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論 文

Stem Biomass and Structure of a Mature *Sequoia sempervirens* Stand on the Pacific Coast of Northern California

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FUJIMORI, Takao: **Stem biomass and structure of a mature *Sequoia sempervirens* stand on the Pacific Coast of northern California J. Jap. For. Soc. 59: 435～441, 1977** Stem biomass and structure of a virgin mature *Sequoia sempervirens* stand on the Pacific Coast of northern California was analyzed nondestructively. The stand was multi-storied with *Sequoia sempervirens* dominant in all strata. Several other tree species occured in the middle and lower strata, and among them evergreen broad leaf trees were most important. Average tree height of the upper stratum was 87.6m. Total volume and dry weight of stem were 10,817m^3/ha and 3,461 ton/ha respectively. Total basal area of stem at 1.7m height was 338m^2/ha. Apparent density of the dry stem per unit volume occupied by the stand (stem dry weight of the stand/product of the average tree height of the upper stratum and the stand area) was 3.95 kg/m^3. A 47-year-old regenerated *Sequoia sempervirens* stand was also measured; the average height of the upper stratum was 45.8m and the total basal area at 1.3m height was 152m^2/ha.

藤森隆郎: カリフォルニア北部太平洋沿岸のセンペルセコイアの成熟林の幹の現存量と構造 日林誌 59: 435～441, 1977 米国カリフォルニア州北部の太平洋沿岸のセンペルセコイア (*Sequoia sempervirens*) の成熟した天然林を調査し，幹の現存量と林分構造を解析した。その構造は複層をなし，センペルセコイアがすべての階層で優占していた。他の木本種は常緑広葉樹が主で，中層の下部と下層に出現した。上層木の平均樹高は 87.6 m で，幹の総材積と乾重量はそれぞれ 10,817 m^3/ha と 3,461 ton/ha であった。地上 1.7 m における幹の断面積合計は 338 m^2/ha，幹の現存量密度（林分の幹の乾重/上層木の平均樹高と林分面積の積）は 3.95 kg/m^3 であった。上記の成熟林のそばにある 47 年生のセンペルセコイアの2次林を測定し，その上層木の平均樹高は 45.8m，地上 1.3m の幹の断面積合計は 152 m^2/ha という値を得た。

I. Introduction

Along the Pacific Coast of the United States, from the middle of California to the southernmost part of Oregon, *Sequoia sempervirens* forests dominate. On good sites, *Sequoia sempervirens* grows fast (LINDQUIST & PALLEY, 1963, 1967) and to unusual heights (ZAHL, 1964; FEININGER, 1968), and its stands are very massive (HALLIN, 1934, 1941; KIMMEY, 1952). The biomass of the most massive *Sequoia sempervirens* forest might presumably be the largest forest biomass in the world; its value could be taken as the upper limit of forest biomass in the world.

From November, 1972 to January, 1973, I had the opportunity to select and measure the most massive mature virgin *Sequoia sempervirens* stand that could be found; the stem biomass was estimated by Allometric method. Measurements were limited to stem, but as the percentage of stem in a massive stand is very high (FUJIMORI et al., 1976), the stem value obtained in this stand would provide at least a basic understanding of the largest forest biomass existing on the earth

II. Location of the Study Area and its Circumstances

The range of *Sequoia sempervirens* extends along the Pacific Coast of the United States from the extreme southwestern corner of Oregon southward to Salmon Creek Canyon in the Santa Lucia Mountains of southern Monterey County, California (LINDQUIST & PALLEY, 1963). In its range, the research plot representing a mature stand (Photo. 1) was located along Bull Creek which is a branch of the Eel River in Humboldt State Park in California.

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Photo 1. The research plot for a mature *Sequoia sempervirens* stand

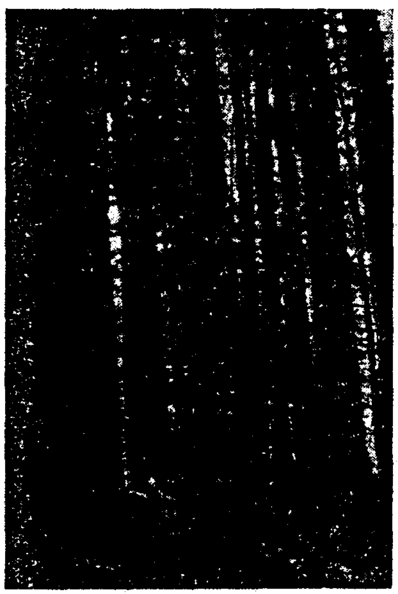

Photo 2. The research plot for a young *Sequoia sempervirens* stand

The elevation of the research plot in the mature stand is 80 m and the inclination is almost 0°. The research plot representing a young stand (Photo. 2) was located along the South Fork River which is also a branch of the Eel River. The plot lies 7 km southeast of the plot in the mature stand mentioned above. The elevation of the plot in the young stand is 50 m and the inclination is almost 0°. The parent materials at the research sites are coastal sedimentary rocks of the upper Cretaceous age (WARING, 1964). The soils consist mainly of alluvial types.

According to the climatic data for Eureka (U. S. Environmental Science Services Administration, 1966) whose weather station is closest to the research stands (52 km north of the research mature stand), the most striking feature of the climate there is the small annual variations in temperature (5.1°C). Neither the average temperature of the coldest (8.6°C in January) nor of the warmest month (13.7°C in August) is extreme; temperatures are moderate throughout the year. Annual precipitation of Eureka is 975 mm but the summer precipitation (June ~ September) is very small (41 mm), as it is over most of the Pacific Coast of the United States (FRANKLIN & DYRNESS, 1973; FUJIMORI et al., 1976). The area around the research plots is frequently covered with summer fogs from the Pacific Ocean and the frequent fog and low clouds compensate for the dry condition even during summer months. The range of *Sequoia sempervirens* is limited to the area where frequent summer fogs cover and the width of the range seldom extends more than 50 km (LINDQUIST & PALLEY, 1963; ROY, 1966).

III. Method

In order to obtain an example of large biomass of *Sequoia sempervirens* stand, I searched out the most massive stand and located the plot representing a mature stand within it (Photo. 1). In the mature stand a 120 m × 120 m plot was laid out and care was taken to insure that the plot was free from the influence of the forest edge. Generally it is required that the length of the square of the plot for forest biomass measurement at least exceeds the height of the tallest tree in the plot. As the height of the tallest tree in this plot was 97.6 m, the size of this plot might satisfy the minimal condition for this kind of research. In the research plot, the percentage of the number of those trees whose diameters (hereafter, diameter is expressed by D in case of necessity) at 1.7 m above the ground are less than 10 cm was fairly high both in *Sequoia sempervirens* and other species. However, since the ratio of the biomass of these trees ($D < 10$ cm) toward the whole biomass was apparently very small, those trees ($D < 10$ cm) were not measured. About one third of these trees were measured for height; they were selected so that the tree sizes were sampled in proportion to their frequency distribution. Diameter and height were measured using a diameter tape and an Abney level, respectively.

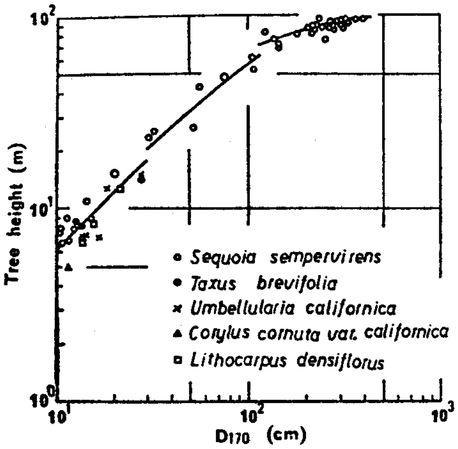

Fig. 1. Relation between diameter and tree height for the mature *Sequoia sempervirens* research stand

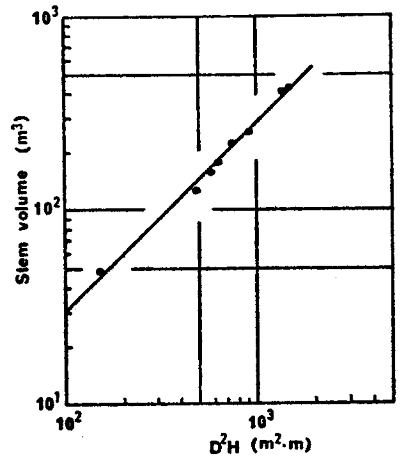

Fig. 2. Relation between D^2H and stem volume for the mature *Sequoia sempervirens* research stand

In this study, tree heights (hereafter, tree height is expressed by H in case of necessity) were estimated by the allometric method (KIRA & SHIDEI, 1967) using logarithmic regressions of individual H on D. The relationship between D and H which were actually measured is shown in Fig. 1, and the following equations for the relationship were obtained:

$$\frac{1}{H}=\frac{0.6336}{D}+0.0086 \quad (D\geqq 115\,\mathrm{cm}) \qquad (1)$$

$$\frac{1}{H}=\frac{1.3211}{D}+0.0041 \quad (114\,\mathrm{cm}\geqq D\geqq 30\,\mathrm{cm}) \qquad (2)$$

$$\frac{1}{H}=\frac{1.5430}{D}+0.0027 \quad (D\leqq 29\,\mathrm{cm}) \qquad (3)$$

All of the H in the plot were calculated by putting D of each tree into each equation in accordance with its size. Sample trees for $H\sim H_B$ relation were selected in proportion to the frequency distribution of D. Here, H_B denotes the height at the bottom of crown.

In order to obtain the relationship between D^2H and stem volume, the sample trees were selected from the fallen stems lying on the stand floor. There were many stems present on the forest floor, but most had been broken into pieces, especially in the higher part. Therefore, the sample trees were necessarily limited in number. The eight stems of *Sequoia sempervirens* chosen as the sample trees were stems whose diameters were measurable from the base to a comparatively high position. In each sample tree, the diameter at 1.7 m and the diameter at every 10 m (or less than 10 m depending on the conditions) from base to top were measured. The stem volume (hereafter, stem volume is expressed by V in case of necessity) was calculated by means of SMALIAN's rule. The relationship between D^2H and V of the sample stems is shown in Fig. 2 and the equation of that relationship was obtained by means of the least square method as follows:

$$\log V=0.9784 \log D^2H-0.4843 \qquad (4)$$

The stem volume of each tree in the research plot was calculated by putting the D^2H of each tree into the Equation (4). Stem volume includes bark volume in this study.

In this research plot, some trees were recognized to have heart rot in their stems, but the percentage of those trees was considered to be small. So the volume of the hole caused by heart rot in a stem was neglected in the measurement and calculation in this study. Although Equation (4) is for the estimation of the stem volume of *Sequoia sempervirens* in the research plot, the stem volume of other species was also calculated using this equation. This is because the ratio of stem volume of other species to that of *Sequoia sempervirens* was very small (the ratio of the total stem basal area of other species against that of *Sequoia sempervirens* was 0.001), and the inexactness of the equation for other species would therefore not significantly affect the plot value.

In addition, a young *Sequoia sempervirens* stand was measured in order to check the growth of young *Sequoia sempervirens* on favorable sites. Mature *Sequoia sempervirens* had been removed from the research plot by clearcutting in 1925*. Soon after that, the seedlings on the forest floor and sprouts from roots and stumps of the previous trees developed rapidly to form a new stand*

* This was verified by the record in the Headquarters of Humboldt Redwood State Park, California.

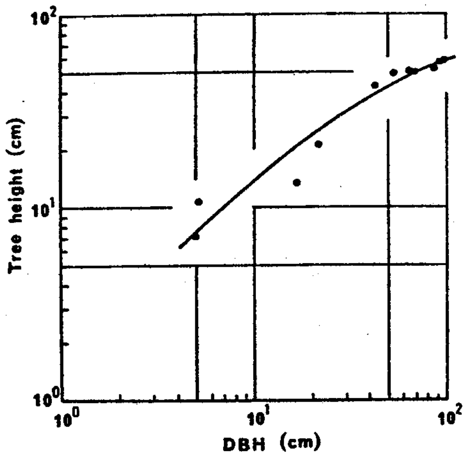

Fig. 3. Relation between diameter and tree height for the young *Sequoia sempervirens* research stand

(Photo. 2). In this stand, a plot of 50 m×50 m was laid out and the diameter of all trees whose diameter at 1.3 m height exceeded 5 cm were measured. Eleven trees, selected so that the whole range of the distribution of the tree size in the plot might be covered, were measured for height. The following Equation (5) was developed using the D and H data from the sample trees in the young stand (Fig. 3). The height of all trees in the plot was then calculated by utilizing this equation:

$$H=\frac{0.6093}{D}+0.0110 \qquad (5)$$

IV. Results

1. Mature stand

The horizontal projections of tree crowns in the research plot are shown in Fig. 4. From this map, it is obvious that the area is quite uniformly covered by the component trees. The frequency distribution of diameter in the research plot is shown in Fig. 5. It has an L shape, which has been recognized as typical in multi-storied forest. If trees with diameters less than 10 cm were added, the frequency of trees in the range of 0~50 cm would be greatly increased. Excepting *Sequoia sempervirens*, several tree species occurred in the range of less than 50 cm of diameter in this plot; specifically, the tree largest in diameter was a 28.0 cm *Umbellularia californica*, and largest in height, a 17.1 m *Taxus brevifolia*. Excepting *Sequoia sempervirens*, *Umbellularia californica* was the most common tree species, and with *Lithocarpus densiflorus* made broad-leaf, evergreen trees the most common. Broad-leaf, deciduous trees (*Corylus cornuta* var. *californica*) were relatively minor.

The only coniferous species in this plot, except for *Sequoia sempervirens*, was *Taxus brevifolia*. *Oxalis oregana* was most common herbaceous species followed by *Polystichum munitum*, *Anemone deltoidea*, and *Viola sempervirens*.

Stand structure of the research stand was expressed by the following method. Crown depth and relationship between tree height and the height of

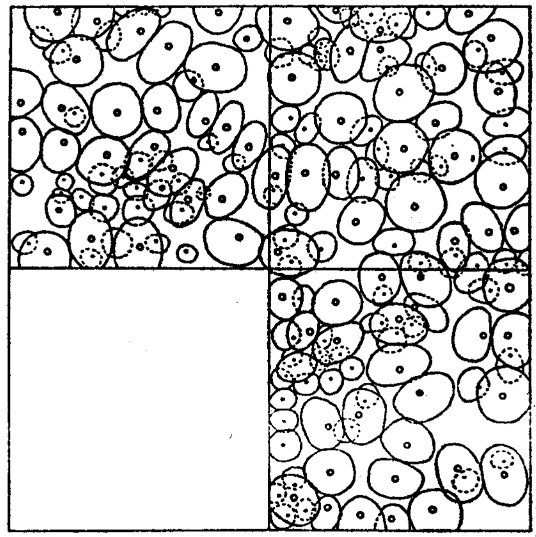

Fig. 4. Horizontal projections of tree crowns and the position of stem bases for the mature *Sequoia sempervirens* research stand

Remarks: Open circles represent the stems of the trees whose heights are larger than 70 m, while solid circles less than that. The map of a quarter of the research stand could not be figured on account of the shortage of time in the field work.

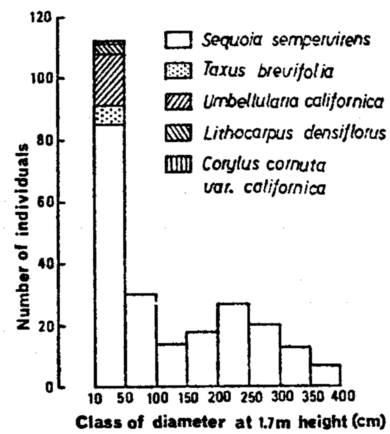

Fig. 5. Frequency distribution of diameter for the mature *Sequoia sempervirens* research stand

Remarks: The trees whose diameters are less than 10 cm are not involved in the figure.

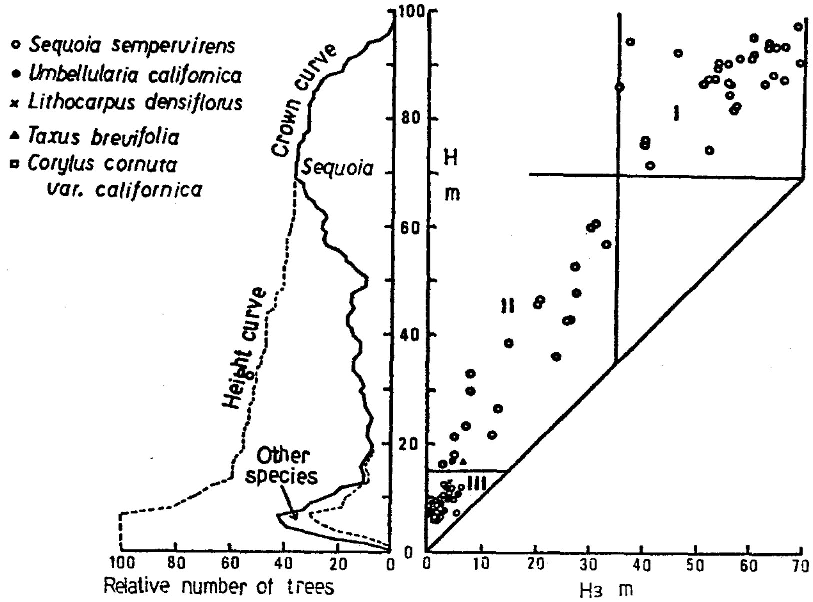

Fig. 6. Crown depth diagram and relation between tree height (H) and the height at the lowest branch (H_B) for the mature *Sequoia sempervirens* research stand

the base of the crown (H_B) in the plot are shown in Fig. 6. The crown curve (OGAWA et al., 1965) expresses the number of crown on each height. At a certain height level H', the crown curve gives the number of trees whose H and H_B satisfy the condition $H>H'>H_B$. The height curve represents the number of trees taller than a certain height level, or it is the cumulative curve of the number of trees according to the order of their height. Tree numbers were expressed by percentage of the total in both curves. Three vertical strata could be recognized on this plot, although their distinction is not necessarily clear (Fig. 6). Assuming three vertical strata in this plot, there is an upper stratum (I) in excess of 70m, a middle stratum (II) between 69m and 15m, and the lower stratum (III) less than 14m in height. The number of crowns in each height is relatively large in the upper stratum and the lower stratum in this stand (Fig. 6).

The values obtained in the mature stand are shown in Table 1. In the upper stratum ($H \geqq 70$m), the tree numbers per ha, average height and diameter, basal area of stems at 1.7m above the ground, and stem volumes were 66, 87.6m, 240cm, 323m²/ha, and 10,552m³/ha, respectively. The ratio of the upper stratum to the total in the number of trees, basal area, and stem volume were 39.4, 95.5, and 97.5%, respectively; most of the biomass in this stand was obviously found in the 40% of trees in the upper stratum. The total stem basal area of this stand was 338.3m²/ha. Except for *Sequoia sempervirens* stands the largest total basal area, to my knowledge, is 147.4m²/ha in a mixed forest of *Abies procera* and *Pseudotsuga menziesii* near Mt. St. Helens in the Gifford Pinchot National Forest in Washington, USA (FUJIMORI et al., 1976).

Table 1. Values obtained in the mature *Sequoia sempervirens* research stand

	Upper stratum $H \geqq 70.0$ m		Middle stratum 69.9 m $\geqq H \geqq$ 15.0 m		Lower stratum 14.9 m $\geqq H$		Total
	Sequoia sempervirens	Other species	*Sequoia sempervirens*	Other species	*Sequoia sempervirens*	Other species	
Number of trees per ha	66.0	0	44.4	2.8	38.2	16.0	167.4
Average tree height (m)	87.6	0	35.5	16.4	9.5	9.7	
Average diameter at 1.7 m height (cm)	240.4	0	57.5	26.4	15.0	15.4	
Basal area of stem at 1.7 m height per ha (m²)	323.0	0	14.1	0.2	0.7	0.3	338.3
Stem volume per ha (m³)	10,552.1	0	258.7	1.1	3.3	1.5	10,816.7
Stem dry weight per ha (ton)	3,376.7	0	82.8	0.3	1.1	0.5	3,461.4

The stem volume of this stand was 10,816.7 m^3/ha. Outside of *Sequoia sempervirens* stands, the largest stem volume I have experienced is 4,200 m^3/ha in the mixed forest of *Abies procera* and *Pseudotsuga menziesii* already cited (FUJIMORI et al., 1976). One of the largest accumulations of stem volume in Japan is about 3,000 m^3/ha of *Cryptomeria japonica* stand at Kaneyama, Yamagata Prefecture, which was measured by MINE (1951) (FUJIMORI, 1972; TADAKI, 1976). When the value of this *Sequoia sempervirens* stand is compared with the values of these stands mentioned above, it is obvious how extraordinarily large a stem volume exists in this *Sequoia sempervirens* stand.

The stem volume was converted to the stem dry weight by multiplying the stem volume and the specific gravity ratio (0.32) of *Sequoia sempervirens* wood (Timber handbook, 1958). The specific gravities for the stem bark of *Sequoia sempervirens* and the stem wood and bark of the other species were also calculated using the specific gravity of stem wood of *Sequoia sempervirens*. Thus the stem dry weight of this stand turned out to be 3,461.4 ton/ha. It is clear that the whole biomass of this stand will exceed 3,500 ton/ha, when the branches, leaves, and roots are added to the large value for stem biomass above.

WESTMAN & WHITTAKER (1975) estimated the biomass of mature *Sequoia sempervirens* stands on good sites in northern California by a non-destructive method. According to that, the biomass above the ground of the three sample stands were 2,980, 3,280, 3,300 ton/ha; the mean tree heights of the upper stratum and the total basal areas of the respective stand were 79, 81, 79 m and 250, 243, 247 m^2/ha. These values are a little smaller than the values of the stand measured by me (Table 1), but with the values estimated by WESTMAN & WHITTAKER, it might be said that among mature *Sequoia sempervirens* forests on good sites in northern California, stands do occur whose biomass exceeds 3,000 ton/ha.

In a forest, the biomass above the ground divided by the average height of dominant trees gives the apparent density of dry organic matter per unit volume occupied by the forest (KIRA & SHIDEI, 1967). In the case of this stand, instead of the whole biomass above the ground, the apparent density of the dry stems was calculated by dividing the stem dry weight (3,461.4 ton/ha) by the average tree height of the upper stratum of this stand (87.6 m, Table 1, Fig. 1); the value thus obtained was 3.95 kg/m^3. The apparent densities of the dry organic matter of the *Tsuga heterophylla-Picea sitchensis*, the *Pseudotsuga menziesii-Tsuga heterophylla*, and the *Abies procera-Pseudotsuga menziesii* stands studied in Oregon were 1.82, 1.06, and 1.76 kg/m^3, respectively (FUJIMORI et al., 1976). In the case of closed stands in Japan, dry matter densities usually range between 1 and 1.5 kg/m^3 with no relation to stand height, although there are several exceptions in the stands of lower class (KIRA & SHIDEI, 1967; YODA, 1971). Judging from these data, the apparent density of dry stems in this *Sequoia* stand is extraordinarily large.

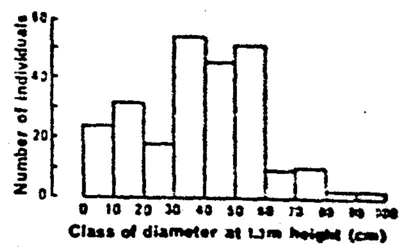

Fig. 7. Frequency distribution of diameter for the young *Sequoia sempervirens* research stand

The annual rings at the base (1.7 m above the ground) of the three trees which had been lying on the floor of the research stand were counted. The sample trees were arbitrarily selected from the trees in the size class belonging to the upper stratum. The number of rings of the three stems were 1,173, 830, and 699, so far as the rings could be counted. Although the number of the sample trees is insufficient, it could be surmised from this data that the ages of the dominant trees in this stand distribute widely, and the trees whose ages exceed 1,000 years are not rare.

2. Young stand

Results of the measurements in the 47-year-old stand are shown in Table 2 and the frequency distribution of diameter at 1.3 m above the ground

Table 2. Values obtained in the young *Sequoia sempervirens* research stand

	Upper stratum $H \geq 40.0$ m	Middle stratum $39.9\text{m} \geq H \geq 15.0\text{m}$	Lower stratum $14.9\text{m} \geq H$	Total
Number of trees per ha	436	448	112	996
Average tree height (m)	45.8	31.5	10.9	
Average diameter at 1.3 m height (cm)	57.4	30.4	7.6	
Basal area of stem at 1.3 m height per ha (m^2)	116.5	35.1	0.5	152.1

is shown in Fig. 7. The largest tree in the plot was 94.3 cm in diameter and 57.0 m in height. When the upper stratum was defined as being higher than 40 m (Fig. 3), the average tree height of the dominant trees was 45.8 m. The total basal area of stem at 1.3 m above the ground was 152 m^2/ha.

These values are extraordinarily large for the stand whose age is 47 years old and suggest a high productivity for *Sequoia sempervirens* on good sites and in its early growing stage. This is also apparent from the empirical yield tables for young-growth *Sequoia sempervirens* (LINDQUIST & PALLEY, 1963) which show average tree height and total stem basal area of 50-year-old stand as 52 m and 160 m^2/ha on the best site quality.

Acknowledgment

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