. 32 shows the relation between site indices and T/R ratios by putting the above-mentioned soil conditions together. The T/R ratios of each species increased, as shown

Table 30. Value of pF in field condition and T/R ratio

Value of pF / Species	2.0	2.5	3.0	3.5
C. japonica	3.6	3.4	3.2	3.1
Ch. obtusa	3.2	3.0	2.9	2.7
P. densiflora	4.4	4.0	3.6	3.2

in the figure, in a slightly concave curve upward as site indices increased.

This can be observed quite clearly and the variance is small. There is a close relationship between them.

Tree Density	Moisture	T/R ratio
Close planting	Moist	High
Sparse planting	Dry	Low

Fig. 33 The conditions concerning T/R ratio.

It is related mainly to the water condition of soil. The stands with small site indices are mostly on the dry soils, and those with large site indices are mostly on the moderately moist soils. Concerning the C/N ratio, it is possible to predict that the T/R ratio goes higher in the sites with the small site index, due to the excessive moisture. When this happens in the sample stands, the relation of the T/R ratios to the site indices is not very clear, as shown in Fig. 32.

The various conditions, which cause the T/R ratios to change, have too close a relationship among them to conform to one rule. Figures 31 and 32 show the different conditions in all sample stands. Variance is caused to increase by the conditions that affect T/R ratio.

Let us pick out of the factors that have a great influence on the T/R ratio on the whole. We can get two factors, namely, tree density and water conditions. Fig. 33 shows that the higher the T/R ratios, the higher the tree densities and the more moist the soils. Furthermore, it shows that they have a tendency to go lower under the sparse planting and dry condition.

The above-mentioned change takes place within the given range of T/R ratio. That ratio can not get to over five even in a close planting and moist stand, and it never goes down under two even in a sparse-planting and dry stand. For example, the S 22 stand of *C. japonica*, close planting, B_E soil-typed and of large diameter trees, showed the T/R ratio of 4.2; whereas the A 6 stand of *P. densiflora* of small diameter trees showed that of 2.6 on the dry Er to B typed soils.

It is possible to predict thereby that each factor does not give an intertwined influence to the T/R ratio, i. e., that the effect of the coaction between each factor on that ratio is not coming out at both ends of each factor. Nevertheless, it is difficult to know these relations by straight regression.

Detailed examination reveals that the tree density and the site condition make the T/R ratio change slightly. No big errors are caused, even when the T/R ratios are, say, 3 to 3.5 in a moderate and ordinary forest on the whole. Even the one to two-year-old seedlings have almost the same values. In other words, the T/R ratios remain constant regardless of tree growth. It has some connection with the given proportion of the assimilated products the under-and-above ground parts make in every growth stage. This is very interesting.

(3) Underground part

Fine root : The ratio of the fine root biomass to the total biomass, as shown in Fig. 29, was high for the small diameter trees of species. It decreased gradually with tree growth, and became almost constant when the basal area arrived at 400 cm².

The similarity takes place in the fine to large roots of the underground parts, corresponding to the changing ratios of the biomass of leaves and branches of the above-ground parts. This can be made a comparison with and correspondency to either of a stem, one of the accumulating parts of the above-ground parts, or of the very large roots and root stock of the underground parts, which increase parabolically. This indicates that their function has a close relationship to their assimilation. It is very interesting in making an analysis of tree growth.

As already explained on the above-ground parts, the decreasing tendency of fine to large roots is different from the parabolic increase of the very large roots and root stock. This is traceable to the different growth property of each part; but in the case of those parts below

Table 31. Ratio of the fine root biomass to the total tree biomass at the basal areas of 100 and 500 cm²

Species / Basal area (cm²)	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
100	1.3	1.8	0.2	0.3
500	0.3	0.4	0.1	0.2

Table 32. Soil type and ratio by root biomass (%)

Stand	S 20	S 12	S 7	S 13	S 10	S 23	S 15	S 18
Basal area	265	267	160	196	208	152	451	554
Tree density index	0.482	0.672	0.575	0.598	0.585	0.798	0.682	0.545
Soil type	BA	B*l*D(w)	B*l*C	B*l*D	B*l*D(d)	BD	B*l*D	BE
f	1.1*	0.6**	1.1*	0.8**	0.9**	0.6*	0.4*	0.2**
s	2.7	1.0	2.0	1.2	1.8	1.5	0.5	0.4
m	3.2	1.8	3.1	2.6	2.8	2.2	1.3	1.3
l	2.8	2.0	2.6	2.7	2.7	1.8	1.6	1.8
L	2.9	3.2	2.8	2.2	3.3	2.7	4.6	5.4
St	11.2	12.2	12.1	12.7	12.3	11.6	13.3	13.9

* **Dry soil.** ** **Moderately moist soil.**

Table 33. Ratio of the small root biomass to the total root biomass (%)

Species / Basal area (cm²)	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
100	2.5	4.0	1.2	1.7
500	0.5	1.2	0.4	0.4

Table 34. Ratio of the medium root biomass to the total root biomass at the basal areas of 100 and 500 cm² (%)

Species / Basal area (cm²)	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
100	3.8	3.5	2.3	4.6
500	1.3	1.2	1.9	1.7

Table 35. Ratio of the large root biomass to the total root biomass at the basal areas of 100 and 500 cm² (%)

Species / Basal area (cm²)	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
100	3.2	3.2	3.5	4.2
500	1.8	2.5	2.5	2.5

a large root, it is caused by the small accumulation and slow growth of root biomass.

These decreasing curves differ according to species. The indices at the basal areas of 100 cm^2 and 500 cm^2 are shown in Table 31. The differences in index between them are, as shown there, 1.4% for *Ch. obtusa*, 1.0% for *C. japonica*, and 0.1% for *P. densiflora* or *L. leptolepis.* From this we see that *Ch. obtusa* has the highest changing rate. Small diameter trees have a difference of 1.6% because of large disparity between species, but large diameter trees have a small difference of 0.3%.

This is partly because a small diameter tree makes a large distribution of the total biomass to the fine roots, and partly because the properties of species must be taken into account. As is clear from Fig. 29, *C. japonica* and *Ch. obtusa* have large values regardless of the small and large diameter of trees, but *P. densiflora* and *L. leptolepis* have not.

The ratios the fine roots of each species occupy, as shown in Table 24, are as follows: 2.8% for *Acacia decurrens*; 0.9% for *C. japonica*; 0.8% for *Ch. obtusa, Ch. pisifera, Eucalyptus globulus*, and *Zelkova serrata*; 0.1 to 0.4% for *P. densiflora, L. leptolepis, Abies firma, Quercus mongolica* var. *grosseserrata, Betula platyphylla* var. *japonica* and *Betula davurica.*

According to Table 25 on the relationship between the density index and the proportion of fine root biomass, the dense stands, such as S 23 and S 22, have the higher percentage of the fine root biomass by 0.2 to 0.3% than the stands of normal tree density. This is a relative decrease caused by the fact that the proportion of the stems increases by density effect. This relation was not clear for *P. densiflora*, and *L. leptolepis.* Particularly in the dense stand of *P. densiflora*, the proportion of the fine root biomass was high, because A 10 was smaller than any other stand. This holds good in the case of the small and medium roots.

The relation between the soil conditions and the portion of fine root biomass was examined in the *C. japonica* stands, in which the basal area and density index are almost equal. Results appear in Table 32. The proportion of fine to medium roots, as shown in the table, goes up in the moderately moist soils, such as B_E to B_D, and down in the dry soils, such as B_A-Bl_D(d). Those of the large roots and root stock decrease.

Small root: The ratio of the small root biomass of the total biomass of the main species in Fig. 29 is shown in Table 33. As revealed there, *Ch. obtusa* showed, regardless of the small and large diameter trees, a higher percentage than *C. japonica, P. densiflora* and *L. leptolepis.* The percentages at the basal area of 500 cm^2 are as follows: 1.2% for *Ch. obtusa*, 0.5% for *C. japonica*, and 0.4% for *P. densiflora* or *L. leptolepis*; the more intricate branching of the small roots accounting for the higher percentage of *Ch. obtusa.* The other species put together, *Eucalyptus globulus* and *Acacia decurrens* showed high percentages. And *Abies firma, P. densiflora, Zelkova serrata, Betula platyphylla* var. *japonica, Quercus mongolica* var. *grosseserrata, Betula davurica*, etc. showed the low percentages of 0.8 to 1.4. It follows from these facts that small roots grow less favourably than any other part.

The stands, such as S 6, S 20, S 24, H 6, A 6 and A 10, all had, as shown in Fig. 29, higher ratios than the average values of the rest. These were all sparse-planting and dry stands, and just as in the case of fine roots, those percentages increased under such conditions. Table 32 proves these relations to soil conditions.

Medium root: As concerns the ratio of the fine and small root biomass to the total biomass, *Ch. obtusa* showed a higher percentage than the rest. This does not apply in the case of the medium root biomass. The root biomass, as shown in Table 34, makes the difference in ratio smaller among species. And the smaller diameter tree of each species caused the percentage to become lower in the order of *L. leptolepis*, *C. japonica*, *Ch. obtusa*, and *P. densiflora*. In the large diameter tree it became lower in the order of *P. densiflora*, *L. leptolepis*, *C. japonica*, and *Ch. obtusa*. The reason for this is that these four kinds of species all have similar properties of the medium roots to each other. Of the other species put together, *Acacia decurrens* showed the higher percentage of 11% in particular. The medium root ratios by biomass of other species, such as *Eucalyptus globulus* and *Quercus mongolica* var. *grosseserrata*, were comparatively high. On the other hand, those of *P. densiflora*, *Ch. obtusa*, *Ch. pisifera*, *Zelkova serrata*, *Abies firma*, etc. ranged from 1.8 to 2.3%. The influences tree density and site condition give to the medium root ratio by biomass are shown in Table 25, from which it can be seen that they have a tendency to make the ratio higher in a sparse-planting and dry stand.

Large root : As shown in Fig. 29 the decreasing curves were not so steep as those of fine root-medium root. The large root ratio by biomass is shown in Table 35 on the small and large diameter trees in the same way as the study of fine to medium roots. In the small diameter trees, *L. leptolepis* showed higher percentage than *C. japonica*, *Ch. obtusa* and *P. densiflora*. In the large diameter trees, *C. japonica* had a lower percentage. At this point, the large roots, like the medium roots, have almost no difference between species.

Large roots are affected not only by the properties of species, but also by tree size, so not all difference are caused only by the former. According to Table 24, *L. leptolepis* has the difference of 4.0%, and *Betula platyphylla* var. *japonica* and *Tsuga canadensis* have 3.3%. Almost species have those differences of 2 to 3%.

The large root ratio changes by tree density. Fig. 29 shows that the stands with high tree density, such as S 23, S 22, S 16, and S 17, take a lower value than the average. On the other hand, as shown in Table 32 it has a tendency to go slightly higher in a dry stand.

Table 36. Ratio of the very large root to the total tree biomass at the basal areas of 200 and 500 cm² (%)

Species / Basal area (cm²)	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
200	3.0	5.5	4.2	4.0
500	5.0	8.0	5.4	6.5

Table 37. Ratio of the very large root to the total tree biomass and tree density index

Stand	S 22	S 26
Basal area (cm²)	419	425
Site index	21.8	19.4
Tree density index	1.2	0.4
Ratio of very large root (%)	3.8	4.9

Table 38. Ratio of the root stock biomass to the total tree biomass at the basal areas of 100 and 500 cm² (%)

Species / Basal area (cm²)	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
100	10.0	9.5	11	8.5
500	14.0	10.5	11.5	9.0

Very large root : The very large root ratio increased, describing a parabolic curve upward, with the increase of basal area. It became constant when the basal area increased from 400 cm^2 to about 500 cm^2. This is different from the changes seen in the fine and small roots, and indicates that the very large root is an accumulating part (See Fig. 29). Table 36 shows the very large root ratio at the basal areas of 200 cm^2 and 500 cm^2 obtained from Fig. 29. Those of the small diameter trees became lower in the order of *Ch. obtusa*, *P. densiflora*, *L. leptolepis*, and *C. japonica*, whereas those of the large diameter trees became lower in the order of *Ch. obtusa*, *L. leptolepis*, *P. densiflora*, and *C. japonica*. *Ch. obtusa* showed the high part biomass ratio in the small and large diameter trees, but *C. japonica* showed the opposite ratio with it.

It is owing to the growth property of the root system of species. The high ratio by the very large root is clear from the morphological observations of those two species, too. The ratio of the very large root biomass to the total root biomass of the species, almost equal in tree size, is shown in Table 24. Those of *Quercus* and *Betula* spp., such as *Quercus mongolica* var. *grosseserrata*, *Betula platyphylla* var. *japonica*, etc. showed, for example, a high percentage from 15 to 18, while those of *L. leptolepis*, *Ch. pisifera*, *Eucalyptus globulus*, *Zelkova serrata*, and *Tsuga canadensis* showed a low percentage from 6 to 10.

The relation between tree density and very large root ratio was compared between S 26 and S 22, both almost equal in basal area and site index, and the finding is shown in Table 37. As is clear from the table, the difference between them was 1.1%, verifying that the very large root ratio is slightly lower in a dense stand.

In relation to soil condition, those ratios change, as shown in Table 32, regardless of the soil type; thus soil condition does not cause difference in ratio.

Root stock : The root stock ratio increased, describing such a parabolic curve as in Fig. 28. Those of *P. densiflora*, *Ch. obtusa* and *L. leptolepis* became constant at an earlier time when the basal areas ranged from 150 cm^2 to 200 cm^2. However, that of *C. japonica* did not become constant until the basal area increased to 300 cm^2.

L. leptolepis showed a rather slightly decreasing tendency, probably because its branching of the root system was remarkable and because it did not form a lump as *C. japonica*. The root stock ratio is shown in Table 38 on the small and large diameter trees. According to the table, those of the small diameter trees became lower in the order of *P. densiflora*, *C. japonica*, *Ch. obtusa*, and *L. leptolepis*. There, *P. densiflora* showed the highest percentage of all because of its developing tap roots; whereas those of the large diameter trees became lower in the order of *C. japonica*, *P. densiflora*, *Ch. obtusa*, and *L. leptolepis*. In this case, *C. japonica* had the highest ratio of 14%, because it took a crumbling root stock.

As already mentioned, *L. leptolepis* tends to diverge very large roots from the root stock. When these roots are cut around the point of branching, the lump left becomes smaller.

Quercus mongolica var. *grosseserrata*, *Betula platyphylla* var. *japonica*, *Betula davurica*, whose root stocks were all crumbled, had the high ratios of 15～18%, contrasting with the root property of *L. leptolepis*. The ratios for *Zelkova serrata*, *Acacia decurrens*, *Ch. pisifera*, *Tsuga canadensis*, *L. leptolepis*, etc., were low, ranging 6～9%. *Zelkova serrata* is easily influenced by density effect.

As mentioned before, tree density effect causes a slight increase of the ratio. The effect is remarkable in all the parts of fine roots to a root stock, and that has a significant effect on the root biomass because a large root, a very large one and a root stock account for the greater part of the total biomass. It would be to good purpose if we examine the influence

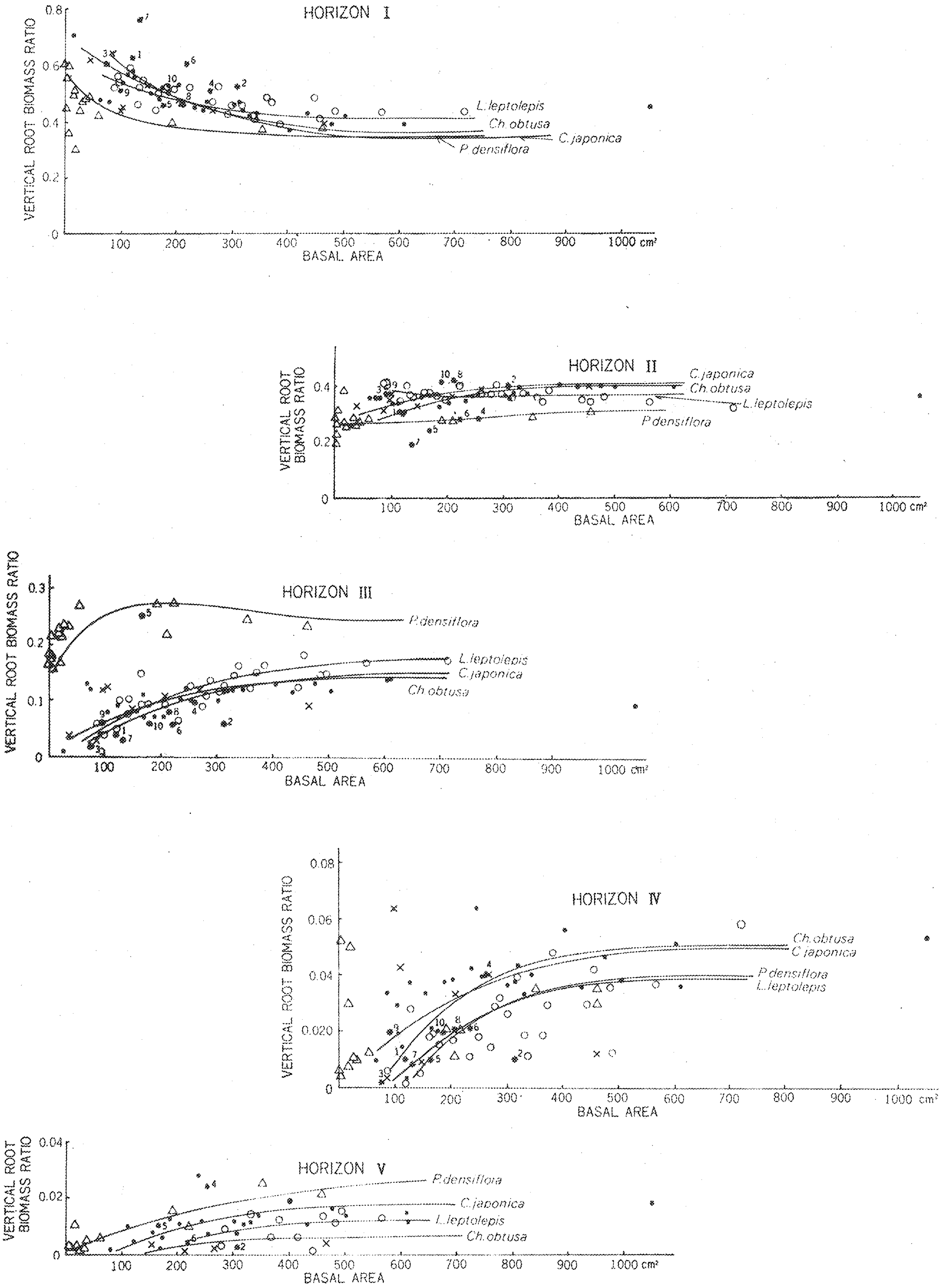
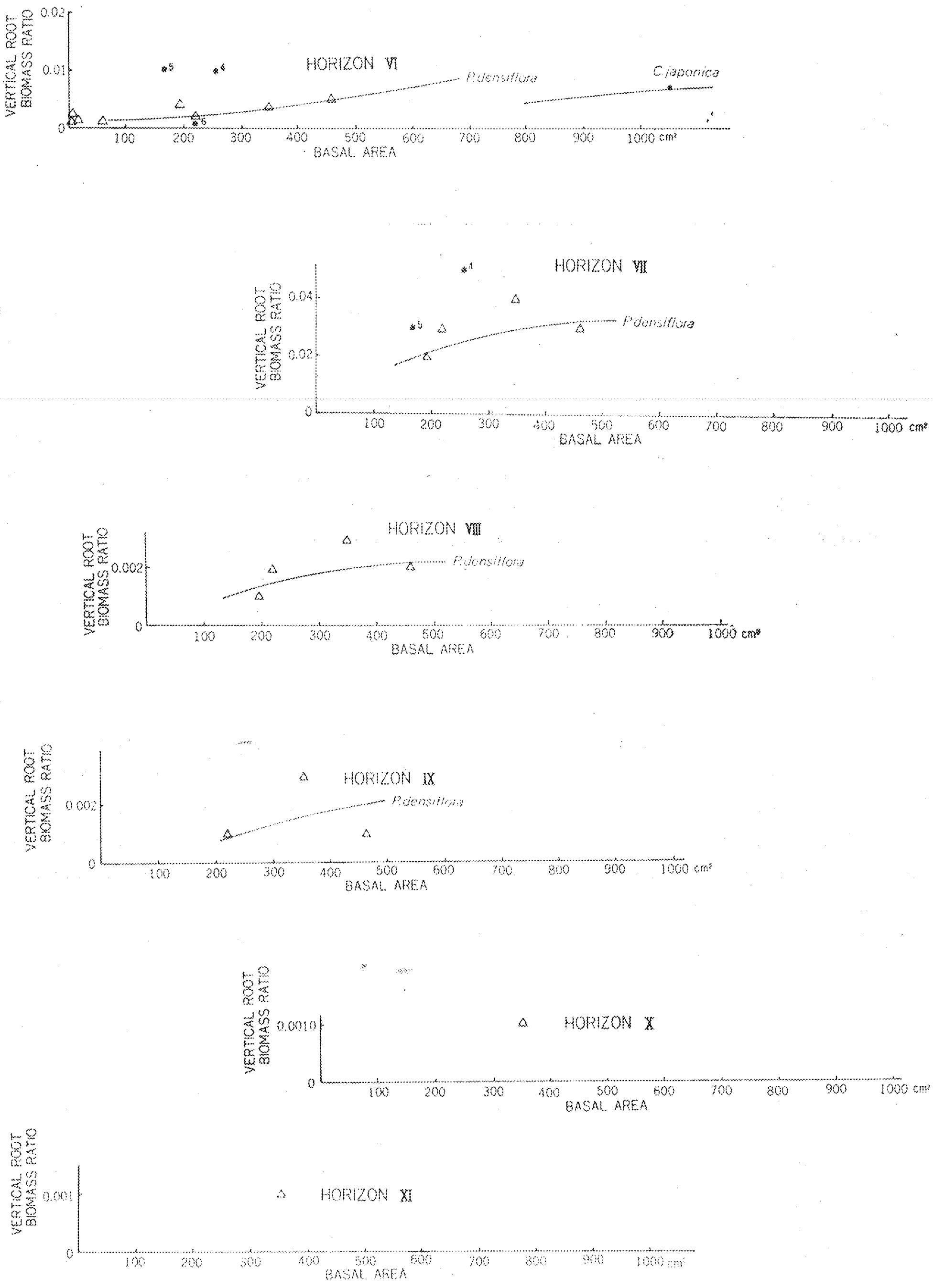

HORIZON Ⅰ
VERTICAL ROOT BIOMASS RATIO
L. leptolepis
Ch. obtusa
C. japonica
P. densiflora
BASAL AREA
1000 cm²
HORIZON Ⅱ
VERTICAL ROOT BIOMASS RATIO
C. japonica
Ch. obtusa
L. leptolepis
P. densiflora
BASAL AREA
HORIZON Ⅲ
VERTICAL ROOT BIOMASS RATIO
P. densiflora
L. leptolepis
C. japonica
Ch. obtusa
BASAL AREA
HORIZON Ⅳ
VERTICAL ROOT BIOMASS RATIO
Ch. obtusa
C. japonica
P. densiflora
L. leptolepis
BASAL AREA
HORIZON Ⅴ
VERTICAL ROOT BIOMASS RATIO
P. densiflora
C. japonica
L. leptolepis
Ch. obtusa
BASAL AREA

Fig. 34



Ratio of the root biomass in each horizon to the total root biomass.

Table 39. Ratio of the root biomass in horizon I to the total root biomass at three basal areas

Basal area (cm^2) \ Species	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
100	58	60	40	58
500	40	42	37	50
1,000	45	—	—	—

of tree density effect on the T/R ratio of those roots.

The influence of the site condition on T/R ratio is remarkable in the fine, small and medium roots, and not in the roots larger than the medium root. It is the reverse of the case of tree density effect.

There is a similar tendency in the change of the ratio either between leaves, which are working parts above the ground, and fine roots under the ground, or between stems, which are an accumulating part above the ground, and the large, very large roots and root stock under the ground. It indicates that there is a close relation between production and accumulation.

5) **Distribution ratios of root biomass according to every soil horizon**

The distribution ratio of all the root biomass from fine root to root stock at every soil horizon, is shown in Fig. 34 in relation to basal area in Table 39. As is clear from the figure, that ratio is different depending on tree size. Examinations were carried out at every soil horizon, and relevant observations are:

Soil horizon I: The ratios of root biomass in soil horizon I, as shown in Fig. 34 are high for small diameter trees, decreasing gradually as trees grow up. And they make a slight increase for large diameter trees. Looked through the main species, they range from 40 to 60% for small diameter trees as shown in Table 39. According to the table, they became lower in the order of *Ch. obtusa*, *C. japonica* or *L. leptolepis*, and *P. densiflora*. There was, however, no great difference in ratio among *C. japonica*, *Ch. obtusa* and *L. leptolepis*. Only *P. densiflora* showed a considerably lower percentage.

At the basal area of 500 cm^2, they were 37 to 50% and lower than those of small diameter trees. They became lower in the order of *L. leptolepis*, *Ch. obtusa*, *C. japonica*, and *P. densiflora*.

Table 40. Ratio of the root biomass in each

Species		*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*	*Ch. pisifera*
Stand		S 10	H 3	A 3	K29	M 2
Basal area (cm^2)		208	254	198	200	238
Soil type		$\mathrm{B}l_{\mathrm{D}}$(d)	B_{D}	$\mathrm{B}l_{\mathrm{D}}$(d)	$\mathrm{B}l_{\mathrm{B}}$	$\mathrm{B}l_{\mathrm{D}}$
Horizon	I	53.2	50.9	39.3	53.0	53.4
	II	34.0	39.0	28.6	36.0	39.2
	III	7.9	9.1	28.0	9.8	6.2
	IV	3.8	0.9	2.1	1.7	1.0
	V	1.1	0.1	1.5	—	0.2
	VI	—	—	0.7	—	—
	I + II	87.2	89.9	67.9	89.0	92.6

The shallow rooted species, *L. leptolepis* and *Ch. obtusa*, had a higher ratio than *C. japonica* and *P. densiflora*. There was, above all, no great difference between *Ch. obtusa* and *C. japonica*. Only *L. leptolepis* had a considerably higher ratio. *P. densiflora* had the lowest ratio of 37%, partly because its roots larger than a large root, which had a greater part of the biomass, were tap-rooted, and partly because they were distributed much wider to deep soils than those of any other species. The decrease of the ratios with tree growth was examined within the range of the basal areas 100 cm^3 and 500 cm^2. It was found that *C. japonica* and *Ch. obtusa* had that of 18%, *L. leptolepis* that of 8%, and *P. densiflora* that of 3%. The change was remarkable for *C. japonica* and *Ch. obtusa*, but not for *P. densiflora* and *L. leptolepis*.

When the other species were included, the ratios of *Acacia decurrens*, *Eucalyptus globulus*, *C. japonica*, *L. leptolepis*, *Zelkova serrata*, etc. ranged from 52 to 77%. They were higher than those of *P. densiflora*, *Abies firma*, and *Quercus mongolica* var. *grosseserrata* (See Table 40).

Fig. 34 shows on *C. japonica* the relation between the tree density and ratios of the root biomass according to every soil horizon. The S 22 stand with high density took a low ratio, and the sparse planting stand was contrary to it.

A comparison of the relation to the basal areas on a few stands which have nearly equal soil conditions was made, and Table 41 gives results. According to the table, the ratio of a sparse stand in soil horizon I is higher by 3 to 6% than that of a dense stand. It was evident from these that a close planting stand had a wider distribution of root biomass in the lower soil horizons than a sparse planting stand. It is not clear whether this phenomenon is due to root competition or not.

They are shown in Table 42 in relation to soil conditions. According to the table, they became higher in soil horizon I of the soils of dry types, such as BA, B*l*c, etc., than of the soils, moderately moist type. The difference between the S 20 stand of BA soil type and the S 12 stand of B*l*D(w) soil type was 1.7%. The same differences were observed among the other species.

According to Fig. 34 and Table 39, *C. japonica* gave the ratio of 40% at the basal area of 500 cm^2, and that of 45% at the basal area of 1,000 cm^2. It is a very interesting phenomenon that the root system may grow selecting the soil horizon after they develop well enough in the soil horizons.

Soil horizon II: Fig. 34 shows the relation of the basal areas to the ratios of the root

horizon to the total root biomass

E. globulus	*Zelkova serrata*	*Abies firma*	*Tsuga canadensis*	*Acacia decurrens* v. *dealbata*	*Quercus mongolica* v. *grosseserrata*	*Betula platyphylla* v. *japonica*	*B. davurica*
M 3	M 4	M 5	M 6	M 7	M 8	M 9	M10
177	188	156	211	135	167	118	157
Im-BF	B*l*D	B*l*D	B*l*D	Er-BA	B*l*D	B*l*D	B*l*D
60.8	51.8	46.2	61.1	76.5	46.2	51.5	50.0
36.3	29.4	24.7	28.6	19.2	42.8	38.6	41.2
2.7	10.1	25.0	6.9	3.4	8.9	7.2	6.3
0.2	4.8	1.5	2.8	0.9	2.1	2.7	2.5
—	2.4	1.2	0.4	—	—	—	—
—	1.5	1.4	0.2	—	—	—	—
97.1	81.2	70.9	89.7	95.7	89.0	90.1	91.2

Table 41. Ratio of the root biomass in each soil horizon to the total root biomass and tree density (%)

Species		*C. japonica*				*P. densiflora*		*L. leptolepis*	
Stand		S 23	S 13	S 22	S 26	A 10	A 11	K 18	K 24
Basal area (cm^2)		152	196	419	425	18	32	346	410
Tree density index		0.798*	0.598**	1.158*	0.449**	1.243*	0.884**	0.811*	0.538**
Horizon	I	50.6	52.4	37.8	43.1	50.6	48.4	42.6	48.9
	II	36.8	37.4	41.6	40.7	26.9	26.0	40.6	36.8
	III	8.5	7.6	13.1	11.5	22.1	24.0	14.9	12.4
	IV	3.3	2.0	5.6	3.6	0.4	1.1	1.9	1.9
	V	0.8	0.6	1.9	1.1	—	0.5	—	—
	I + II	87.4	89.8	79.4	83.8	77.5	74.4	83.2	85.7

* Close planting stand ** Sparse planting stand

Table 42. Soil type and ratio by root biomass in each soil horizon (%)

Stand		S 20	S 12	S 7	S 13	S 10	S 23	S 13	S 18
Basal area (cm^2)		265	267	160	196	208	152	451	554
Tree density index		0.482	0.672	0.575	0.598	0.585	0.798	0.682	0.545
Soil type		BA	BlD(w)	Blc	BlD	BlD(d)	BD	BlD	BE
Horizon	I	48.9	47.2	53.5	52.4	53.2	50.6	39.8	39.1
	II	37.8	37.6	33.7	37.4	34.0	36.8	41.4	40.4
	III	11.0	10.6	7.8	7.6	7.9	8.5	14.0	13.9
	IV	2.1	3.9	3.7	2.0	3.8	3.3	3.6	5.1
	V	0.2	0.7	1.3	0.6	1.1	0.8	1.2	1.5
	I + II	86.7	84.8	87.2	89.6	87.2	87.4	81.2	79.5

Table 43. Ratio by root biomass in soil horizon II (%)

Species Basal area (cm^2)	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
100	35	36	27	39
500	40	40	30	35

Table 44. Ratio by root biomass in soil horizons I and II (%)

Species Basal area (cm^2)	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
100	93	96	67	97
500	80	82	67	85

Table 45. Ratio by root biomass in soil horizon III and below (%)

Species Basal area (cm^2)	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
100	7	4	33	3
500	20	18	33	15

biomass in soil horizon II 15 to 30 cm deep. According to the figure, the ratio of *L. leptolepis* decreased gradually with the tree growth, but those of *C. japonica*, *Ch. obtusa* and *P. densiflora* increased, describing a parabolic curve upward. The curves were drawn very gently, however, as shown in Table 43, and the difference between the basal areas, 100 cm^2 and 500 cm^2, was very small; 3～5%.

The ratios got lower in the order of *C. japonica* or *Ch. obtusa*, *L. leptolepis*, and *P. densiflora*. *C. japonica* got a higher percentage in this horizon than in soil horizon I, because of its root system's property of growing well in a deep moist soil condition which soil horizon II has. On the other hand, *L. leptolepis* distributed the root system much wider to the surface horizon than to soil horizon II, because it grew well on an aerobic condition. *P. densiflora* spread fewer roots in this horizon than in lower soil horizons because of its tap rootedness.

The other species added to the distribution ratios of root biomass ranged from 19 to 43% in this horizon as shown in Table 40. *Quercus mongolica*, *Betula davurica*, *Betula platyphylla* var. *japonica*, *Ch. obtusa*, *Ch. pisifera*, etc. showed the high percentage from 39 to 43 while *Acacia decurrens*, *Abies firma*, *Tsuga canadensis*, etc. showed the low one from 19 to 29.

The difference in ratio due to tree density and site condition was low, as shown in Tables 41 and 42. Soil horizon II appeared to be more or less like a transitional horizon between soil horizons I and III.

Soil horizons I and II: The ratios of the root biomass distributed to soil horizons I and II, 30 cm deep from the surface horizon, as shown in Table 44, range from 67 to 97% at the basal area of 100 cm^2 and from 67 to 85% at that of 500 cm^2.

These percentages are very high, because the large root, through the very large root to the root stock, are maldistributed to the surface horizon. When the other species were included, for exapmle, *Eucalyptus globulus*, *Acacia decurrens*, *Betula platyphylla* var. *japonica*, *Betula davurica*, *Ch. obtusa*, *Ch. pisifera*, etc. showed the high percentage of over 90 as given in Table 40. *Eucalyptus globulus* went above all to take the highest percentage of 97. Although they had a relation to soil conditions, these species showed a special property of shallow rootedness. It is very interesting if added either to a result of general observation or to such a phenomenon as windfall. Next to *Ch. obtusa*, *L. leptolepis* registered the percentage of 89, making a special feature of shallow rootedness.

P. densiflora and *Abies firma* had the comparatively low percentages from 68 to 71 in soil horizons I and II. All those species were tap-rooted and their root biomass were distributed more widely to soil horizon III.

The relation between the tree density and ratios of the root biomass in soil horizons I and II is shown in Table 41. The ratio was found to be higher by 3 to 4% in a sparse-planting stand than in a close-planting stand. In a dense stand the root system tended to distribute wider to deeper soils.

Similarly, as concerns the soil conditions, even in the stands almost equal in basal area and density index, the distribution ratio in a dry soil tended, as shown in Table 42, to be high in the surface horizon rather than in the moderately moist colluvial soil (these results, however, were not clear owing to the physical and chemical changes of soil in S 13 and S 10).

Soil horizon III and below: The distribution ratio to soil horizon III and below increased, as shown in Fig. 34, describing a parabolic curve upward as the basal areas increased. This is entirely contrary to that to soil horizon I.

From these facts, it was recognized that the root distribution changed distinctly at the depth of 30 cm. This depth has, therefore, an important meaning for the root function.

The distribution ratio becomes higher as the diameter gets larger in such a low horizon. But in the large diameter trees the rate of increase gets down to almost constancy. It means that the root system grows rapidly to a certain diameter but that its growth rate decreases after then. Owing to this tendency, the curve of basal area and root biomass moves upward gently as the horizon descends from horizon III to V. And the lower soil horizons go, the less root distribution such shallow-rooted species as *Ch. obtusa* and *L. leptolepis* show. The upturn point of the curve moves to the larger diameter tree. In soil horizon IV, the root distribution becomes narrower in such stands as H 1 and S 11 of small diameter trees. In soil horizon V, *Ch. obtusa* and *L. leptolepis* have no root biomass at the basal area of 150 cm^2 and below.

On the other hand, the root distribution of *P. densiflora*, of which the main root grew well in lower horizons, reached even to soil horizons V in the small diameter trees, 50 cm^2 in basal area. At the basal area of 350 cm^2 it reached to soil horizon VI over 3 m deep.

The distribution ratios of root biomass to soil horizon III and below are shown in Table 45. At the basal area of 100 cm^2, as shown there, they became lower in the order of *P. densiflora* (33%), *C. japonica* (7%), *Ch. obtusa* (4%), and *L. leptolepis* (3%). There, *P. densiflora* had the considerably higher percentage. *Ch. obtusa* and *L. leptolepis* had almost the greater part of the total root biomass within the horizon 30 cm deep from the surface horizon. At the basal area of 500 cm^2, the developed root system made the difference in distribution decreasing among each species. The distribution ratio of the root biomass became lower in the order of *P. densiflora* (33%), *C. japonica* (20%), *Ch. obtusa* (18%), and *L. leptolepis* (15%). Three species except for *P. densiflora* showed ratios decreased in the lower horizons. The contrary applies in soil horizons I and II.

The rate of increase of root biomass at the basal areas 100 cm^2 and 500 cm^2 were 13% for *C. japonica*, 14% for *Ch. obtusa*, 0% for *P. densiflora*, and 12% for *L. leptolepis*. In short, *C. japonica*, *Ch. obtusa* and *L. leptolepis* took an almost similar percentage, but *P. densiflora* did not. This is because the curve in soil horizon II was described at the considerably high points for small diameter trees as shown in Fig. 34. That species, however, made an almost parabolic curve as did the other species in soil horizon IV or below.

In soil horizon III, *P. densiflora* had the highest ratio of 25% at the basal area of 500 cm^2. However, *L leptolepis*, *C. japonica* and *Ch. obtusa* had the ratios of 10～15%. There was no great difference between each species.

In soil horizon IV, that ratio became lower in the order of *C. japonica*, *Ch. obtusa*, *P. densiflora*, and *L. leptolepis*. The difference among species ranged only from 4 to 5% at the basal area of 500 cm^2.

In soil horizon IV, the shallow-rooted species such as *Ch. obtusa* and *L. leptolepis* had the lower ratios. They became lower in the order of *P. densiflora*, deep rooted, (2.5%), *C. japonica* (1.9%), *L. leptolepis* (1.1%), and *Ch. obtusa* (0.5%).

The difference between the shallow-rooted type and deep-rooted type was clear in this soil horizon. Only *P. densiflora*, deep rooted, and the S 17 stand of *C. japonica*, a large diameter tree, distributed the root system to soil horizon VI or below. In soil horizons VII and below, only *P. densiflora*, tap-rooted, took roots. The effect of tree density on the ratio of root biomass in soil horizon III or below is shown in Table 41. According to the table, a close planting stand took the higher distribution ratio in lower soil horizons than a sparse planting stand. The difference in ratio between S 22, one of the typical close planting stands, and S 26, one of

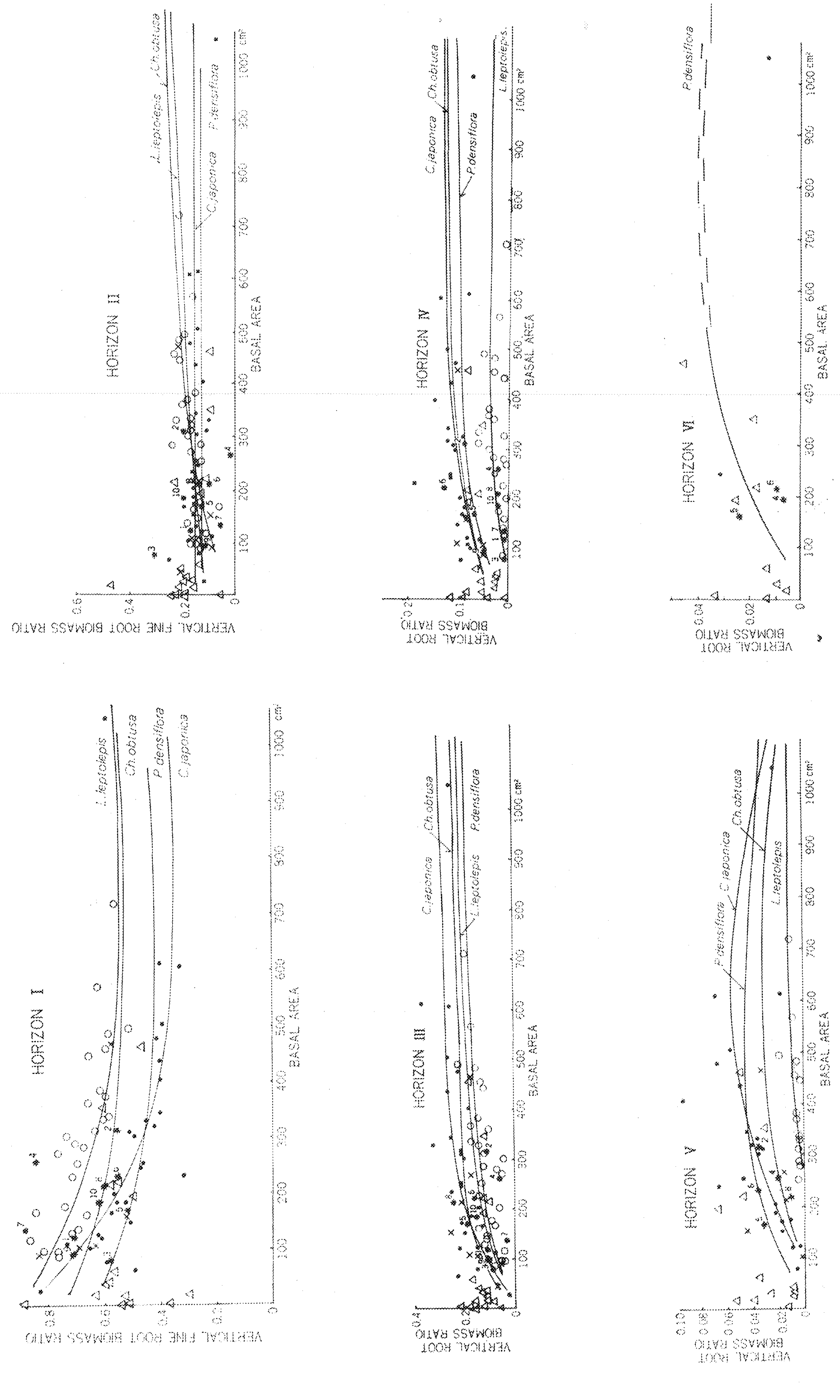


Fig. 35 Ratio of the fine root biomass in each horizon to the total.

Table 46. Ratio by fine root biomass in horizon I and basal area (%)

Species / Basal area (cm²)	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*
100	65	65	55	78
500	38	52	45	55
1,000	60	65	58	70

the typical sparse planting stands, was 1.6% in soil horizon III, 2.0% in IV, and 0.8% in V When comparison is carried out between these differences and the ratios of the sparse planting S 26 stand, it becomes clearer that the ratios are higher in the under horizons than in the upper horizons.

The ratios, as shown in Table 42, are higher in the under horizons of a moderately moist colluvial soil than of a dry residual soil. When a comparison of ratio was made between S 20 on the B_A typed soil and S 12 on the $Bl_D(w)$ typed soil, the ratios of the latter were higher by 0.4% in soil horizon III, by 1.9% in IV and by 0.5% in the V than those of the former. Hence it is that the latter stand had a higher percentage in each soil horizon, I to III.

6) **Distribution ratios of each root class according to every soil horizon**

We have so far examined the distribution ratios of the total biomass each root has at every soil horizon. These relations may also be applicable to each root classification.

Fine root: Fig. 35 shows the relationship between the basal areas and the distribution ratios of fine roots at every soil horizon. As can be seen in the figure, the fine root biomass made a concave curve upward in soil horizon I, a straight or gently parabolic one upward in II, and a parabolic one upward in III or below. In this case, it had the smaller and clearer variance than the total root biomass.

Table 46 shows the ratios of fine roots by biomass in soil horizon I at the basal areas, 100 cm² and 500 cm², obtained from Fig. 35. At the basal area of 100 cm², they became, as shown there, lower in the order of *L. leptolepis* (78%), *Ch. obtusa* or *C. japonica* (65%), and *P. densiflora* (55%).

At the basal areas of 500 cm² and 1,000 cm², they became lower in the order of *L. leptolepis*, *Ch. obtusa*, *P. densiflora*, and *C. japonica*. There, *C. japonica* and *Ch. obtusa* had an almost equal percentage of 65 for the small diameter trees. Those order in ratio was constant for the grown-up trees. In soil horizon I, those of *L. leptolepis*, and *Ch. obtusa* were higher than those of *C. japonica* and *P. densiflora*, which tended to go higher in the lower horizons. This was compatible with the tendency of distribution of all root biomass.

The distribution ratio of the total root biomass in soil horizon I ranged from 40 to 60% at the basal area of 100 cm², and from 37 to 50% at that of 500 cm². The fine roots of small and large diameter trees, therefrom, were distributed more widely to soil horizon I.

For fine roots grow well, judged from their function, near the surface horizon with good aerobic. In short, they are distributed much wider there.

The distribution ratios of the fine roots in soil horizon I according to tree size concerning *C. japonica* were investigated and results shown in Table 34. According to the table, they are 65% at the basal area of 100 cm², 38% at that of 500 cm², and 60% at that of 1,000 cm². When a comparison is made between these and each ratio of the total root biomass in Table 39, it is 58%, 40 or 45% respectively at each basal area. It would seem that fine roots have a tendency to take high increasing and decreasing ratios in general, indicating that the various conditions have a stronger effect on the growth of these roots than on that of thicker roots.

As already explained, the large-diameter trees made the ratios of root biomass increase in soil horizon I, which was due to the selective growth by root in soil horizons. The special feature was remarkable for a fine root, one of the working parts.

In soil horizon II or below: Fig. 35 shows that the fine root biomass draws a straight line downward or a remarkably gentle and parabolic curve upward in soil horizon II. Besides, the small and large-diameter trees both have their ratio by root biomass (from 15 to 20%) almost unchangeable.

In horizon III or below, as with the total biomass, they draw a parabolic curve upward. Their variance, however, is small, and instead their coefficient of correlation is larger than that of the total biomass.

In soil horizon III, each species increases the ratio by root biomass for the small-diameter tree very remarkably. A tree, 100 cm^2 in basal area, for example, showed the percentage of only 10. And yet it increased parabolically to get to 15 to 20% at the basal area of 500 cm^2. It became lower in the order of *C. japonica*, *Ch. obtusa*, *L. leptolepis*, and *P. densiflora*. There was no clear difference in ratio between deep-rooted species and shallow-rooted species.

In soil horizon IV, the ratios by root biomass at the basal area of 500 cm^2 were 12% for *C. japonica*, 10% for *Ch. obtusa*, 8% for *P. densiflora*, and 2% for *L. leptolepis*. *C. japonica* and *Ch. obtusa* showed almost the same. *L. leptolepis*, shallow-rooted, took a remarkably lower ratio in this horizon than any other species. It is because *L. leptolepis* are prevented by the anarobic condition in particular from growing the fine root freely.

In soil horizon V, they were 6% for *C. japonica*, 4.5% for *P. densiflora*, 3% for *Ch. obtusa*, and 1% for *L. leptolepis*. *Ch. obtusa* decreased the distribution ratio in this horizon. The difference between *P. densiflora* and *C. japonica*, deep-rooted, and *Ch. obtusa* and *L. leptolepis*, shallow-rooted, became clear in soil horizon IV, 90 to 120 cm deep.

And what is more, *L. leptolepis* and *Ch. obtusa*, shallow-rooted, had no distribution of root biomass for the small diameter trees in this horizon. The conclusion to be drawn from the foregoing is that this horizon plays an important role, physiological and ecological, in influencing root distribution and tree growth.

Only the root distribution of *P. densiflora*, deep-rooted, was observed in soil horizon VI and below. Moreover, its distribution reached to soil horizon XI.

The above-mentioned changes in fine root biomass according to soil horizon prove that fine roots function as a working and growing part. Those changes either correspond directly to soil condition or characterize the properties each species has. Accordingly, they are very meaningful in examining the growth property of root system (The correspondence to tree

Table 47. Ratio by root biomass of *C. japonica* in horizon I and tree size (%)

Stand	Basal area (cm^2)	f	s	m	l	L
S 11	19	83	80	80	99	—
S 1	61	50	42	45	47	100
S 24	99	63	61	43	50	98
S 4	335	41	34	29	21	40
S 18	554	34	21	13	10	27
S 17	1,042	60	53	41	41	33

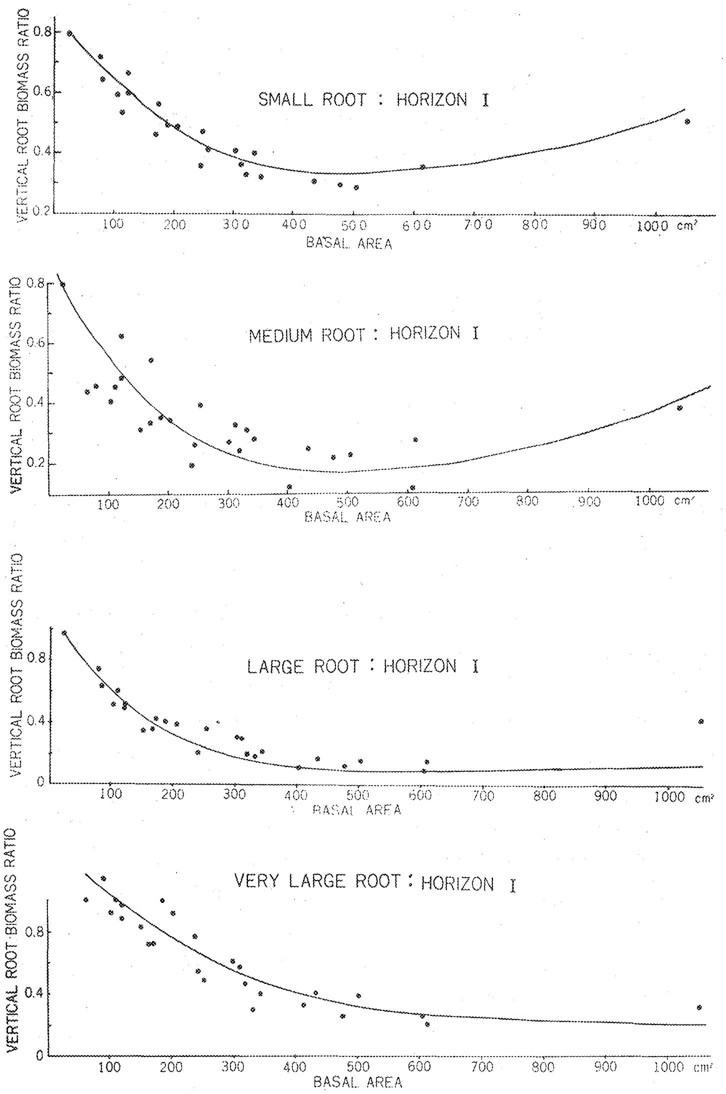


Fig. 36 Vertical disribution by biomass of each root class of *C. japonica.*

density and soil condition will be mentioned when root density is referred to).

Small root to root stock : As mentioned above, the ratio by root biomass-basal area curve changes from a decreasing curve to an increasing curve according as roots become larger. This relation may be recognized in each soil horizon. It is shown in Fig. 36 on each root class larger than a small root in soil horizon I, where fine roots make the most distinctive changing curve. According to the figure, each ratio by biomass from a small to very large root became lower as the tree grew from a small-diameter tree to a large-diameter tree. This inclination of decrease became steeper with tree diameter. Table 47 shows those ratios on the stands which take the average values from Fig. 36. As is clear from the table, they decrease disproportionately with basal areas. For example, the differences in root biomass a

Table 48. Ratio by root biomass of *C. japonica* in horizon III and tree size (%)

Stand	Basal area (cm^2)	f	s	m	l	L
S 11	19	4	6	5	—	—
S 1	61	24	27	22	28	—
S 24	99	15	15	29	10	—
S 4	335	25	30	30	36	28
S 18	554	25	24	34	48	31
S 17	1,042	25	26	32	24	25

tree between S 11 and S 18, both small in diameter, were 49% for a fine root, 59% for a small root, 67% for a medium root, and 89% for a large root. That they became bigger as the root system got thicker is partly because among small-diameter trees the root biomass tended to maldistribute to the upper horizons as the root system got thicker, and partly because among large-diameter trees it tended to decrease.

In the stand of S 11, small in diameter, 99% of the root biomass of a large-diameter tree was distributed to soil horizon I and there were no very large roots. The very large root, however, made the distributions of 100% and 98% in the stands of S 1 and S 24 respectively. That is, when the root system became thicker, the distribution ratio by root biomass became higher in soil horizon I. And at the same time, its maximum value moved toward the large diameter tree. This relation is remarkable in the large and very large roots.

These phenomena are regarded as the combination of the root class and soil horizon. The ratios by root biomass increased, corresponding to basal area and described a parabolic curve upward as the soil horizon went down. This is the reverse of those on soil horizon I. The origin of the parabolic curve, however, moved towards the larger area.

The distribution ratios by root biomass to soil horizon I, as mentioned so far, are different in each root class. The S 11 stand of Table 47 shows, for example, the distribution proportion of 83, 80, and 99% to the fine roots, small or medium roots, and large roots respectively. In short, the fine and large root took the larger value than the small and medium roots. It is also dominant over the other stands. As a stand is growing up, the minimum value moves toward a large root, as shown in Table 47. In the S 1 stand, the small root took the minimum percentage of 42; in the S 24 stand, the medium root took 43, and in the S 4–S 18 stands, the large root took 21 or 10.

Hence it is that tree growth causes thick roots to go toward the increasing distribution of root biomass in deep soils. When adding it to the fact that the proportion to each root class go down disproportionately with increasing basal area, it turns out that the propoption to soil horizon I is decreasing as a stand is growing up or as the root system is enlarging. Since distribution is greatly affected by the soil properties, such as aeration, fertility, etc., fine roots take a higher percentage in soil horizon I than small and medium roots in all stands. This, however, goes opposite to the distribution ratio to soil horizon III as Table 48 proves. There, the ratio is increasing in parabolic form as a tree is growing. And the point showing the maximum value moves to a large root. It follows from Tables 47 and 48 that root distribution is different according to soil horizon, tree size, and root class, and that although the root system of small-diameter trees are maldistributed to the surface soil horizon, the distribution ratios of large diameter roots increase gradually in the horizons downward as trees grow up.

Table 49. Average root volume of the

Species	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*	*Chamaecyparis pisifera*	*Eucalyptus globulus*
Stand	S 5	H 5	A 8	K14	M 2	M 3
Basal area (cm²)	439	427	361	422	238	177
Root volume (m³)	0.13	0.13	0.09	0.14	0.07	0.02

Table 50. Root volume per ha

Species	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*	*Chamaecyparis pisifera*	*Eucalyptus globulus*
Stand	S 5	H 5	A 8	K14	M 2	M 3
Basal area (cm²)	439	427	361	422	238	177
Root volume per ha	116.2	91.3	69.7	105.0	34.3	58.4

3. **Root volume**

From the root biomass and the bulk density, the volumes of each class of the root system in each soil horizon were calculated.

1) **Volume of a root system per tree**

As the bulk density differs among species, the root volume of each species have some difference in relativity from the root biomass. The average root volumes of each species per tree are shown in Table 49. According to the table, those of main trees ranged from 0.09 to 0.14 m³ at the basal areas of 360～440 cm², and those of the other species ranged from 0.02 to 0.09 m³ at the same basal areas. They differ according to tree size and bulk density. *L. leptolepis*, *Acacia decurrens*, *Quercus mongolica*, and *Betula davurica* with low bulk density, for example, showed a large average root volume per tree for their basal areas. Since each species does not make a great difference in bulk density, the average root volume goes up and down almost proportionately with the root volume.

Table 51. Ratio of each root volume to the total root volume (%)

Species	Stand	f	s	m	l	L	St
C. japonica	S 5	2.3	2.4	5.4	7.8	22.0	60.1
Ch. obtusa	H 5	3.7	6.5	5.4	10.0	32.6	41.8
P. densiflora	A 8	0.4	3.3	9.3	12.7	24.7	49.4
L. leptolepis	K14	1.2	2.2	6.9	11.4	34.2	44.1
Chamaecyparis pisifera	M 2	5.8	7.3	10.4	12.1	29.5	34.9
Eucalyptus globulus	M 3	4.2	18.3	25.2	10.1	13.1	29.1
Zelkova serrata	M 4	9.3	7.8	16.7	14.0	15.5	36.2
Abies firma	M 5	2.2	4.2	10.7	10.6	8.9	63.4
Tsuga canadensis	M 6	3.3	11.6	17.3	14.3	16.4	37.1
Acacia decurrens v. *dealbata*	M 7	14.0	15.3	38.4	6.4	6.0	19.9
Quercus mongolica v. *grosseserrata*	M 8	1.0	5.5	19.3	7.8	9.3	57.1
Betula platyphylla v. *japonica*	M 9	1.0	4.6	13.2	11.0	10.5	59.7
B. davurica	M10	1.1	7.4	17.3	9.1	10.0	55.1

sample trees of each species (m³)

Zelkova serrata	*Abies firma*	*Tsuga canadensis*	*Acacia decurrens* v. *dealbata*	*Quercus mongolica* v. *grosseserrata*	*Betula platyphylla* v. *japonica*	*B. davurica*
M 4	M 5	M 6	M 7	M 8	M 9	M10
188	156	211	135	167	118	157
0.06	0.03	0.05	0.09	0.06	0.02	0.04

of each species (m³)

Zelkova serrata	*Abies firma*	*Tsuga canadensis*	*Acacia decurrens* v. *dealbata*	*Quercus mongolica* v. *grosseserrata*	*Betula platyphylla* v. *japonica*	*B. davurica*
M 4	M 5	M 6	M 7	M 8	M 9	M10
188	156	211	135	167	118	157
80.1	55.3	72.1	65.1	10.5	36.3	40.4

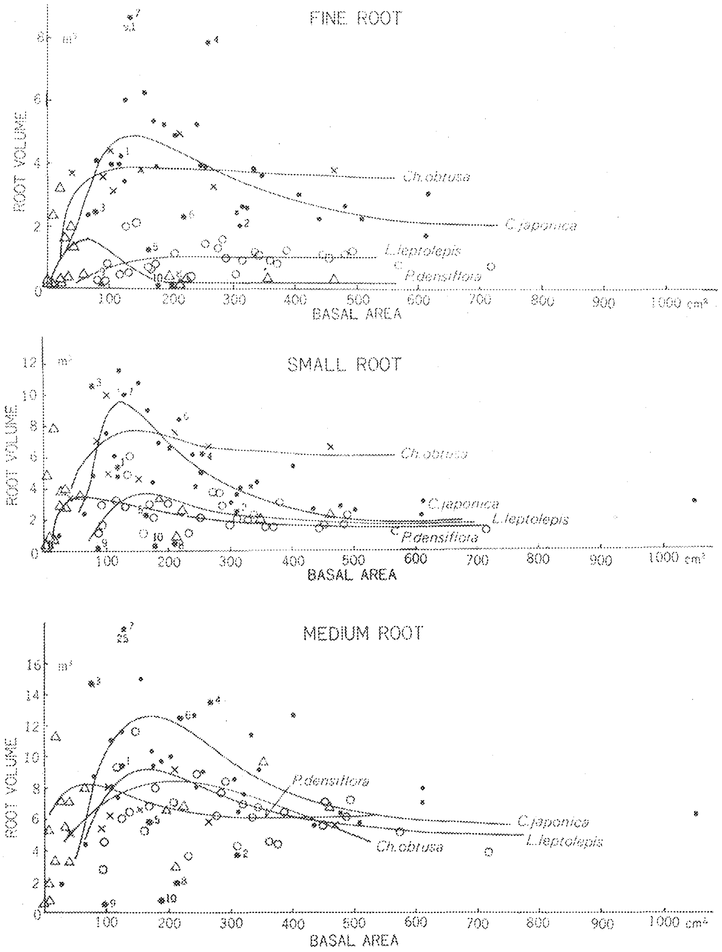


Fig. 37 Root volume per ha, and basal area.

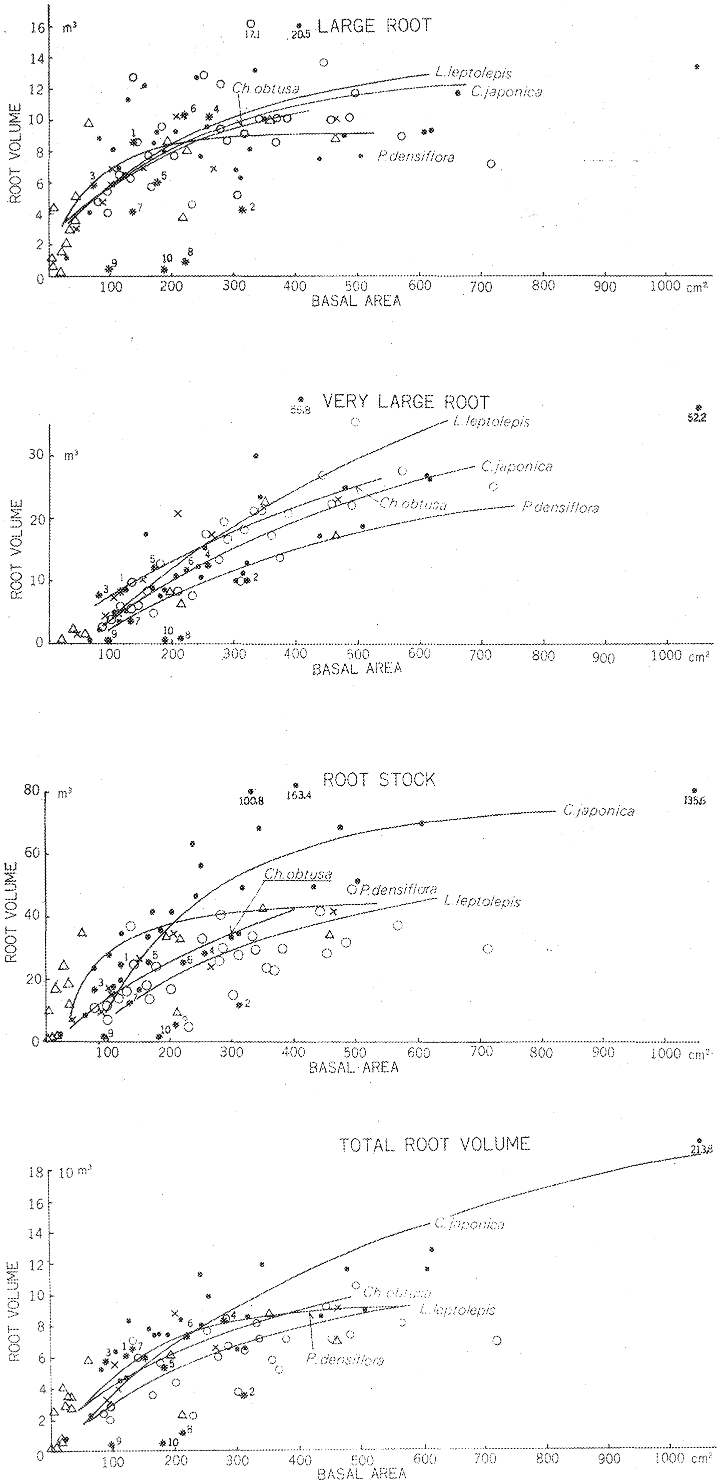


Fig. 37 (Continued)

2) **Volume of a root system per ha**

The root volumes per ha are shown in Table 50. As is evident from it, they range from 70 to 116 m^3 at the average basal areas from 361 to 439 cm^2 in the stands of *C. japonica*, *Ch. obtusa*, *P. densiflora*, and *L. leptolepis*.

3) **Tree size and root volume per ha according to each root class**

The change of the root volume in each root class, answering tree growth, is shown in Fig. 37. The root volume per ha from a fine root through a small root to a medium root, as with the root biomass, increases, as shown in the figure, to the peak when the basal area ranges from 150 to 200 cm^2, then decreases with tree growth. And that volume from a large root through a very large root to a root stock draws a parabolic curve upward. That runs almost parallel to the change in root biomass. The average bulk density of the root system does not go up and down greatly with tree size.

4) **Root volume ratio by every root class**

Table 51 shows the volume ratios by root class in the stands from Table 49 and 50.

Those to the fine roots ranged from 0.40 to 3.70% although difference in growth has some influence on them. Of all main trees, *P. densiflora* got the lowest percentage and *Ch. obtusa* the highest. Those to the small roots ranged from 2.2 to 6.5%, and those to the medium roots from 5 to 9%. It is evident from the fact that as the root system becomes

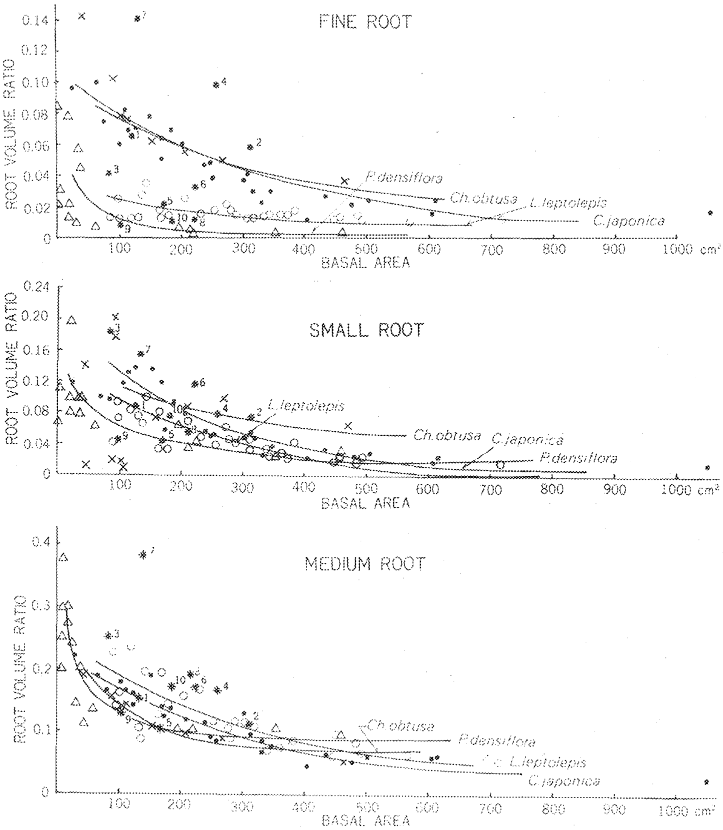


Fig. 38 Ratio each root volume to the total, and basal area.

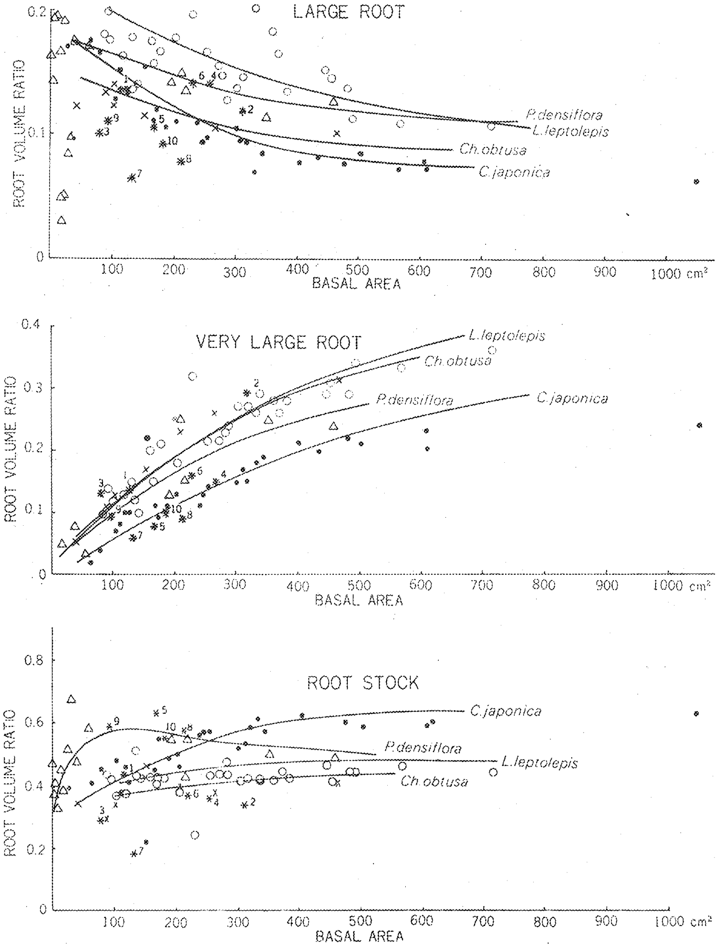


Fig. 38 (Continued)

larger, the difference in ratio between species becomes lower. For example, those to root stocks ranged from 42 to 60%.

In the other species, such as *Acacia decurrens, Zelkova serrata* and *Ch. pisifera,* the volume ratios to the fine roots were 6～14%, and those to the small roots 7～15%. In *Abies firma, Quercus mongolica, Betula platyphylla* and *Betula davurica,* those to the fine or small roots were comparatively low. Those to the root stock, however, occupied 55 to 63% of the total root volume.

(1) Tree growth and volume ratio by root class

The relation between basal area and ratio in root volume is shown in Fig. 38. As is clear from it, the ratios to the fine, small, medium, and large roots decreased gradually with the growth of trees. However, those to the very large root and the root stock increased, describing a parabolic curve.

These changes in volume ratio are due to the different stages in growth between the whole root system and each part of a root. They are also due to the increasing ratios the accumulated part occupies in the root volume as trees get older.

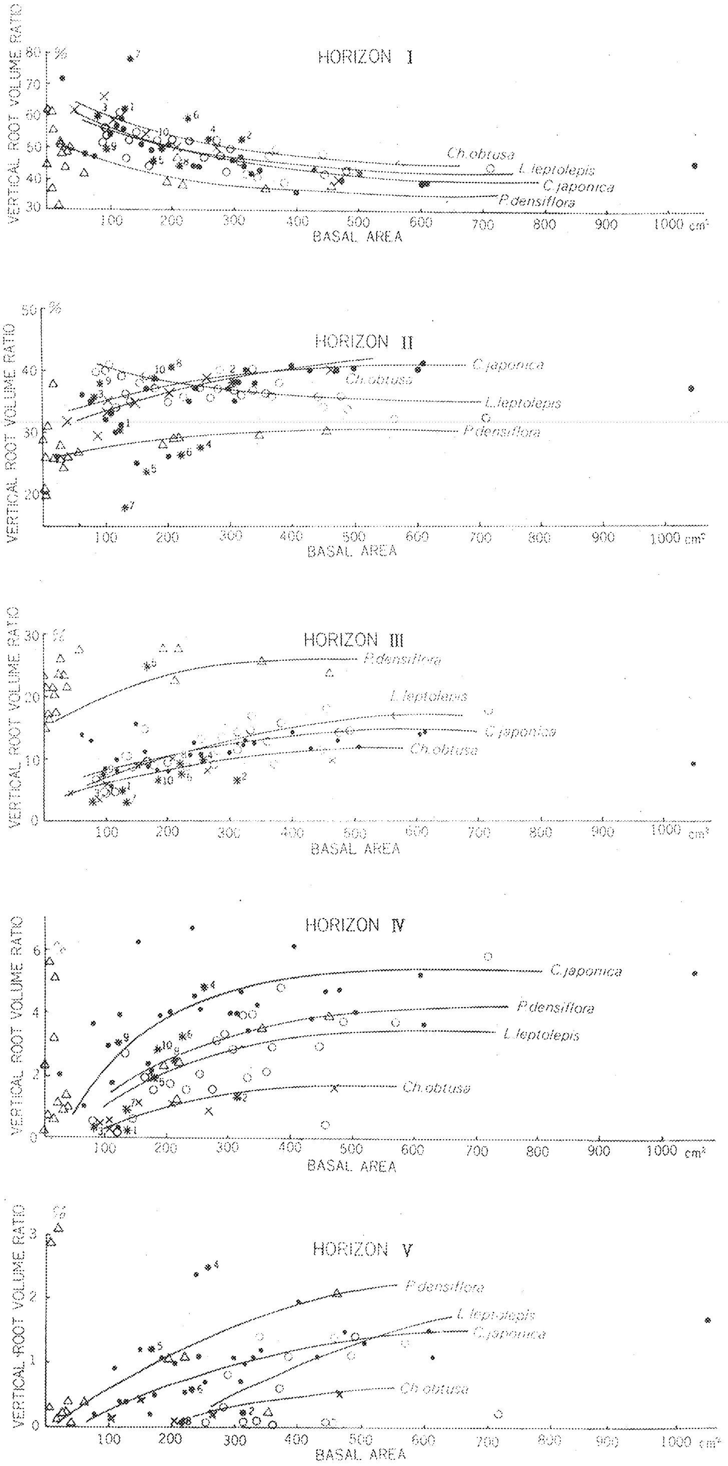


Fig. 39 Ratio of the root volume in each horizon to the total, and basal area.

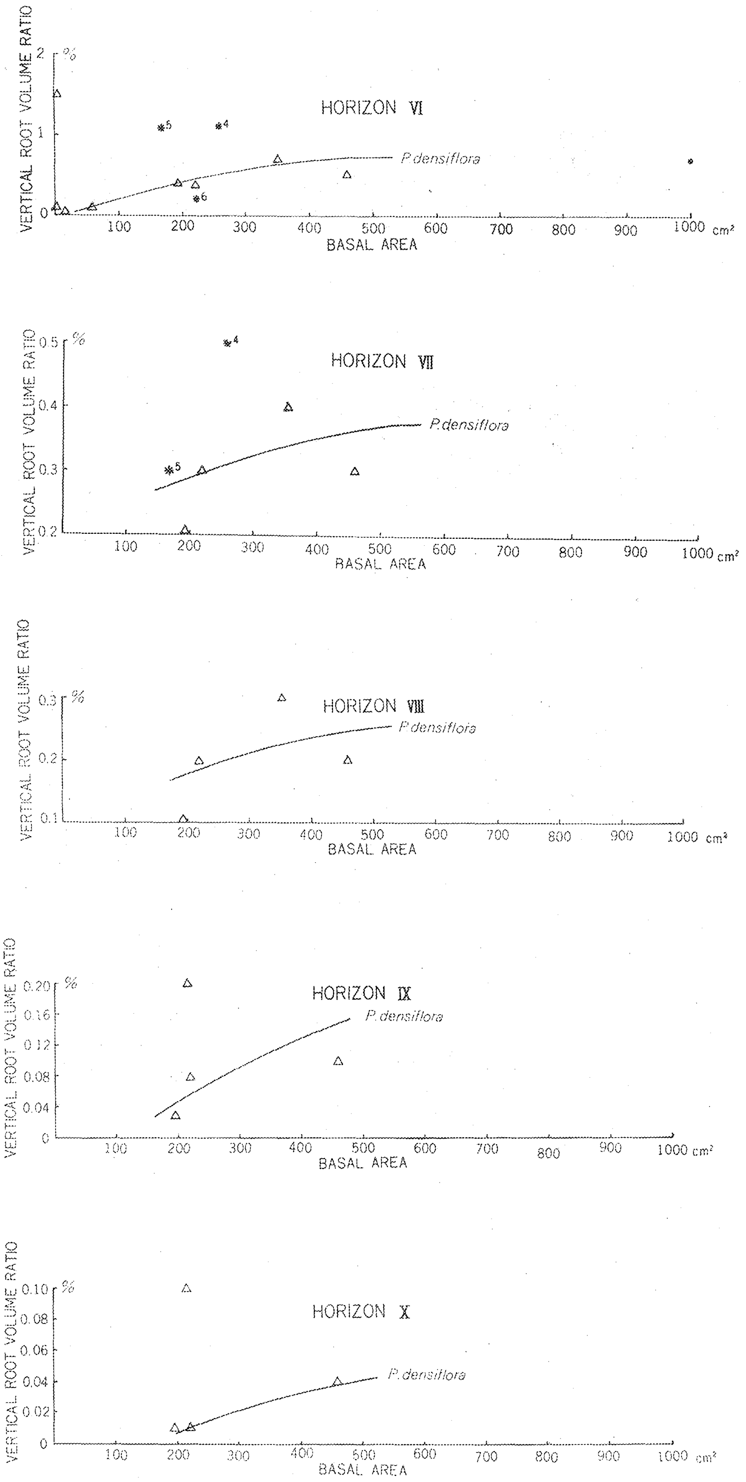


Fig. 39 (Continued)

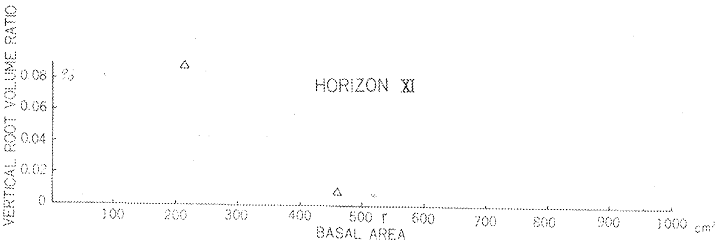


Fig. 39 (Continued)

Table 52. Ratio of the root volume to the total root volume in each horizon (%)

Species		*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*	*Zelkova serrata*	*Acacia decurrens*	*Eucalyptus globulus*
Stand		S 5	H 5	A 8	K 14	M 4	M 7	M 3
Basal area (cm²)		439	427	361	422	188	135	177
Soil type		B*l*D(w)	BD	B*l*D	B*l*D	B*l*D	Er-BA	Im-BF
Horizon	Ⅰ	40.0	46.9	38.3	43.5	53.8	79.6	60.6
	Ⅱ	40.7	41.1	30.8	34.0	27.3	16.2	36.1
	Ⅲ	13.1	9.9	23.8	14.3	10.0	3.3	3.0
	Ⅳ	4.7	1.6	3.9	6.8	4.8	0.9	0.3
	Ⅴ	1.5	0.5	2.1	1.4	2.5	—	—
	Ⅵ	—	—	0.3	—	1.1	—	—
	Ⅶ	—	—	0.2	—	0.5	—	—
	Ⅷ	—	—	0.1	—	—	—	—

This relation was also observed in each soil horizon. In soil horizon I, the ratio of each root volume to the whole root volume had a tendency, as shown in Fig. 39, to decrease gradually with the growth of trees. Contrary to it, a tendency to increase slowly, describing a parabolic curve, was seen in soil horizon II or below.

Small trees maldistribute most of their roots to the surface soil horizon, but decrease such distribution to the lower horizon; on the other hand, large trees distribute a number of their roots to it.

Table 52 shows on a few stands the root volume ratios by soil horizon. In soil horizon I, they were, as shown there, 47% for *Ch. obtusa*, 44% for *L. leptolepis*, 40% for *C. japonica*, and 38% for *P. densiflora*. Of all four species, the fourth species had a low volume ratio by root in the horizons upward and a high one in the horizons downward. Otherwise expressed, the roots of *Ch. obtusa* larger than the large roots which occupy the greater part of the root volume are distributed mostly to the surface soil, and that those of *P. densiflora*, tap-rooted, are distributed mostly to the deeper soils.

The ratios distributed to soil horizons I and II 30 cm deep from the surface soil horizon were 81% for *C. japonica*, 88% for *Ch. obtusa*, 69% for *P. densiflora*, and 78% for *L. leptolepis*. *Zelkova serrata*, *Acacia decurrens*, and *Eucalyptus globulus* had the high root distribution ratios by volume of 54 to 80% in soil horizon I. Possibly this is one of the reasons why they are small trees. *Acacia decurrens* had 80%, the highest ratio of all. Hence it is that it has a greater part of the root volumes in the surface soil horizon.

Table 53. Ratio of the root volume to the total root

Species	*C. japonica*						
Soil water condition	Moderately moist soil			Dry soil			
Stand	S 3	S 13	S 23	S 24	S 6	S 7	S 20
Basal area (cm²)	109	196	152	99	105	160	265
Soil type	Bl_D(d)	Bl_D	B_D	B_A	Bl_A	Bl_C	B_A
Site index	17.0	24.5	15.0	11.0	11.3	13.6	15.4
I	47.8	52.7	51.1	56.3	57.7	53.7	49.0
II	35.3	36.7	25.8	31.0	33.8	33.1	37.2
III	13.1	8.0	15.7	8.4	5.9	8.2	11.3
IV	3.6	2.1	6.2	3.9	1.7	3.9	2.3
V	0.2	0.5	1.2	0.4	0.9	1.1	0.2

Table 54. Average root length a

Species	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*	*Chamaecyparis pisifera*	*Eucalyptus globulus*
Stand	S 5	H 5	A 8	K 14	M 2	M 3
Basal area (cm²)	439	427	361	422	238	177
Root length (km)	4.1	6.4	1.2	3.1	5.4	2.4

(2) Soil conditions and vertical distribution of the root volume

In looking through soil types for the relationship between the soil conditions and root volume, we get the results shown in Table 53. According to the table, *C. japonica* and *Ch. obtusa* show the high ratio by volume in the lower horizons of the moderately moist soils and the low ratio in the surface horizon of the dry or moist soils. This tendency was more remarkable in the dry or moist soil for *L. leptolepis* than for *C. japonica*.

As mentioned before, the root volumes are distributed in the same way as the root biomass. Fine and small roots, however, have a considerably low bulk density, because they take much higher water content than large roots, very large ones, and a root stock. Those roots, therefore, occupy the greater ratio by volume than the ratio by biomass. As concerns the vertical distributions at every soil horizon, the ratios by volume in the surface soil horizon, where fine and small roots are maldistributed, are higher than those by biomass.

After trees are cut down, their roots remain in the soil, get rotten and in time leave cavities in the soil. They affect the physical and chemical features of soil, and there come to be many fine porosities in the surface soil horizon.

4. **Root length**

From the average root length per tree got from the root length per unit weight multiplied by the average root biomass per tree, the root length per ha was calculated through the basal area ratio estimate.

1) **Average root length per tree**

(1) Tree species

Each species has its own biomass ratio, branching pattern, average diameter, and bulk volume in each soil horizon and soil types (%)

L. leptolepis								
Moist soil			Moderately moist soil			Dry soil		
K 3	K 6	K 7	K18	K11	K 4	K23	K29	K26
183	92	128	346	310	86	141	200	164
Bl_{E}	Bl_{E-F}	Bl_{G}	Bl_{D}	Bl_{D}	Bl_{F}	Bl_{D}-m	Bl_{B}	Bl_{D}
14.8	6.8	11.0	18.4	16.8	8.2	9.5	10.5	9.6
44.8	56.8	59.8	42.9	42.3	52.5	53.0	53.4	55.4
38.4	41.4	34.6	40.6	40.3	40.8	36.6	35.1	35.5
14.9	1.8	5.4	14.6	13.3	6.2	10.4	9.8	8.5
1.9	—	0.2	1.9	3.3	0.5	—	1.7	0.6
—	—	—	—	0.8	—	—	—	—

tree of each species

Zelkova serrata	*Abies firma*	*Tsuga canadensis*	*Acacia decurrens*	*Quercus mongolica* v. *grosseserrata*	*Betula platyphylla* v. *japonica*	*B. davurica*
M 4	M 5	M 6	M 7	M 8	M 9	M10
188	156	211	135	167	118	157
17.3	0.7	2.4	10.5	2.3	0.8	2.0

density of the root system, and naturally, root length. Let us make thereupon a comparison of the average root length per tree between the main species with nearly the same basal areas and some other species with different basal areas from the detailed table on the root length. Table 54 gives results, and according to the table, the maximum of those of the main trees were 6.4 km for *Ch. obtusa* with many fine roots, 4.1 km for *C. japonica*, 3.1 km for *L. leptolepis*, and 1.2 km for *P. densiflora*. The last species had the extremely shorter root length, due to having a considerably smaller amount of fine roots.

The root length of the other trees was the maximum of 17.3 km for *Zelkova serrata*, or 10.5 km for *Acacia decurrens*. It was 2 to 3 times as long as that of *C. japonica* or *Ch. obtusa* with broader basal area.

The fine root of *Zelkova serrata* is so small in diameter that its length per unit weight is very remarkable. Although its length by unit is short, the fine root of *Acacia decurrens* has a large amount, so its root is long on the whole. For *Ch. pisifera* the amount is large and its length is almost the same as that of *Ch. obtusa*. The roots of *Betula platyphylla*, *Betula davurica*, *Quercus mongolica* and *Abies firma* are much shorter, because their fine roots grow sparsely and their amount is small.

Generally speaking, the trees with longer roots have a strong drought resistance because their roots are distributed wider to absorb water and nutriment from broad areas. The examples are such trees as *Ch. obtusa*, *Zelkova serrata*, and *Acacia decurrens*. This idea, however, proves to be imperfect when it is shown that the root is comparatively short in the case of *P. densiflora*, *Tsuga canadensis*, *Quercus mongolica*, and *Betula* species, all with strong drought resistance.

Table 55. Tree growth and average root length a tree

C. japonica

Stand	S 1	S 3	S 2	S 4	S 15	S 17
Basal area (cm²)	61	109	249	335	451	1,042
Root length (km)	1.4	2.0	3.1	4.1	4.4	7.4

Ch. obtusa

Stand	H 1	H 2	H 3	H 4	H 5	—
Basal area (cm²)	42	104	254	274	427	—
Root length (km)	1.6	1.6	3.1	2.8	6.4	—

P. densiflora

Stand	A 1	A 2	A 3	A 4	A 8	—
Basal area (cm²)	24	63	198	311	361	—
Root length (km)	0.1	0.2	0.6	0.8	1.2	—

L. leptolepis

Stand	K 5	K 23	K 25	K 27	K 22	K 20
Basal area (cm²)	90	141	273	363	459	599
Root lnegth (km)	0.8	2.0	2.8	2.8	2.6	2.8

(2) Tree growth and root length

Table 55 shows the relationship to the basal area of the increasing root length with tree growth. As can be seen from the table, the root length increased steadily with the basal area in the case of *C. japonica*, *Ch. obtusa*, *P. densiflora*, and *L. leptolepis.* At the basal area of over 200 cm², however, it made a parabolic increasing curve as the rate of increase became lower. In this case, the species were almost 20 to 25 years old.

This is the result of rapid growth of the fine and small roots in the case of small trees. And at the same time, the rapid increase of the root length in a sapling stage is due to the increase of these roots. The rate of increase of the root length falls off in the case of large trees, because the growth of roots occurs mostly in large roots, instead of the fine or small root.

(3) Soil type and the root length of a tree

The relation between the soil types and the average root length per tree is shown in Table 56.

The root length per tree of every species is longer in the dry soils than in the wet or moderately moist soils. *C. japonica*, taken here as an example, had the root length per tree of 2.6 km in the stand of S 12, B*l*D(w) soil-typed, and 4.3 km in the stand of S 20, BA soil-typed.

Table 56. Soil types and average

	C. japonica							*Ch. obtusa*		
	Moderately moist soil			Dry soil				Moderately moist soil		Dry soil
Stand	S 5	S 8	S 12	S 24	S 6	S 7	S 20	H 4	H 2	H 6
Basal area (cm²)	439	238	267	99	105	160	265	274	104	91
Soil type	B*l*D(w)	B*l*D(w)	B*l*D(w)	BA	B*l*A	B*l*C	BA	BD(w)	BD	BB
Site index	19.3	20.7	23.4	11.0	11.3	13.6	15.4	15.0	17.6	11.4
Average root length a tree	4.1	2.5	2.6	4.1	2.5	5.2	4.3	2.7	1.6	3.6

There was a great difference between them even though the basal area was almost the same in these two stands. And it was the same 2.5 km in both stands, S 8 of Bl_D(w) soil-type and S 6 of Bl_A soil-type. The basal areas, however, were 238 cm^2 and 105 cm^2 in the former and the latter stand respectively. If calculated as the tree in which basal area is almost the same, the root length per tree may be much longer in the latter stand than in the former.

This is true of the root length of *Ch. obtusa.* The root length was 3.6 km in the B$_B$ soil-typed stand of H 6. It was 1.6 km in the moderately moist soil-typed stand of H 2, larger in diameter, and 2.7 km in the stand of H 4, over twice in diameter. That is to say, it was shorter in both stand than in the stand of H 6.

That holds true in the case of the root rength of *P. densiflora* and *L. leptolepis.* For instance, the average root length was 2.6 km both in the Bl_{DE}(m) soil-typed and wet stand of K 24, 410 cm^2 in basal area, and in the Bl_D(d) soil-typed and slightly dry stand of K 16. The basal area, however, was 271 cm^2 in the latter stand.

The difference in root growth by this soil condition tends to be greater for *L. leptolepis* and *P. densiflora*, and yet to be smaller for *C. japonica.* The roots become longer in the dry soils and absorb water and nutriment in the broad areas, while in the wet and moist soils they become comparatively shorter and absorption is done in the narrow areas. Either the deterioration of absorption efficiency due to the lack of water or a large consumption of energy by the increase of shifting distance of water and nutriment has also to be taken into account in regard to the function of the root system in the dry soil. In other words, these cause the production efficiency of the root system to be lower in the dry soils than in the moderately moist soils.

(4) Ratios of the root length to the total of every root class

As concerns the main species in Table 54, the ratios by root length of every root class which composes the total root length are shown in Table 57.

The ratio of a fine root stock was the highest of all regardless of species. It ranged from 59% for *P. densiflora* to 96% for *Zelkova serrata.* Most species had the ratios of 80 to 90%.

Although the ratio by weight a fine root took was only 1 to 5% of the total root weight, the root was remarkably long because of its narrow average diameter and of its low bulk density. The very large root, on the other hand, was short. Accordingly, the order of roots in length was the reverse of their order in biomass. The species with the particularly high ratios (over 90%) by fine root length were *C. japonica*, *L. leptolepis*, *Ch. pisifera*, and *Zelkova serrata.* The last species had 96%, the highest ratio of all. As concerns the main species, they became lower in the order of *C. japonica* (93%), *L. leptolepis* (91%), *Ch. obtusa* (88%).

root length of a tree

P. densiflora						*L. leptolepis*							
Moderately moist soil			Dry soil			Moderately moist soil				Moderately dry soil			
A 3	A 7	A 9	A 6	A 12	A 11	K 3	K 11	K 12	K 24	K 26	K 16	K 17	K 23
198	18	228	17	49	32	183	310	297	410	164	271	238	141
Bl_D(d)	Bl_D	Bl_D	Er$_{-B}$	B$_A$	B$_A$	Bl_E	Bl_D	Bl_D	Bl_{DE}(m)	Bl_C	Bl_D(d)	Bl_D(d)	Bl_D-m
13.8	24.0	14.2	6.6	11.8	12.0	14.8	16.8	14.5	14.8	9.6	12.7	14.7	9.5
0.6	0.2	0.5	0.2	0.4	0.4	1.4	1.9	1.9	2.9	2.2	2.9	2.1	1.9

Table 57. Ratio of each root length to the total root length when the total length is to be 1 (%)

Species	Stand	f	s	m	l	L
C. japonica	S 5	92.6	6.0	0.9	0.3	0.1
Ch. obtusa	H 5	87.9	11.3	0.5	0.2	0.1
P. densiflora	A 8	58.6	36.2	3.7	1.0	0.5
L. leptolepis	K14	90.7	7.1	1.3	0.5	0.4
Chamaecyparis pisifera	M 2	90.8	8.1	0.8	0.2	0.1
Eucalyptus globulus	M 3	79.6	18.5	1.8	0.1	0.0
Zelkova serrata	M 4	96.0	3.4	0.5	0.1	0.0
Abies firma	M 5	80.2	16.1	3.2	0.4	0.1
Tsuga canadensis	M 6	69.6	26.9	3.1	0.3	0.1
Acacia decurrens v. *dealbata*	M 7	84.8	12.5	2.6	0.1	0.0
Quercus mongolica v. *grosseserrata*	M 8	79.0	16.5	4.2	0.2	0.1
Betula platyphylla v. *japonica*	M 9	81.5	15.0	3.1	0.3	0.1
B. davurica	M10	76.9	20.3	2.6	0.2	0.0

and *P. densiflora* (59%). The species with low ratio by fine root length (about 60%) were *P. densiflora*, *Tsuga canadensis* and so forth.

The ratios by small root length were 6 to 36%. That of *P. densiflora* was higher, as compared with the ratio by fine root length, and highest of all those of other species. Contrary to *P. densiflora*, *Zelkova serrata* had the lowest ratio of only 3%. Those of the main species became lower in the order of *P. densiflora*, *Ch. obtusa*, *L. leptolepis*, and *C. japonica*.

Table 58. Tree growth and ratio of each root length to the total root length (%)

Stand	S 11	S 3	S 12	S 4	S 5	S 17
Basal area (cm^2)	19	109	267	333	451	1,042
f	93.5	92.8	92.8	92.4	92.6	94.2
s	5.5	6.3	6.0	6.4	6.0	4.7
m	0.8	0.8	0.9	0.9	0.9	0.7
l	0.2	0.1	0.2	0.2	0.3	0.3
L	—	+	0.1	0.1	0.1	0.1

Table 59. Ratio of the root length in each horizon

Species		*C. japonica*						
Soil water condition		Moderately moist soil			Dry soil			
Stand		S 3	S 13	S 23	S 24	S 6	S 7	S 20
Basal area (cm^2)		109	196	152	99	105	160	265
Soil type		Bl_D(d)	Bl_D	B$_D$	B$_A$	Bl_A	Bl_C	B$_A$
Site index		17.0	24.5	15.0	11.0	11.3	13.6	15.4
Horizon	I	63.4	55.6	56.3	67.5	72.0	61.1	60.1
	II	16.2	16.7	18.2	16.7	11.1	18.0	20.4
	III	12.7	19.7	16.5	10.8	9.1	13.5	12.4
	IV	7.3	7.3	8.0	4.7	6.2	6.1	6.1
	V	0.4	0.7	0.1	0.3	1.6	1.3	1.0

There was a considerable difference between that (36%) of *P. densiflora* and those (6 to 11%) of the latter three species.

The ratios by medium root length were 1 to 4% and lowest of the total root length. *P. densiflora*, *Abies firma*, and *Quercus mongolica* had comparatively high ratios, while *Ch. obtusa*, *Zelkova serrata* and *C. japonica* had low ratios.

The ratios by large root length were 0.1 to 1.0%. The ratios by very large root length were + to 0.5%. They both had a small part of the total root length.

From the stand point of ecology, it is not unreasonable to conclude that the species having a high proportion of the fine root length absorb nutriment and water sufficiently and thereby stand well against drought. To know the species' drought resistance, this is applicable, as a temporal standard, though not for *P. densiflora*, *Quercus mongolica* and *Betula davurica*, for *Ch. obtusa*, *L. leptolepis*, and *Zelkova serrata*.

P. densiflora, the fine root of which is short, has the root hairs, develops the small and the medium roots, and thereby makes more effective the absorptive structure in functioning. Thus, each species has its own characteristic of the absorptive structure for nutriment and water. It is therefore inappropriate to construe the physiological difference of the water in trees only by the above-mentioned proportion of fine root.

(5) Tree growth and the changes of the ratios by root length according to each root class

Table 58 shows on *C. japonica* the changes of the ratios by root length according to each root class to the total root length. In the immature stand S 11, 94% of the total root length was that of the fine root as shown in the table. It decreased with tree growth to 92% in the S 4 stand at the basal area of 335 cm^2, increasing again to 94% in the mature stand of S 17. This verifies that the fine roots of large trees grow densely in the surface soil with favorable condition for their growth, and besides that, it causes them to increase their growth amount. Those of small roots were 6% in the S 11 stand, 6% in the S 5 stand and 5% in the S 17 stand. They decreased slightly in the case of large trees. Those of large roots were, however, the reverse of these changes.

The above-mentioned relation between the tree growth and the ratios by root length has a connection with each root's own growing pattern. In the case of the young and small trees, the fine and small roots grow more remarkably than the large root, absorbing water

to the total root length and soil types (%)

L. leptolepis								
Moist soil			Moderately moist soil			Dry soil		
K 3	K 6	K 7	K18	K11	K 4	K23	K29	K26
183	92	128	346	310	86	141	200	164
Bl_E	Bl_{E-F}	Bl_G	Bl_D	Bl_D	Bl_F	Bl_D-m	Bl_B	Bl_D
14.8	6.8	11.0	18.4	16.8	8.2	9.5	10.5	9.6
66.6	79.9	83.9	61.4	68.5	75.4	71.3	82.4	74.9
18.8	17.5	13.2	23.3	15.8	15.5	19.1	11.2	15.1
13.2	2.6	2.9	13.7	11.4	7.9	9.6	5.8	8.8
1.4	—	—	1.2	4.0	1.2	—	0.6	1.2
—	—	—	0.4	0.3	—	—	—	—

and nutriment from considerably broad areas for large individuals. In the case of the large trees, contrary to them, those two roots are not distributed so widely when compared with their increasing individual biomass. These special growth properties of the root system have a great influence on the tree growth through absorption of water and nutriment.

(6) Soil conditions and the vertical distribution ratio of the root length

Table 59 shows the ratios of each root length to the total root length in each soil horizon under different soil conditions.

The root length ratios of *C. japonica* in the moderately moist soils were 56 to 63% in soil horizon I, 56% in the S 13 stand with the largest site index of 24.5, and 63% in the S 3 stand with the site index of 17.0 and Bl_D(d) soil type, while in the dry soils 60 to 72%. When the difference in distribution by tree size was taken into account, the ratios were higher by 4 to 5% in the dry soils than in the moderately moist soils. In the dry soil they were inclined to be distributed mostly to the surface soil.

L. leptolepis has the same tendency as before; its ratios by root length become higher in the dry soils than in the moderately moist soils. They were, for example, 69% in soil horizon I of the Bl_D soil-typed stand of K 11, and yet, 82% in the same horizon of the dry stand of K 29. That means a difference of 13% between them. This species has a stronger tendency than *C. japonica*. It follows from the fact that *L. leptolepis* has a tendency that its root length is maldistributed to the surface soil horizon under the dry conditions. Moreover, it is clear that the root system of *L. leptolepis* are distributed mostly to the surface soil under the wet condition.

The distribution ratio, on the one hand, was 69% in soil horizon I of the Bl_D soil-typed stand of K 11, and on the other hand, 84% in the same horizon of the Bl_G soil-typed and heavy wet stand of K 7. That shows a difference of 15% between them. From this it follows that the root length is maldistributed to the surface soil horizon on the dry and the moist condition. In addition, both of the stand have a small site index on the condition like those. The site indices were 17 in the moderately moist stand of K 11, and yet, 11 both in the Bl_G soil-typed stand of K 7 and in the Bl_B soil-typed stand of K 29.

This is because the growth of the fine roots which occupy the greater part of the root length is restricted by the soil condition. As it is relative to the diameter of the fine root, the root becomes longer in the dry forest ground where the root becomes smaller in diameter, especially in the surface soil.

2) **Root length per ha**

The root length per ha is quite different from the root length per tree as it is greatly influenced by tree density. The root length per ha of each stand in Table 54 was calculated and shown in Table 60.

According to Table 60, the root length per ha was 4,848 km, the greatest, in the H 5 stand

Table 60. Root length per ha

Species	*C. japonica*	*Ch. obtusa*	*P. densiflora*	*L. leptolepis*	*Chamaecyparis pisifera*	*Eucalyptus globulus*
Stand	S 5	H 5	A 8	K 14	M 2	M 3
Basal area (cm^2)	439	427	361	422	238	177
Root length per ha (km)	3,596	4,848	922	2,263	2,574	6,031

of *Ch. obtusa*, 3,596 km in the S 5 stand of *C. japonica*, 2,263 km in the K 14 stand of *L. leptolepis*, or 922 km, about one-fifth of *Ch. obtusa*, in the A 8 stand of *P. densiflora*. This is not only because *P. densiflora* with intolerance takes a low tree density, but because its fine roots grow sparsely, its root amount being remarkably smaller than that in the other species. *Zelkova serrata* with a large amount of fine roots and long root length per unit weight has the remarkable root length of 22,684 km, although the species has a basal area narrower than *C. japonica* or *Ch. obtusa*. *Acacia decurrens* has the comparatively long root length of 7,843 km, because the species has a large amount of the fine roots for short root length per unit.

On the other hand, the broad-leaved trees, such as *Quercus mongolica*, *Betula platyphylla* and *Betula davurica*, had a remarkably shorter root length per ha than the former, ranging from 138 to 421 km. Among the coniferous trees, the root length of *Tsuga canadensis* is comparatively long as its fine and small roots are highly ramified.

(1) Tree growth and root length per ha

The root length of a tree increases with the tree growth. Its rate of increase, however, grows lower as the tree grows larger, increasing in a parabolic curve. In the immature stand, the increase of the root length per ha falls in spite of the growth of the stand, because of its low tree density.

This growth of roots in length in relation to the basal area is shown in Fig. 40. As can be seen from it, the total root length of every species increased temporarily at the basal areas of 150 to 200 cm^2, decreasing slowly at the broader areas, and then remaining constant at the basal areas of 300 to 400 cm^2. This is mainly due to the change in root biomass.

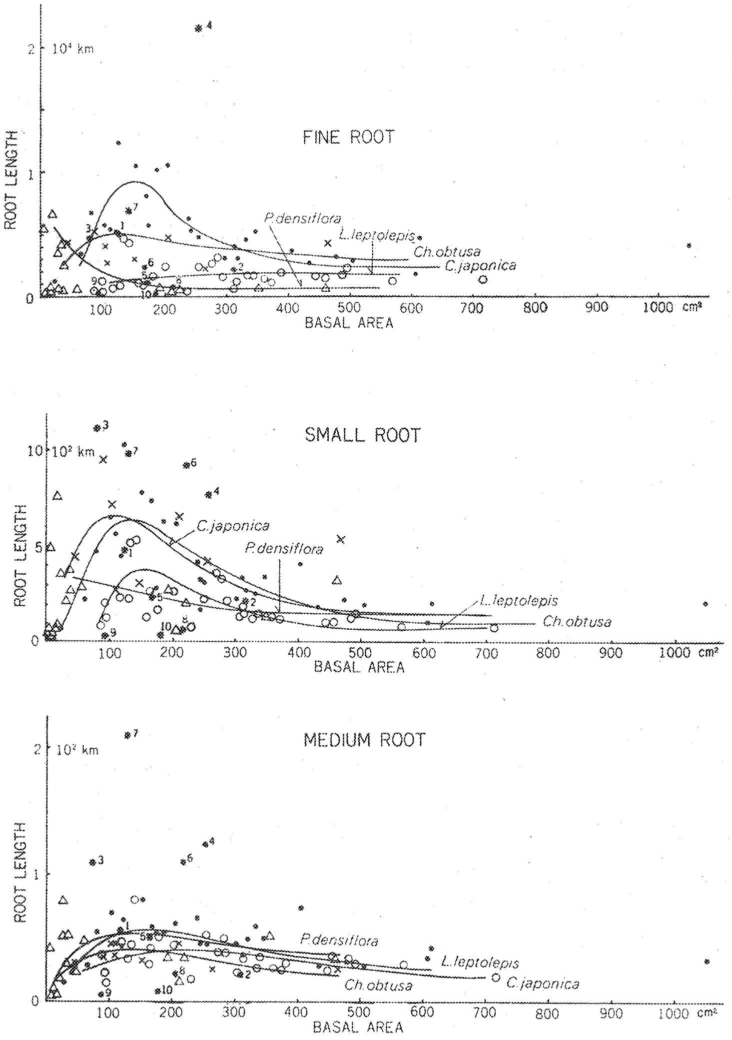
Table 61 was derived from the root length per ha at each basal area in Fig. 40. Investigation revealed that the total root length was 10,000 km in a young forest of *C. japonica*, and for *Ch. obtusa* it ran to 6,000 km. In the young stands, the difference between species was very big, and was about 8,000 km between *C. japonica* and *L. leptolepis*. This is due to the differences in the special properties of the root system and the tree densities. The total root length was 3,500 km in the mature forest of *C. japonica* and *Ch. obtusa* and 1,000 km in the mature forest of *P. densiflora*. The difference in root length between *C. japonica* and *L. leptolepis* is smaller by 2,500 km than it was at the young stage. This is mainly due to the different patterns of branching of the fine root and the different fine root biomass.

Fig. 40 shows the relation between the basal area and the length per ha according to each root. As is evident from it, the fine or small root length increases temporarily at the young stage when the basal area ranges from 100 to 200 cm^2. As, however, the root system becomes larger from the medium to very large root, the increase becomes less remarkable, and the length of the large root increases in a parabolic curve. It decreases little for large trees.

It is due to the vigorous branching and growth of fine and small roots at the young stage, and to the increasing secondary growth at the middle-aged stage or over. Such a phenomenon

of each species

Zelkova serrata	*Abies firma*	*Tsuga canadensis*	*Acacia decurrens* v. *dealbata*	*Quercus mongolica* v. *grosseserrata*	*Betula platyphylla* v. *japonica*	*B. davurica*
M 4	M 5	M 6	M 7	M 8	M 9	M10
188	156	211	135	167	118	157
22,684	1,458	3,491	7,843	421	138	195


FINE ROOT

SMALL ROOT

MEDIUM ROOT

Fig. 40 Root length per ha and basal area.

Table 61. Maximum root length in an immature stand age and root length in a mature stand age (km/ha)

Basal area (cm²) \ Species		C. japonica	Ch. obtusa	P. densiflora	L. leptolepis
Maximum root length in an immature stand age	100～200	10,000	6,000	5,000	2,000
Root length in a mature stand age	400～500	3,500	3,500	1,000	1,500

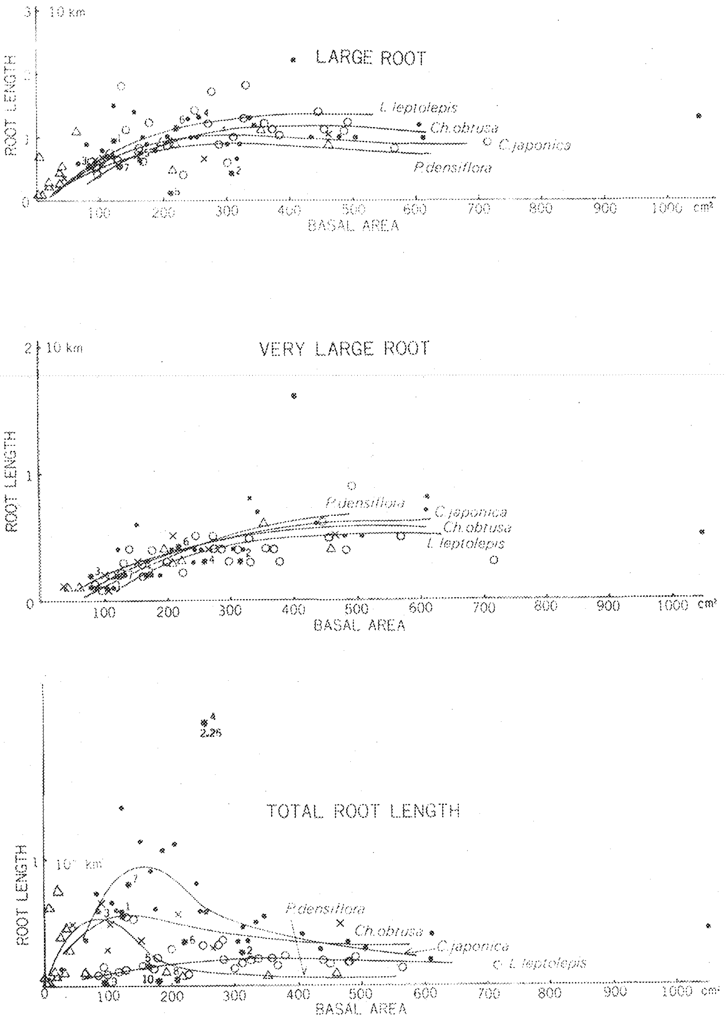


Fig. 40 (Continued)

Table 62. Root length per ha in close planting stands

Species	C. japonica		Ch. obtusa	P. densiflora			L. leptolepis	
Stand	S 8	S 22	H 5	A 6	A 10	A 11	K 23	K 26
Tree density index	0.90	1.16	0.57	1.27	1.24	0.88	1.03	1.27
Soil type	BlD(w)	BE	BD	Er-B	BA	BA	BlD-m	BlC
Root length (km)	6,859	4,120	4,848	6,114	7,631	4,542	5,510	5,342

Table 63. Tree density and root length per ha

Stand	A 10	A 11	A 12
Tree density index	1.24	0.88	0.62
Root length (km)	7,631	4,542	3,764

is also observed at the factors such as the biomass, length, volume, and surface area of the root system. For the amount of the fine root is large at the young stage, on which calculation of these factors is based.

The root length in Table 60 or in Fig. 40 is beyond our imagination. Photo. 1 shows an exposed root from a *C. japonica* stand, 25 years, taken in the jurisdiction of Shirakawa Regional Forestry Office, and the surface soils washed off by a pump. It shows that the root systems are distributed mattedly on the forest floor, and that they are very long.

(2) Tree density and root length per ha

The root length per ha goes along with increasing tree density. Let us pick out of the detailed table the root length in stands. By so doing, we see that it was, as shown in Table 62, 4,000 to 7,000 km for *C. japonica* in the moderately moist soil, 5,000 km for *Ch. obtusa* with the density index of 0.57, 5,000 to 8,000 km for *P. densiflora* in the dry soil, or 5,000 to 6,000 km for *L. leptolepis* in the dry soil.

The root length per ha of *P. densiflora* stands, A 10, A 11 and A 12, of the same age and of the different densities is shown in Table 63. The total root length was 7,631 km in the dense stand A 10 (density index : 1.24), while it was 3,764 km in the sparse stand A 12 (density index : 0.62).

The density index and the root length were both half of those in the stand of A 10.

The basal areas were 18 cm², 32 cm² and 49 cm² for the dense planting stand of A 10, the stand of A 11, and for the sparse planting stand of A 12 respectively. This proves that tree density causes a very big difference in tree size. The root biomass per ha were 18 tons, 17 tons and 12 tons for the stands of A 10, A 11 and A 12 respectively. The biomass in the stand of A 10 was two-thirds of that in the stand of A 12. The root was short for root biomass in the latter stand and half of that in the former.

The total length was 4,120 km and comparatively short for its high density in the dense S 22 stand of *C. japonica*. For its root length per unit was short on account of the moist soil, and the trees were large in diameter.

V **Literature cited**

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2) ―――――― : Root growth and tree density. Sanrin, 10～21, (1963)

3) ―――――― : Root growth and density of the seedling of *Pinus Thunbergii*. Transactions Jap. For. Soc., 74, 269～271, (1963)

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森林生産の場における根系の機構と機能 II

根量とその分布

苅住　昇(1)

摘　要

林業試験場報告259号「森林生産の場における根系の機構と機能」に関連して，ここでは「根量とその分布」について報告する。この報告ではモデル林分と一般林地における根量分布について考察を加えた。

一般林地では立地や生育の条件が複雑なことと，孤立状態における根系分布を知ることができないので，苗畑で主要樹種の植栽密度を変えて根量の水平・垂直分布を細かく調査した。その結果，水平的にはアカマツ・カラマツの根系は分散型，スギ・ヒノキは集中型，垂直的にはカラマツ・ヒノキは浅根型，スギ・アカマツは深根型であることがわかった。この調査から水平・垂直の根密度変化曲線を解析するために片対数式や GRAM-CHALIER の式が用いられた。片対数式では根密度が急速に変化する深さ，または根株からの距離までは直線で表現でき，この係数によって根量変化の相違を表わすことができたが，緩曲線部分は表現できなかった。この部分を正確に示すには GRAM-CHALIER の式の利用が適当で，根密度比数を用いて計算すると水平分布では分散型のアカマツ・カラマツは積率を示すμの値が大きく，垂直分布では深根性樹種が大きくなった。

この苗畑試験において，木数密度と地上部・地下部の成長について競争密度効果は地上部よりも大きくて，密度が増加するとT/R 率がやや上側に凹形の曲線で増加し，最低密度区では3.5であったが最高密度区では4.4となった。これらの関係は林分調査においても認められた。

つぎに，一般林地について，単木および ha あたり現存量とその比数の変化について検討した。とくに地下部については根量の水平・垂直分布を明らかにした。

ha あたり現存量は樹種，立木密度，立地条件によって相違があるが，平均胸高断面積 500 cm^2 の林分で約200トンの総量があった。このうち，幹は100～120トン，枝はアカマツ・カラマツ・ヒノキが多くて15トン，スギは10トン，葉量はスギ20トン，ヒノキ5トン，カラマツ3トン程度であった。

地下部の ha あたり根量は40～60トンで樹種による大きな差はなかったが，細根や小径根は樹種によって異なり，細根ではヒノキ1トン，スギ0.7トン，アカマツ0.1トン，カラマツ0.2トンでヒノキ・スギはアカマツ・カラマツよりも著しく大きい。

胸高断面積と各部分重との関係は，幹や地下部の根株，特大根，大径根などの蓄積部分では，その現存量は胸高断面積の増加にともなって，ほぼ放物線状に増加した。一方，葉や細根などの働き部分の現存量は林齢20～25年の幼齢林で最大となり，林齢が高くなると，幼齢時より減少してほぼ一定の値となった。スギの葉では幼齢時増加して25トンになり，高齢林では20トン程度で変化が安定した。細根では

1974年5月9日受理

(1) 造林部

1.5トン程度になったのち1トン程度に減少した。このように地上部と地下部の働き部分の量が幼齢時代に一時的に増加する現象は，幼齢時の立木密度の増加によるものではなくて林木の成長特性によるものと考えられる。幹材積の連年成長量や最近1年間の生産量の増加とも一致し，この時代に葉量，細根量など働き部分の増加が生産量と直接関連して林木の活力が高まることが推察できた。

つぎに成木林において，葉量と細根量がほぼ一定の割合で変化するが，これは同化と吸収の間に一定の均衡があることを意味している。

全重に対する部分重の割合は林分の成長段階によって異なり，葉・細根などの働き部分の割合は林分が成長すると減少する。スギの葉量比は平均胸高断面積100 cm^{2}の林分では18～20%であったが，500 cm^{2}では10%程度となった。また細根量比は1.5%から0.5%に減少した。これは幹や根株などの蓄積部分の割合が増加することによっている。この割合がほぼ一定になる胸高断面積500 cm^{2}では細根は0.1～0.5%，小径根は0.3～1.2%，中径根は1.1～1.7%，大径根は1.7～2.8%，特大根は4.9～7.9%，根株は10.1～13.3%で，アカマツは細根が少なくて大径根が多く，ヒノキは細根と小径根が多い。

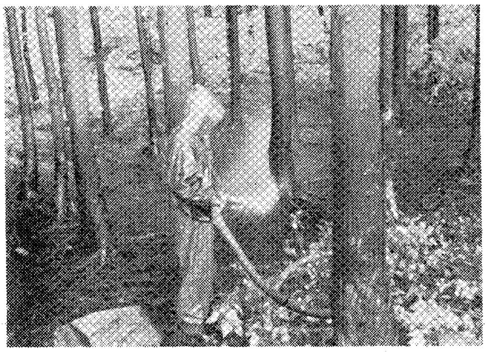
地下部重比は20～23%で樹種による差は認められなかった。林木が大きくなると，この割合は多少減少する傾向があるが，明らかではない。根系の各部分の割合は樹種によってかなり違うが，地上部と地下部の割合がほぼ一定であることは，地上部と地下部の働きや成長がほぼ一定の関係であることを意味している。

細根量は土壌の水分条件に影響されやすく，スギ林で，乾燥のB_A型土壌では全量中の細根量比は1.1%であったが，湿性のB_E型土壌では0.5%となった。

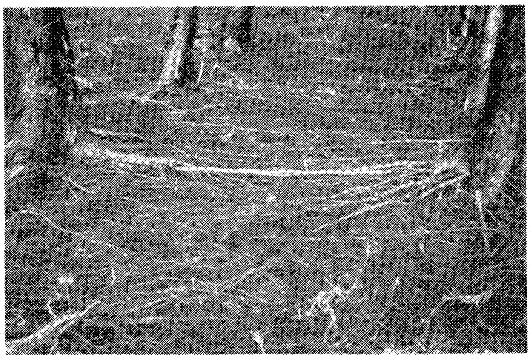
根量の垂直分布は表層にかたより，樹種によって差はあるが，スギ・ヒノキ・アカマツ・カラマツの4樹種を通じて，I層には39～76%，I・II層には80～90%で，根量の大部分が地表層から30 cmの範囲に分布した。細根のI層の土層分布比はスギ38%，ヒノキ52%，アカマツ45%，カラマツ55%で，スギは他の樹種に比べて吸収構造が下層で大きく，深根性樹種の特徴が認められた。

根系区分ごとの平均直径とその容積密度比数から計算した根長は，胸高断面積400 cm^{2}程度の単木でスギは4 km，ヒノキ6 km，アカマツ1 km，カラマツ3 kmとなり，haあたりではスギ・ヒノキは3,500 km，アカマツは1,000 km，カラマツは1,500 km程度となった。

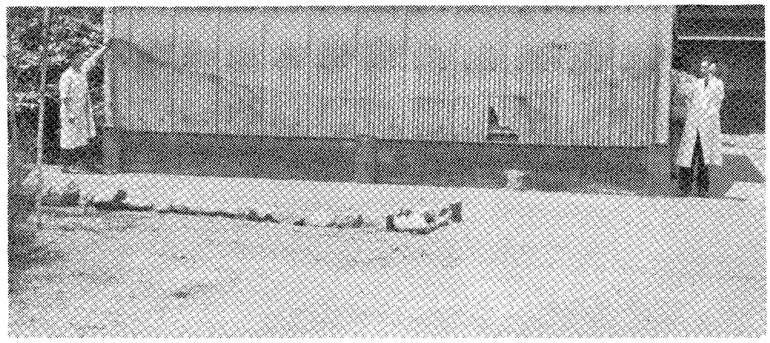
Photo. 1 Washing method of roots in the stand.



1—1. Washing method of roots by a gasoline pump. Stand age 25 yrs, D. B. H 15 cm, tree height 11 m.



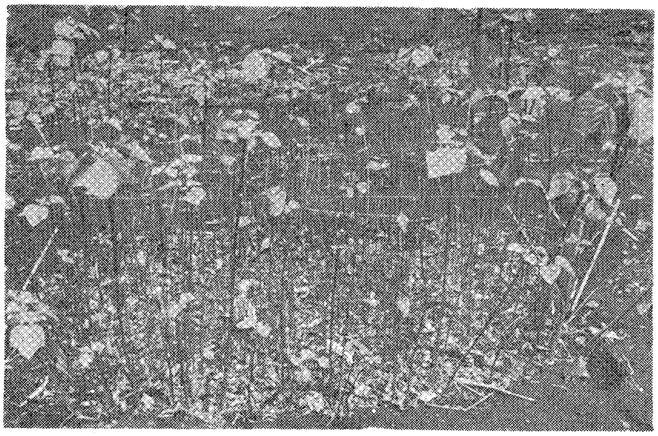
1—2. The roots cover the mat-like forest floor.



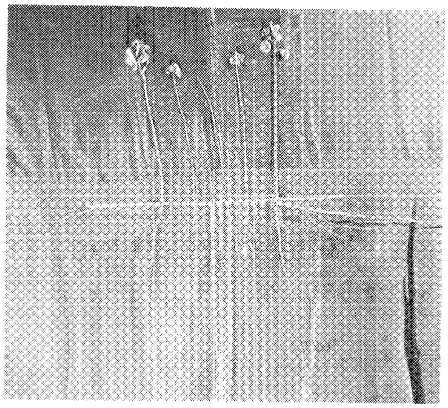
1—3. A sample tree having a lateral root of more than 10 m in that stand above Photo. 1—2. Stand age 25 yrs, D. B. H 14 cm, tree height 10 m.

1—4. A sample tree having a lateral root that runs more than 18 m in the surface soil of the *Acacia decurrens* stand M 7. Tree No. 1, D. B. H 16 cm, tree height 6 m.

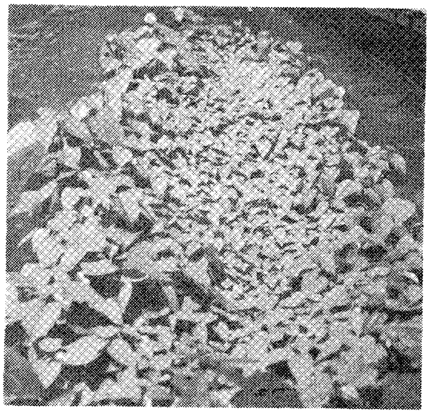
Photo. 2　Root competition



2—1.　Vegetation of *Mallotus japonicus*

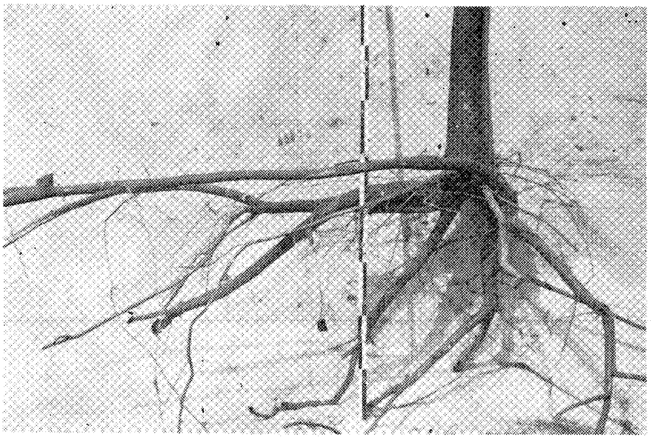


2—2.　The lateral roots are short and the top roots long in the center of the vegetation. The roots around the vegetation grow outward of the vegetation.

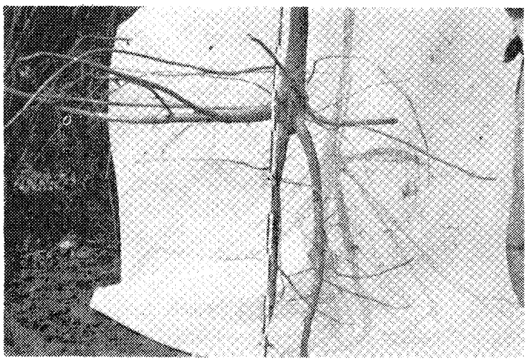


2—3.　Vegetation of *Idesia polycarpa*

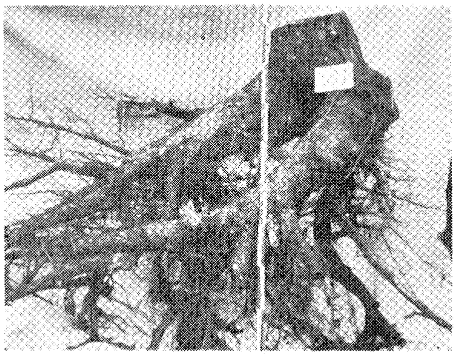
2—4.　The difference in root growth in the center and the side of the dense vegetation.



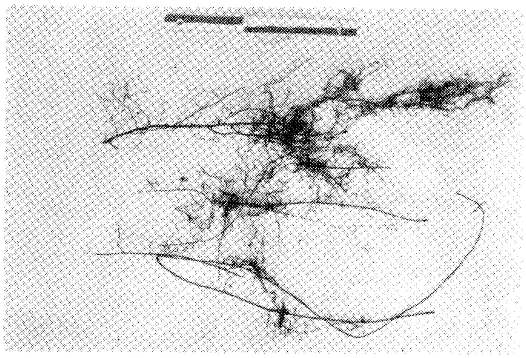
2—5. Inclined growth of roots by the competition with the neighboring trees, the roots of *Mallotus japonicus*.



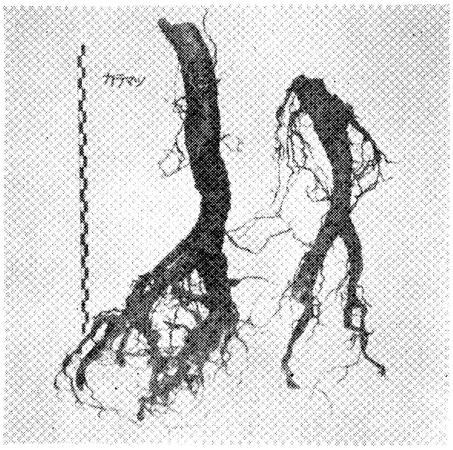
2—6. Root of *Zanthoxylum ailanthoides*



2—7. Root of *L. leptolepis*

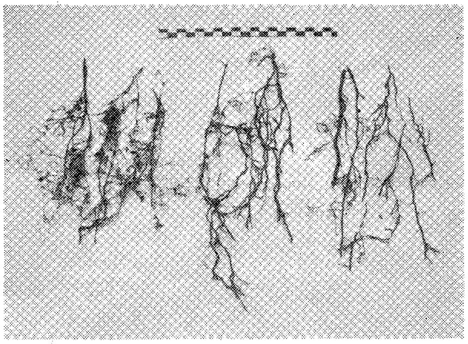


2—8. Fine roots of *Zelkova serrata* in soil horizon I.

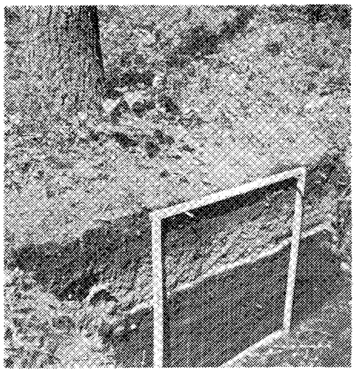


2—9. Pendant roots stopped growing in the volcanic gravel horizons.

Photo. 3 Fine roots in different soil horizons.

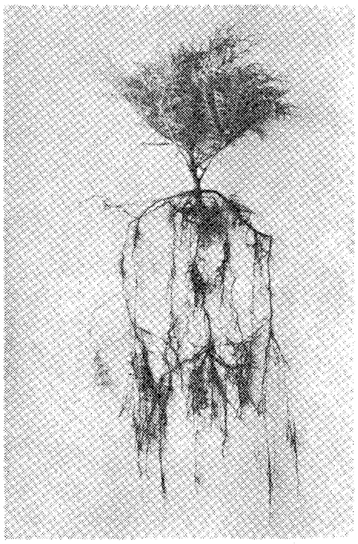


3—1. A : Fine roots in horizon I, B : Fine roots in the volcanic gravel horizon, C : Fine roots in horizon V.

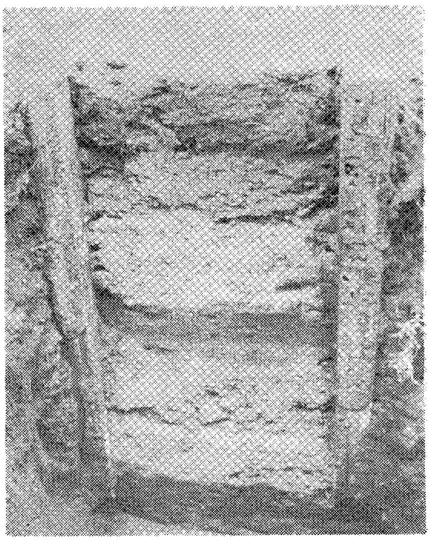


3—2. The soil in Oneyama National Forest is deposited alternately by the volcanic gravel and ashes in the *C. japonica* stand S 11–S 17.

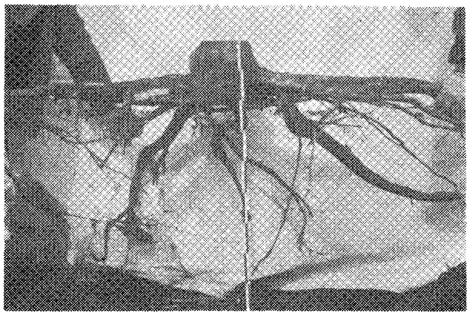
Photo. 4 The relationship between soil properties and root growth.



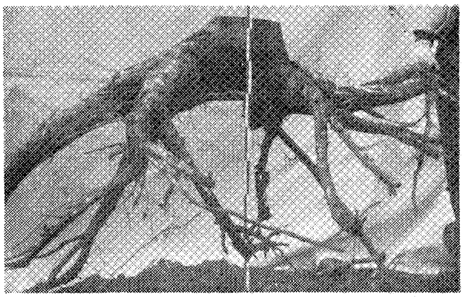
4—1. The roots of *Ch. obtusa* grown with the change in the soil texture of each horizon. Fine roots are many in the fertile soil.



4—2. Section of the root observation box arranged with the defferent soil of each horizon.



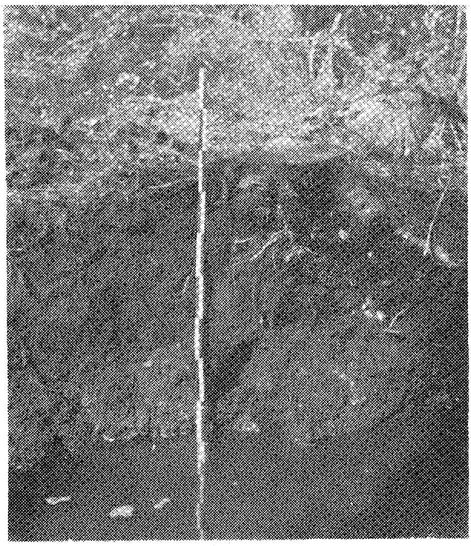
4—3. Stand K 5, tree No. 2, D. B. H 9 cm, tree height 7 m. Dead fine and small roots by much moisture.



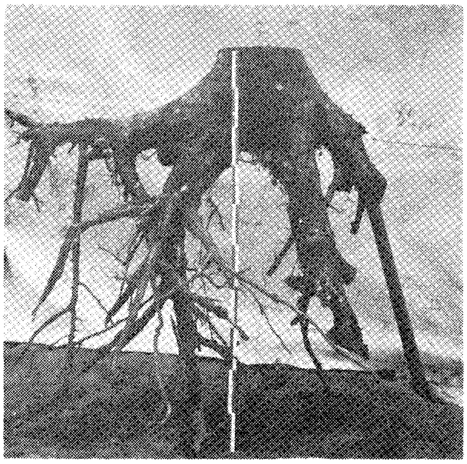
4—4. Stand K 12, tree No. 35, D. B. H 19 cm, tree height 16 cm. Dead fine and small roots by much moisture.

Photo. 5 *L. leptolepis* forest in the very moist soil and their roots.

5—1. Stand K 6 : The above-ground parts grow remarkably poor through the decay of absorptive structure in the underground part.

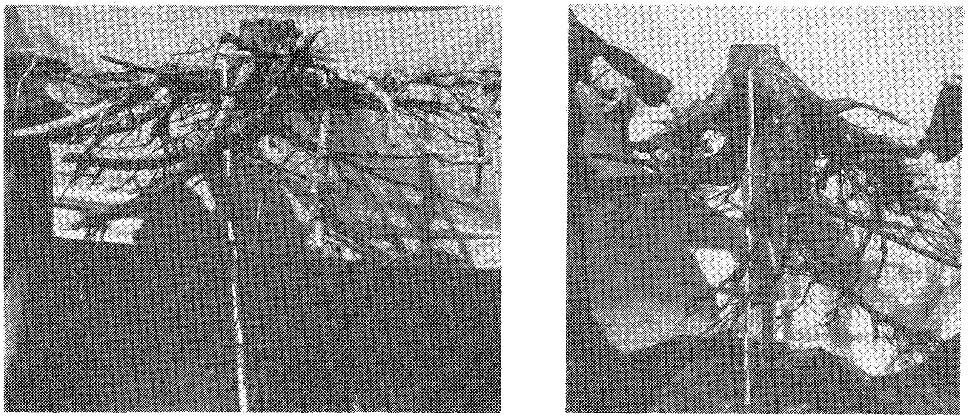


5—2. Stand K 7 : Forest of very moist soil through much underground water, soil type B*l*G.



5—3. Stand K 7, tree No. 6, D. B. H 14 cm, tree height 12 m, maximum depth of root 65 cm, soil type B*l*D.

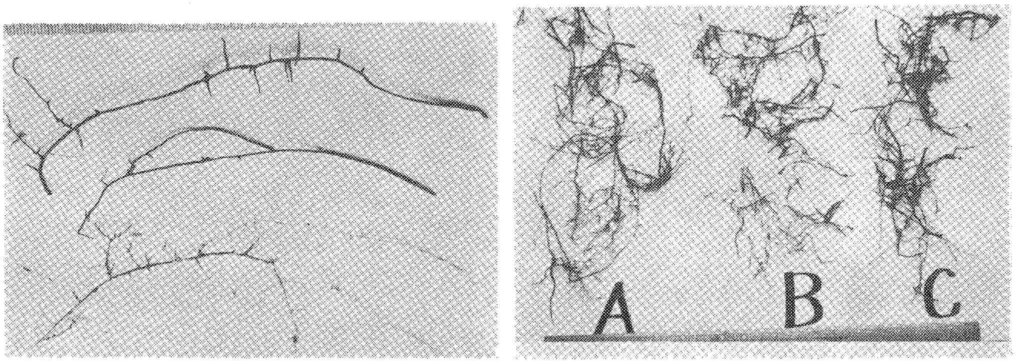
Photo. 6 Decayed fine and small roots of *L. leptolepis* because of very moist soil.



6—1. Stand K 4, tree No. 22, D. B. H 9 cm, tree height 7 m, maximum depth of root 65 cm, soil type Bl_E.

6—2. Stand K 6, tree No. 37, D. B. H 11 cm, tree height 8 m, maximum depth of root 65 cm, soil type Bl_G.

Photo. 7 Fine roots in various soil water conditions.



7—1. A : The fine roots of *L. leptolepis* in moderately moist soils.
B : The fine roots of *L. leptolepis* in very moist soils become black and decayed.

7—2. A : The fine roots of *L. leptolepis* in moderately moist soils.
B : The fine roots of *L. leptolepis* in dry soils.
C : The fine roots of *L. leptolepis* in very moist soils.

Photo. 8 The roots of *P. strobus* whose absorptive structure is decaying and whose fine root biomass is decreasing remarkably. Stand A 14, tree No. 2, D. B. H 16 cm, tree height 11 m.