THE TREE LIMIT AND ITS DYNAMICS ON THE WESTERN AND NORTHWESTERN SLOPES OF MOUNT FUJI, CENTRAL JAPAN

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Abstract The tree limit on Mount Fuji is mainly composed of larches (*Larix leptolepis*) that are the dominant forest species there. The limit ranges from 1400 to 2900 meters, depending on the slope. On the western and northwestern slopes of Mount Fuji, where the forest vegetation reaches a high altitude, we have investigated the altitudinal changes of larch growth, *e.g.*, tree height, diameters at breast height and ground level, buried seed number, and tree age. They were compared with some environmental factors, especially thermal condition. As a result, the following facts were concluded. The tree limit attained the 2900-meter altitude nearly 110 years ago on the western slope. The time period during which a tree limit ascends seems to be identical to the time period during which low-growth periods, that is, low-temperature periods occur frequently.

Key words : tree limit, *Larix leptolepis*, growth analysis, tree ring, Mount Fuji

1. Introduction

Mount Fuji is the highest mountain in Japan. On this mountain, however, we observe no alpine plants and creeping pines (*Pinus pumila*) that normally grow in the Japanese alpine zone, because Mount Fuji is a relatively new mountain which erupted intermittently until 1707. Alpine plants contain a lot of relic elements originating from the ice age, and thus these plants had a very slender chance of establishing themselves on Mount Fuji. In addition, this mountain is not capable of retaining sufficient moisture because its surface is covered with porous lava, sand and lapilli. Therefore, Mount Fuji has been almost inaccessible to alpine hygrophytes including snow patch vegetation.

The pioneer vegetation growing in the bare land of Mount Fuji includes the *Larix leptolepis* scrub and open communities of *Polygonum weyrichii, Polygonum cuspidatum*, and so on. *Larix leptolepis* becomes a shrub near the forest limit, and its growth form completely changes into prostrate shape near the tree limit, looking like a creeping pine. The forest limit is basically composed of *Larix leptolepis*. The evergreen needle-leaved trees, mainly of *Avies veitchii*, are not well grown. These characteristics of Mount Fuji are not typical of high mountains in Central Japan (Numata and Iwase, 1975).

It is worth notice, however, that Mount Fuji is high enough to allow the growth of tree species which reach 2,900 meters a.s.l. This is also the case with Mount Kitadake of the Akaishi Mountains where *Pinus pumila* is distributed up to the same level and the forest limit is located at 2,700 meters a.s.l. (Nakamura, 1985). This fact suggests that vegetation on Mount Fuji is not affected by its altitude, although the altitude of mountain is an absolutely controlling factor of vegetation zones. *Larix leptolepis*, which constitutes the upper part of the forest zone, becomes a shrub, forming a forest limit there. From the viewpoint of the transformation of growth form, however, this indicates a similar structure to the forest limit, above which lies *Pinus pumila*. This allows us to discuss the forest limit without having to take account of competitive association. Furthermore, it enables us to observe vegetation going through various stages of development according to the processes of soil formation that can be identified by the accumulation age of eruptive substances and their varieties (Ohsawa *et al.*, 1971).

The purpose of this paper is to investigate the distributional and structural characteristics of the tree limit and the dynamics of it on the northwestern and western slopes of Mount Fuji. In order to execute the purpose, from the standpoint of vegetation science, we are now going to study a plant community in the vicinity of the tree limit on Mount Fuji, making extensive use of various scientific methods such as forest mensuration, growth analysis, buried seed number analysis, and dendro-chronology. In addition, we will examine the formation process of a tree limit as well as the environmental factors related to it. Investigation concerned with these subjects was conducted for a period of three years from 1987 through 1989.

2. Methods

By using an aerial photograph analysis and a quadrat method, distributional and structural characteristics of the tree limit were surveyed.

Then, tree height, diameter at breast height (DBH), diameter at ground level, and tree age were checked at approximately every 50 meters of altitude along the courses of the Shichitaro Ridge and the right bank of Kengamine-Osawa on the northwestern and western slopes respectively. The age of trees was determined from core samples collected with a Swedish-made increment borer at 50 cm-level above the ground surface.

To verify what reproduction is under way in the vicinities of a tree limit, the quantity of buried larch seeds are checked at 5 points on two courses. With the fringe of larch crowns located at each point as a basis, we set plots, 50×50 centimeters each, at intervals of 1 meter within the range of 3 meters outside and 1 meter inside. The soil was taken out to the depth of about 3 centimeters, and larch seeds contained in the soil were counted after having been selected through a screen of 3.5-millimeter mesh. The plots were arranged in the direction conforming to the deviated direction of the deformed trees. At the same time, we also checked up the number of seedlings growing around.

Tree-ring width samples were collected by extracting cores (about 5 millimeters in diameter) from living trees using an increment borer on the right bank of Kengamine-

Osawa. The sampling positions were set at a height of approximately 50 centimeters above the ground from above the slope. Only one core per tree was taken. So it remains somewhat questionable whether or not the bias of thickening growth could be grasped accurately. Using a binocular microscope connected to a reading appliance on its stage, the interannual variation of collected cores were recorded after reading their tree-ring width up to degree of 0.01 millimeters. Even in the case of tree-rings created in the same year, some disparities arise in their width depending on tree age and social environment. In order to make a comparison among them, it is necessary to erase such disparities by standardization (Fritts, 1976). The method of standardization: apply the exponential curve (Horiba, 1980; Sato *et al.*, 1987), polynomial curve (Takechi, 1983), or moving average curve (Mitsutani and Tanaka, 1986) as a trend line; divide measured values by standardized values; and put them into indices (Tree-Ring Width Index). The adaptability of these curves to standardization was already examined by Horiba (1980) and Takechi (1989). It seems that these curves had better be used each in its proper way depending on the changing patterns of tree-ring width. Because there was something questionable about the accuracy of core sampling as stated before, several moving average curves in which term numbers were varied were used in this study. Later their relationship with climatic values was reviewed in the manner of trial and error.

3. Results

Distribution and structure of the tree limit

As shown in Fig. 1 which is drawn basing on an aerial photograph analysis as well as a field survey, the tree limit composed mainly of the *Larix leptolepis* scrub is found above 2900 meters on the steep western slope along Kengamine-Osawa. On the southeastern slope, where the scoria left from the eruption of Mount Hoeizan in 1707 accumulated over a vast area, the tree limit descends greatly and the open community of *Polygonum weyrichii* and *Cirsium purpuratum* comes down to the level of 1300 to 1400 meters. The *Larix leptolepis* scrub edges the forest slightly on the southeastern slope. However, on other slopes where the tree limit goes up, it often develops so extensively that it exceeds the relative height of 200 meters. Therefore, the altitude of the forest limit distinguished by the edge of continuous stand of *Larix leptolepis* is a little less than 2800 meters maximum at the right bank of Osawa on the western slope. On the southeastern slope, the forest limit comes down to the lowest level, ranging from 1300 to 1400 meters.

Looking into this situation in more detail, we find that this conical mountain is whittled by many radial valleys, with a community dominated by *Larix leptolepis* growing on its dry ridge like a peninsula. On the valley side grow *Alnus maximowiczii* and *Betula ermanii*, and further outside of these we see the growth of *Salix reinii*. Below the altitude of 2500 meters, there are evergreen needle-leaved trees consisting mainly of *Abies veitchii* and partly of *Tsuga diversifolia* and *Picea jezoensis* that grow inside the community. Thus, as the vegetation growing in the form of a peninsula moves toward the center, its site becomes more stabilized and the soil and vegetation are well developed. The

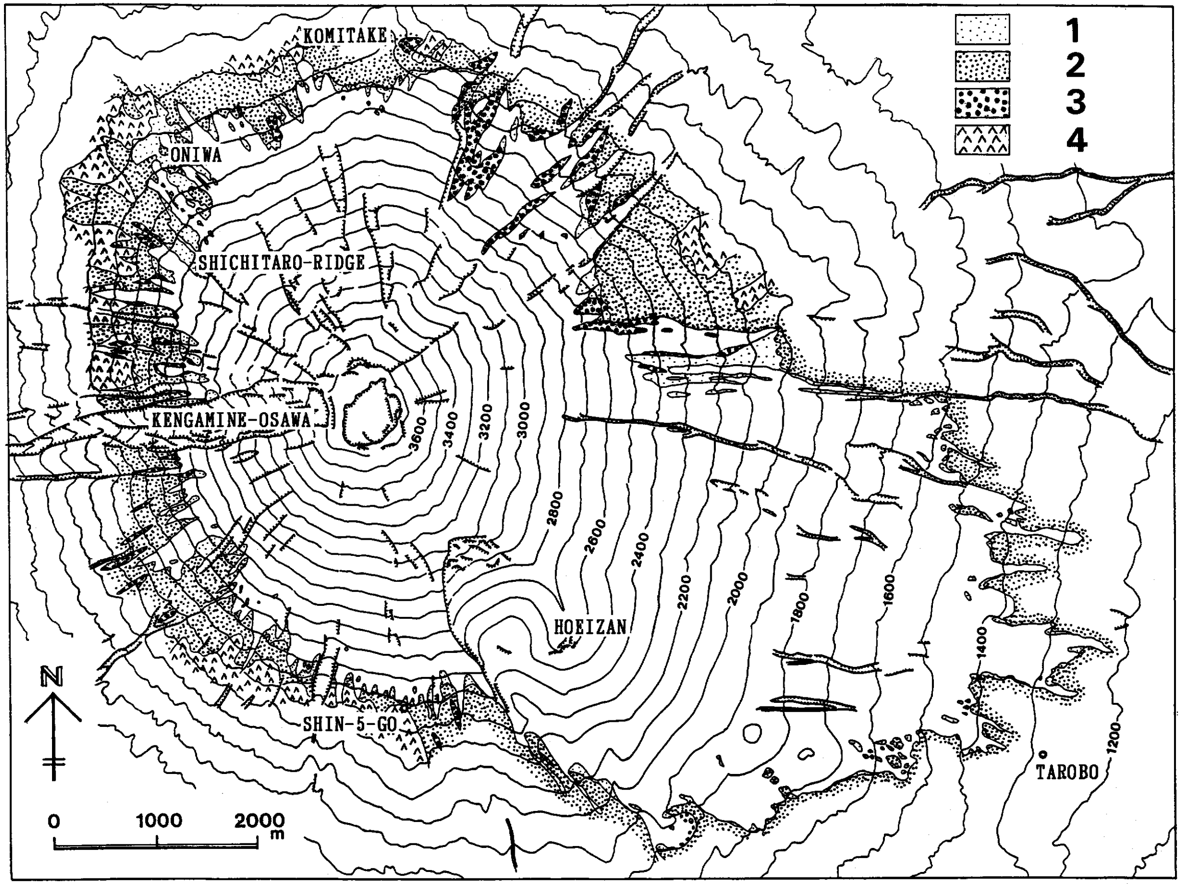

Fig. 1 Physiognomical vegetation map around the forest limit on Mount Fuji
1: larch (scrub), 2: larch, 3: deciduous broad-leaved trees, 4: evergreen coniferous forest (after Oka, 1992)

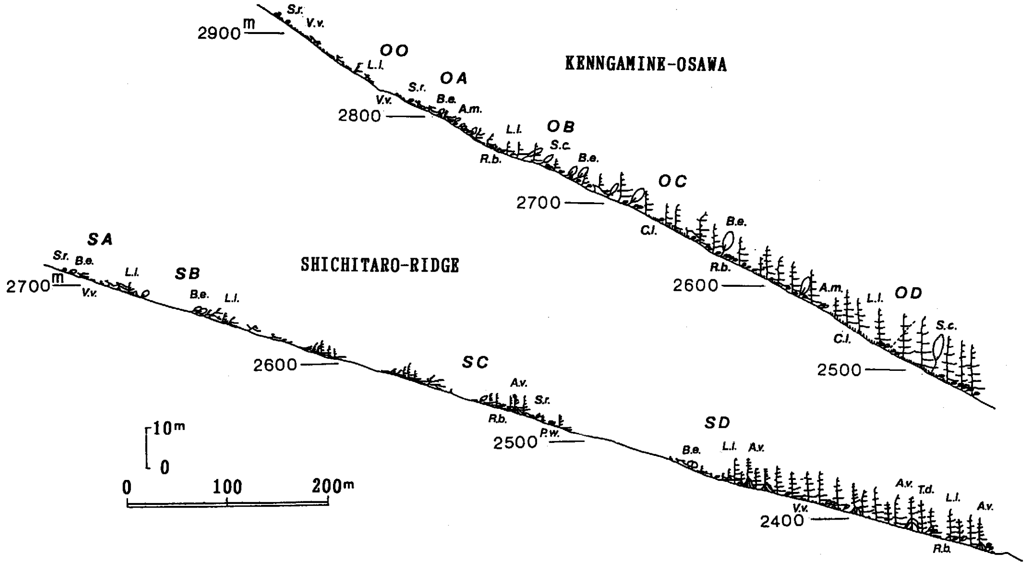

Fig. 2 Profile diagrams along the right bank of Kengamine-Osawa and the Shichitaro-Ridge *A.m.*: *Alnus maximowiczii*, *A.v.*: *Avies veitchii*, *B.e.*: *Betula ermanii*, *C.l.*: *Calamagrostis langsdorffii*, *L.l.*: *Larix leptolepis*, *P.w.*: *Polygonum weyrichii* var. *alpinum*, *P.b.*: *Phododendron brachycarpum*, *S.c.*: *Sorbus commixta*, *S.r.*: *Sarix reinii*, *T.d.*: *Tsuga diversifolia*, *V.v.*: *Vaccinum vitis-idaea* var. *minus*

pioneer vegetation trends to gather around the fringe (Ohsawa *et al.*, 1971).

Fig. 2 shows the profile diagrams along the Shichitaro Ridge and the right bank of Kengamine-Osawa on the northwestern and western slopes where forest vegetation is well grown. A steep slope composed of a lava flow is formed on the Osawa right bank, whereas a relatively gentle slope composed of scoria is formed over the Shichitaro Ridge (Tsuya, 1971). On the Osawa right bank, the forest is established in the form of a peninsula, and the tree limit exceeds 2900 meters a.s.l. On the Shichitaro Ridge, vegetation is scattered in patches forming an island, where the tree limit is 2700 meters. In the former case, flag-like deformed trees emerge above the altitude of 2650 meters and prostrate deformed trees emerge near the tree limit. In the latter case, all "islands" are made up of flag-like and prostrate deformed trees (Oka, 1972, 1980). When the forest limit at each profile is defined as the continuous growth limit of forest stand 3 meters high, the forest limit reaches 2770 meters at the Osawa right bank and 2460 meters at the Shichitaro Ridge. We find that *Abies veitchii* emerges below the altitudes of 2400 and 2550 meters respectively.

Fig. 3 is a physiognomical vegetation map that shows details of the Osawa right bank based on an aerial photograph analysis. Here, a forest of needle-leaved trees including *Abies veitchii*, which belong to the so-called subalpine zone, is situated on a slightly gradual slope. The altitude of this forest exceeds 2500 meters in some places. In the neighborhood of the forest limit, however, vegetation is basically composed of larches and deciduous broad-leaved trees including mainly *Betula ermanii*, and *Alnus*

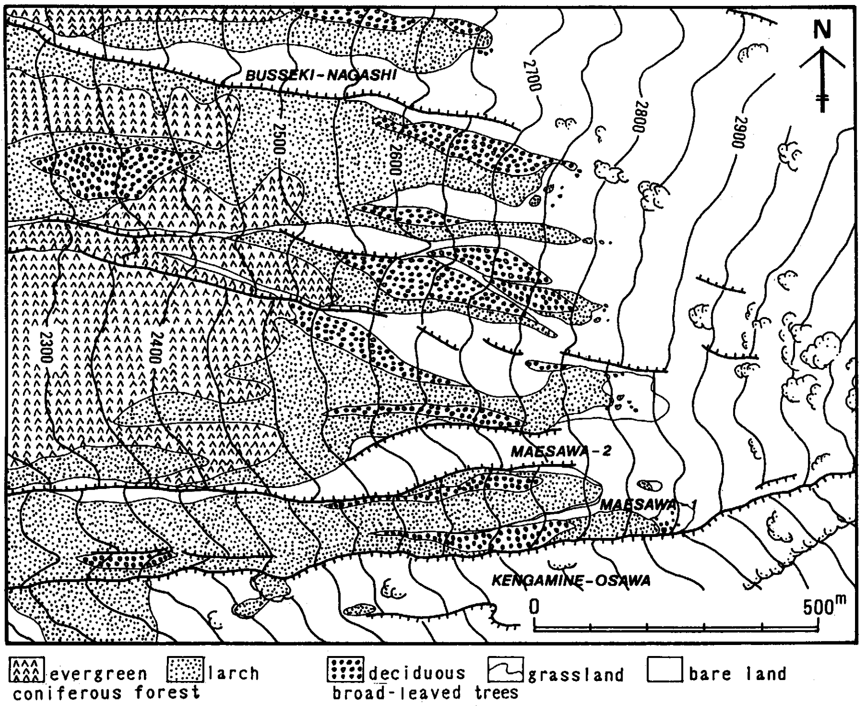

Fig. 3 Vegetation map around the Osawa right bank based on an aerial photograph analysis (after Oka, 1992)

maximowiczii. Characteristically, the distribution of these deciduous broad-leaved trees tends to concentrate on the northward slope. The investigation route on the right bank of Osawa was set along Maesawa-1. Points OO to OD on the cross section of Kengamine-Osawa in Fig. 2 are all located on the right bank of Maesawa-1. Thus Point OA is located near the tree limit on the right bank of Maesawa-1, and Point OO lies above it. As a result, the community extending along Maesawa-1, which rises to the level of 2900 meters, is called the Osawa Right Bank Series in this paper.

Fig. 4-1 is a crown projection diagram, based on the results surveyed using a quadrat method, at Points OA to OD in the Osawa Right Bank Series. Point OA corresponds to the fringe of a "peninsula". Crowns corresponding to each individual trunk cannot be identified because larches have a prostrate growth form. At Points OB, OC, and OD, on the contrary, trees are well grown and crowns are distinctly identifiable. At all of these points, *Larix leptolepis* occupies the upper layer of the forest, containing *Betula ermanii* within its territory. *Rhododendron brachycarpum* prevails in the shrub layer, whereas *Vaccinium vitis-idaea* and *Calamagrostis langsdorffii* are dominant in the herb layer.

Fig. 4-2 is also a crown projection diagram drawn by the same manner to the Osawa Series, at Points SA to SD in the patch-like communities extending like islands on to the Shichitaro Ridge. This is called the Shichitaro Ridge Series. At Points SA and SB, *Larix leptolepis* shows a prostrate growth form. Dwarfed *Betula ermanii* is contained within

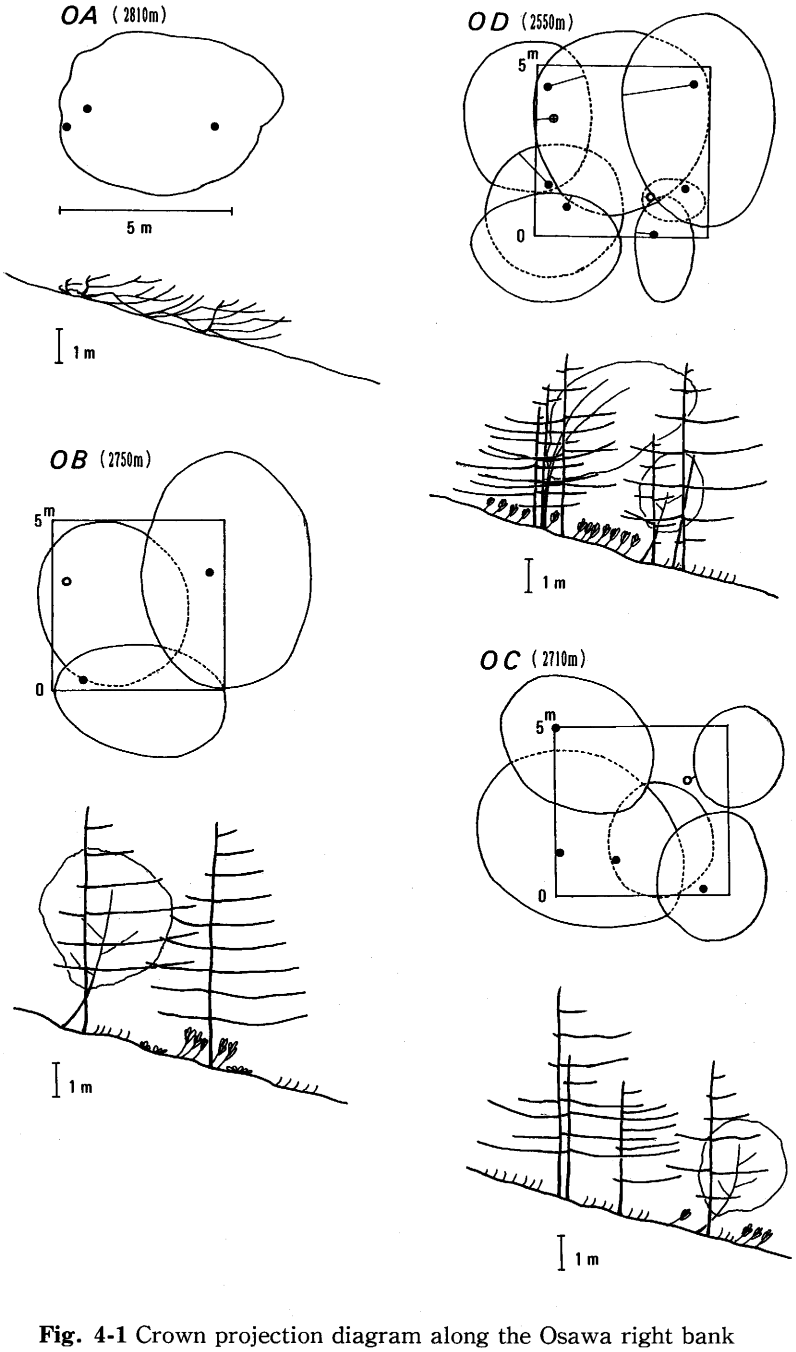

Fig. 4-1 Crown projection diagram along the Osawa right bank
See the symbols in Fig. 4-2.

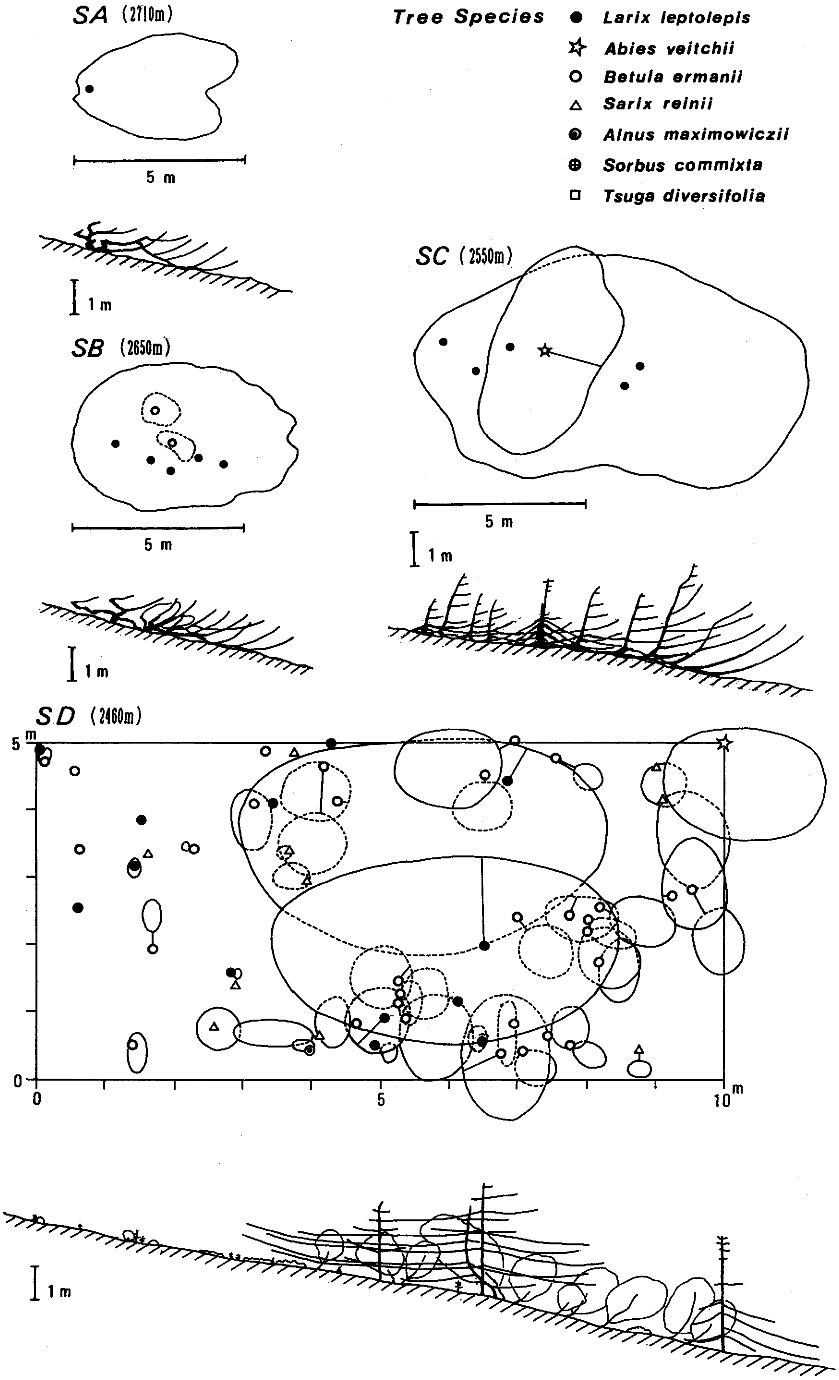

Fig. 4-2 Crown projection diagram along the Shichitaro Ridge (after Oka *et al.*, 1992)

SB, but crowns form a complete whole at both SA and SB. At SC, upright trunks become dominant, but the expansion of crowns is not clearly distinguishable because of the branches prostrating over the ground. Here at SC, the central part of the patch has already been occupied by *Abies veitchii*. Point SD is the spot that virtually constitutes the forest limit in this series. A quadrat, 5×10 meters, has been specifically set at this point, where the size of an individual crown is very clearly distinguishable. The upper layer of the forest is occupied by *Larix leptolepis*, including *Abies veitchii*. Young trees of *Betula ermanii* grow pretty densely in the shrub layer. On the outskirts of this forest, many seedlings of *Larix leptolepis* and *Betula ermanii* are beginning to germinate.

Analyzing the growth of trees in the vicinity of the tree limit

Fig. 5 shows changes in tree height at different altitudes on the Osawa right bank. Trees 15 meters high near the altitude of 2500 meters becomes only 1 meter high at the 2900-meter altitude. Among these changes, a large discontinuity between the altitudes of 2750 and 2800 meters is especially worth notice. This indicates that a limit of continuous high forest stand, *i.e.* the forest limit, is located in this discontinuity. Specifying the altitude in little more detail based on Fig. 5, it would be reasonable to set the forest limit at the 2770-meter altitude, above which no tall trees are seen. Fig. 6 shows changes in tree height at different altitudes observed on the Shichitaro Ridge. The scattering "islands" are put together in this figure, in which we recognize a very smooth

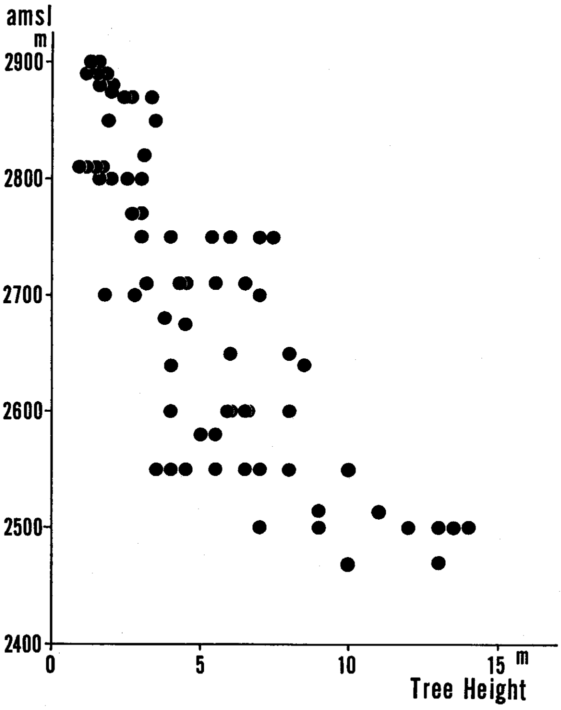

Fig. 5 Changes in tree height at different altitudes on the Osawa right bank
See the symbols in Fig. 4. (after Oka, 1992)

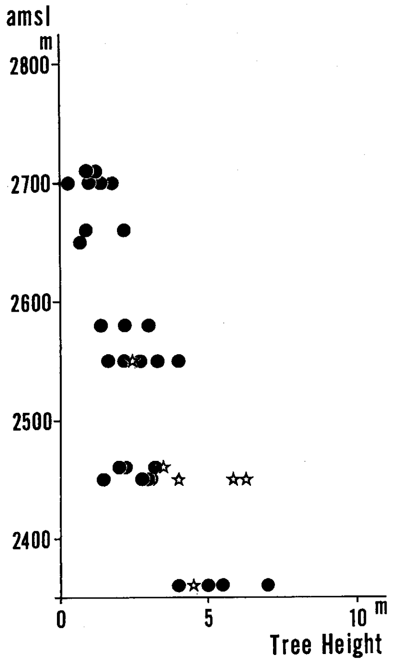

Fig. 6 Same as Fig. 5, but for the Shichitaro-Ridge (after Oka *et al.*, 1992)

change in the height of trees including *Abies veitchii*. In comparison with the Osawa right bank, tree size itself is very small, and the growth in elongation of trees is extremely suppressed.

The relationships between the growths in elongation and thickness of trees are shown in Fig. 7. In the Osawa Right Bank Series, we can observe both a group of trees showing a stronger tendency toward the growth in elongation and another group showing a stronger tendency toward the growth in thickness. Giving an extreme example each, there is a tree 30 centimeters in diameter and 15 meters in height in the former case as compared with a tree 2 or 3 meters high with the same diameter in the latter case. All tree species excluding *Larix leptolepis* belong to the group tending toward the growth in elongation. These growth patterns change depending on altitudes. As for the elongation group: the lower the altitude, the greater the growth, proving that they are affected by altitudes. As for the thickening group: a similar growth pattern is barely recognized. The relationship with their base diameter is also observed for both groups, as shown in Fig. 7-b. Fig. 8-a shows the data on trees whose DBH were measurable in the Shichitaro Ridge Series. These trees belong to the elongation group, although their size is rather short. Fig. 8-b shows the relationship with the diameter at ground level, from which the thickening growth pattern of trees becomes distinguishable, and we find that they show a pattern almost identical with the tendency observed on the Osawa right bank. In this example, too, trees like *Abies veitchii* belong to the group tending toward the growth in elongation.

Fig. 9 shows changes in the age of *Larix leptolepis* at different altitudes as observed on the Osawa right bank. This figure demonstrates their maximum (longest) age in every

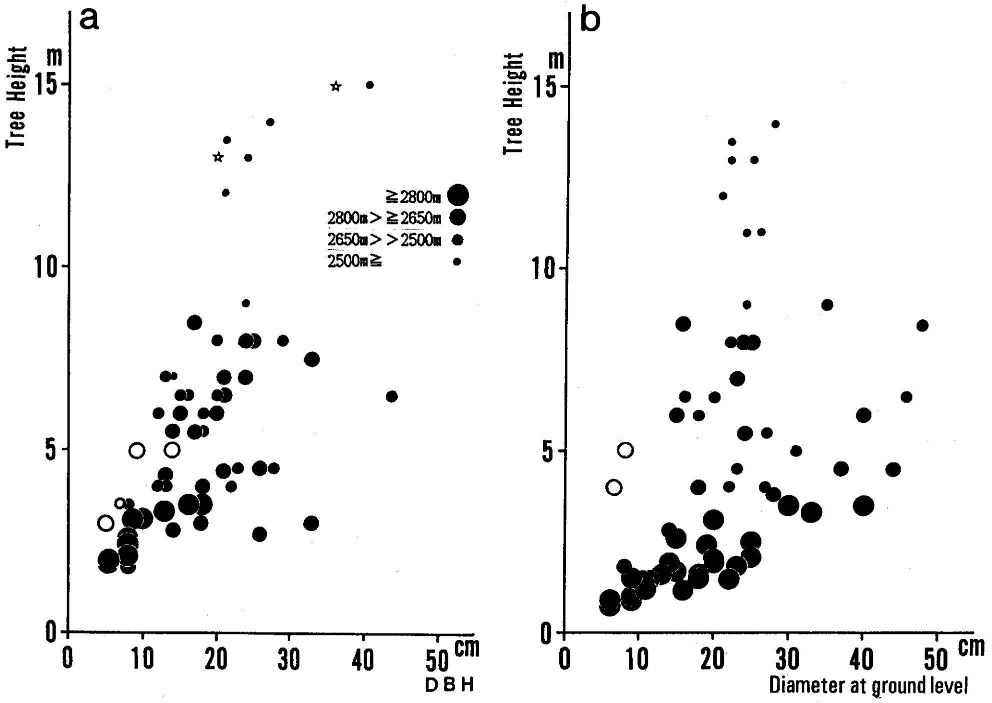

Fig. 7 Relationship between growths in elongation (tree height) and thickness (diameters at breast height and ground level) on the Osawa right bank
See the symbols in Fig. 4.

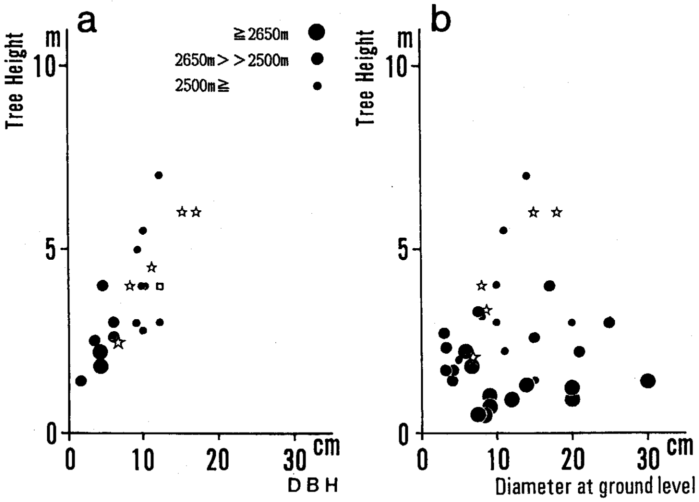

Fig. 8 Same as Fig. 7, but for the Shichitaro Ridge (after Oka *et al.*, 1992)

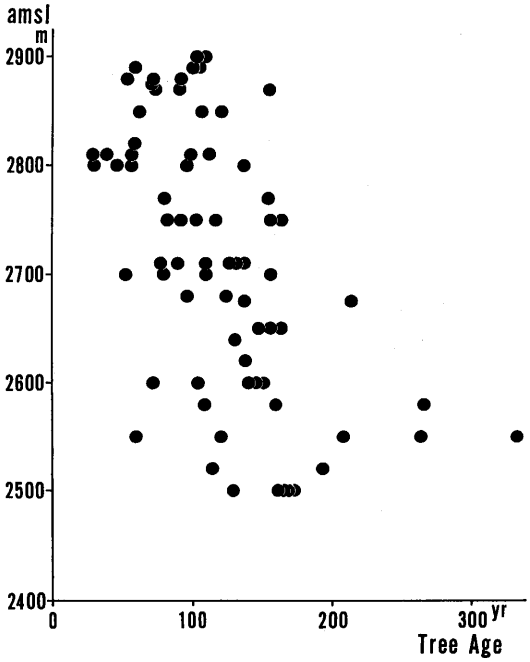

Fig. 9 Changes in age of *Larix leptolepis* at different altitudes on the Osawa right bank (after Oka, 1992)

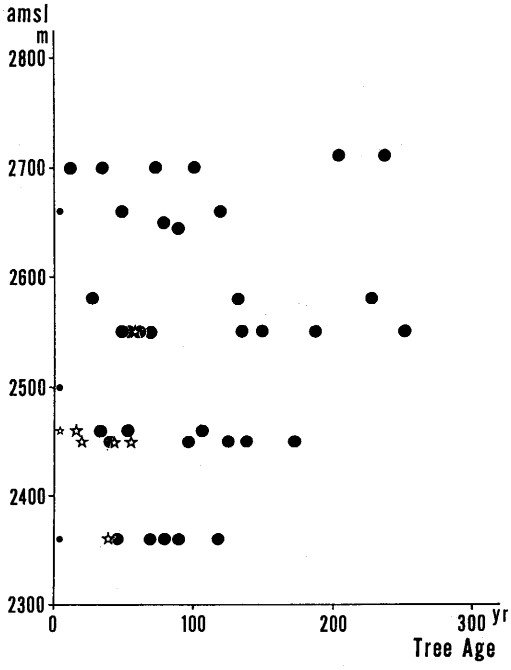

Fig. 10 Changes in tree age at different altitudes on the Shichitaro Ridge
See the symbols in Fig. 4, small symbols show the seedlings. (after Oka *et al.*, 1992)

step with altitudes changes systematically. For instance, the maximum age of *Larix leptolepis* lengthens like this: 110 years old at an altitude 2900 meters, 150 yrs. at 2800 m, 200 yrs. at 2700 m, and 250 yrs. at 2600 m. Hence, the higher the altitude, the shorter their age. The maximum age does not shorten gradually toward 2900 meters, where the tree limit lies. It shortens immediately and dramatically when the altitude reaches 2900 meters. In the Shichitaro Ridge Series, on the contrary, such a clear systematic feature is not recognizable (Fig. 10). Characteristically, young trees symbolized by the existence of seedling are established in this series. Changes in the maximum age of trees, affected by altitudes, are quite ambiguous. However, according to the result of a survey conducted by Ohga and Numata (1971), there was a tree, about 400 years old, measured at the 2180-meter level. Considering the result, it would be safe to say that the lower the altitude, the longer the age. At any rate, there is something abnormal about the changes of tree age in this series. This suggests that some significant disturbances occurred after the community was established.

Fig. 11 shows the relationship between tree age and tree height in Osawa Right Bank Series, where the presence of two different groups is distinctly recognizable. The first group (Group A) consists of trees that grow to a height of 15 meters in less than 150 years. The second group (Group B) comprises trees that become barely 5 meters high in 300 years. In both groups, the lower the altitude, the higher the tree. In the Shichitaro Ridge Series, trees are low on the whole, and therefore the distinction between groups is not so clear as in the Osawa Right Bank Series. Still, a similar tendency is

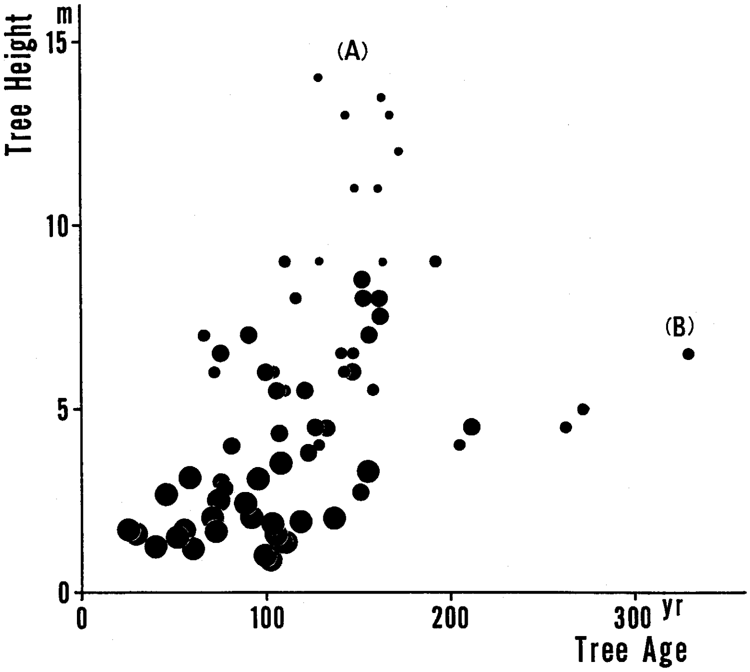

Fig. 11 Relationship between tree age and tree height on the Osawa right bank
Symbols are shown in Fig. 4, and their sizes are shown in Fig. 7. (after Oka, 1992)

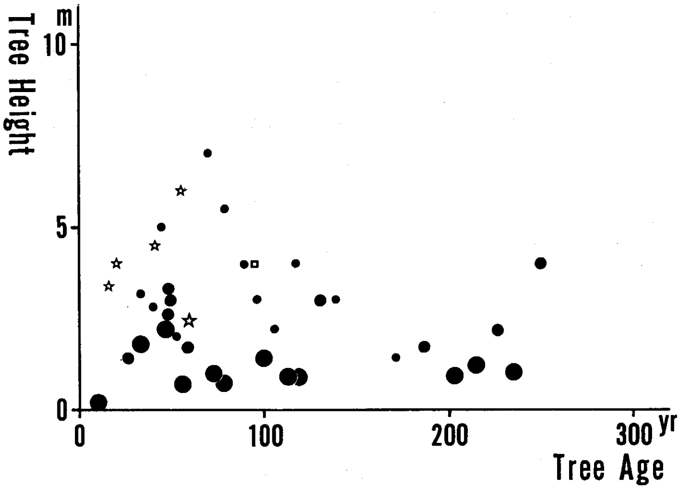

Fig. 12 Same as Fig. 11, but for the Shichitaro Ridge

recognizable (Fig. 12). Yet the level-off condition observed in Group B is extreme. Additionally, *Abies veitchii* belongs to Group A.

Distribution of buried larch seeds in the vicinity of the tree limit

The results are shown in Table 1. The quantity of buried seeds was completely different between Points OA and SA. At SA, approximately 200 to 300 pieces were discovered from the soil of 7500 cc in the plot of 1 meter close by the crown. At OA, however, only a few pieces were found at most. At a distance of 2 meters, these numbers changed to dozens at SA and a few at OA. In the Shichitaro Ridge Series, the numbers at SB were nearly the same as those at SA. At SC, a slightly different tendency was seen both inside and around the crown, but the numbers were almost equal to those at SA and SB at a distance of 2 meters. Basically, therefore, SC was supposed to have a seed bank of similar dimension. At a distance of 3 meters away from the crown, the number of seeds decreased sharply at all points. This fact indicates that seeds will not fly very far away from their mother trees. If this range is defined as the "back ground area", both OA and SA ought to have a back ground area that contains almost the same quantity of

Table 1 Distributoion of buriedseeds of *Larix leptolepis*

Loc.	Alt. (m)	No. of buried seed grains/7500cc Distance from the edge of a crown (m)					No. of seedlings/5m²
		−1	0	1	2	3	
OO	2830					9	0
OA	2810	−	27	4	5	−	1
SA	2710	339	147	295	51	8	1
SB	2650	209	267	65	97	16	1
SC	2550	12	51	60	30	−	3
SD	2460	−	−	−	−	24	11

− : unsurveyed

seeds, although their series and altitude are different. Nevertheless, the quantity of seeds buried in the back ground will obviously increase along with the descent of an altitude, as observed at Points SB and SD within the same Shichitaro Ridge Series.

We counted the number of seedlings per 5 m^2 space. The numbers were very small at OA and SA, but began to increase at SC, and became pretty large at SD. At Points OB, OC, and OD in the Osawa Right Bank Series, where forest crowns are closed, we could not survey the quantity of buried seeds because the litter was thick. Neither could we find a single piece of larch seedlings.

Time series change in the tree-ring width in the vicinity of the tree limit

Fig. 13 shows the secular changes of some tree-ring widths which were put into indices based on the 15-year moving average values. The area below index 1 corresponds to the period of unfavorable growth, and the area above index 1 corresponds to the period of favorable growth. We can observe in these indices some common inequalities. Paying attention to the secular change of 5-year moving average indices in particular, we find that the periods of unfavorable growth include: the latter half of 1960, the latter half of 1940, the middle part of 1920, around 1900, the latter half of 1880, around 1870, the latter half of 1850, the latter half of 1840, around 1820, around 1810, and so on.

4. Discussion

Distribution and structure of the tree limit

To begin with, the Osawa Right Bank Series is reviewed in an orderly way. In the neighborhood of its tree limit (Point OA), the altitude is high, forming a steep slope (about 30 degrees), where the site is unstable and trees cannot stand upright, making it difficult for new seedlings to be established. Their propagation depends solely on layering. The altitude of this limit is almost identical with the lower limit altitude of permafrost estimated by Fujii and Higuchi (1972). Points OB, OC, and OD are located on a steep slope of 27 to 28 degrees, but they maintain a relatively stable soil condition because they are established on a lava flow. As a result, trees are well grown at these points, and the continuous community composed of high silva reaches nearly 2800 meters on the Osawa Right Bank Series. However, as pointed out by Ohsawa *et al.* (1971), *Larix leptolepis* trees are found only in the upper layer of the forest, and their regeneration is exceedingly poor. This is a phenomenon suggesting that *Larix leptolepis* will be replaced by other species such as *Betula ermanii*, and *Tsuga diversifolia* someday in the future.

Regarding the Shichitaro Ridge Series, we can pigeonhole the following properties. At points SA and SB, the volcanic gravel is easy to move and the soil is undeveloped, making it not only impossible for trunks to stand upright but also difficult for new seedlings to be established. Their propagation depends solely on layering. In the vicinity of Point SC, soil stability allows trunks to stand upright, and enables *Abies veitchii* to grow in a patch, which is reportedly unable to prostrate. But here at this point, the

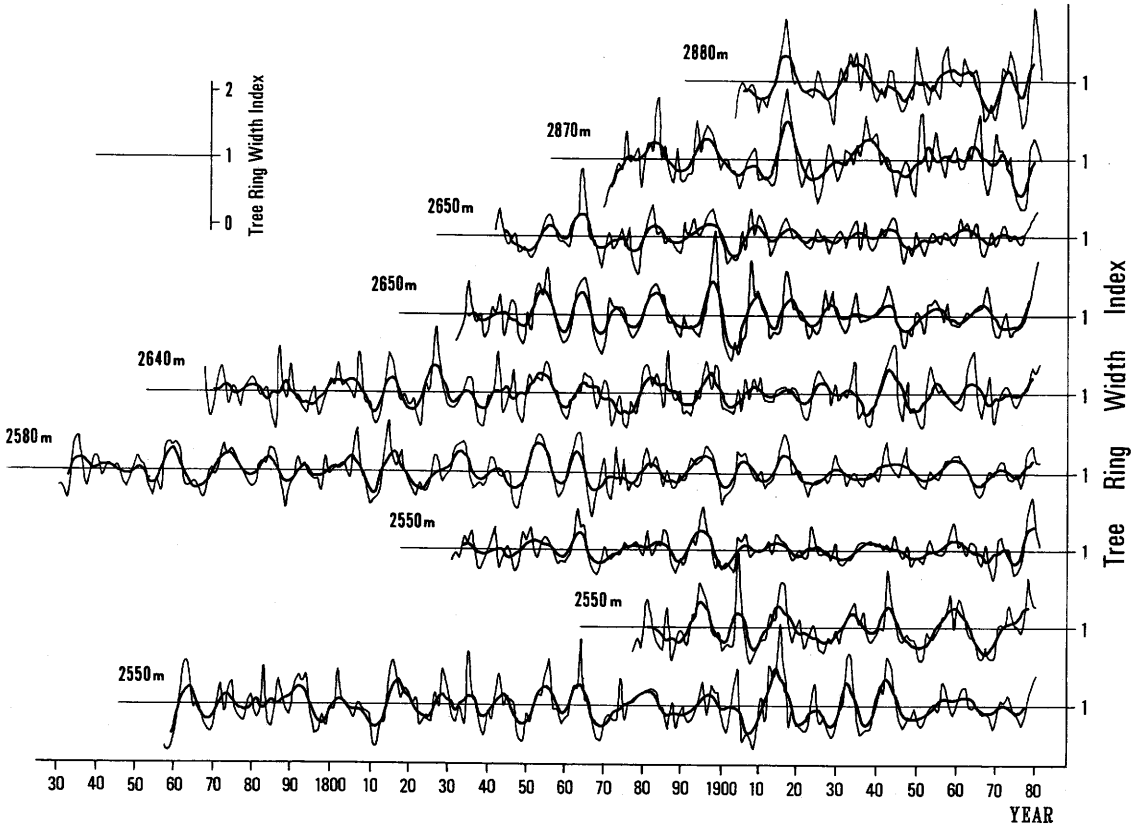

Fig. 13 Secular changes of Tree Ring Width Index on the Osawa right bank
Thick solid lines show 5-year moving average. (after Oka, 1992)

movement of gravel also prevents new seedling from being established. Around the forest limit at Point SD, the regeneration of *Betula ermanii* and *Larix leptolepis* is active, indicating that the soil is stable enough to facilitate the establishment of seedlings. Therefore, along with the stabilization of soil in this series, the limit line will most probably go up. In other words, the relatively low altitude of forest limit in this series is largely attributable to the instability of soil. Inspecting a profile section of soil at this point, we observe the presence of A-horizon containing a root system under a layer of sediments, composed of relatively fresh basaltic gravel with a thickness of about 20 centimeters below the ground surface. This fact leads us to assume that a continuous community might have been developed further upward in this series at one time. This is the reason why the growth of *Abies veitchii* is observed up to 2550 meters. The present island-like structure is assumed to have been caused by the primary or secondary accumulation of eruptive substances occurring thereafter. In the Shichitaro Ridge Series, there has been virtually no accumulation of new eruptives during the last several hundred years' period (Machida, 1964; Miyaji, 1988). So we must assume that the current structure was brought about by the secondary accumulation including the effect of avalanches.

Growth of trees

The extent of growth deriving from the age, height, and diameter of trees shall be reviewed. Changes in tree height observed on the Osawa right bank are characterized by a large discontinuity between the altitudes of 2750 and 2800 meters as well as by a lower tree height with a higher altitude. Inspecting the relationship between tree height and DBH (or diameter at ground level), we find that the growth pattern represented by both factors shows a certain tendency conforming to altitudes. The tendency is quite clear: the growth in thickness is quite conspicuous above the 2800-meter altitude, whereas the growth in elongation becomes dominant below the 2500-meter altitude. This implies that a prevailing growth pattern differs clearly according to altitudes.

Adding the factor of tree age to the above conditions, we can assert that a lower tree height caused by a higher altitude may roughly be regarded as a representation of changes in tree age depending on altitudes. Regarding the discontinuity between the altitudes of 2750 and 2800 meters, however, there is no discontinuity corresponding to this in the changes of tree age. We can affirm, therefore, that this discontinuity tends to be affected most often by current environmental conditions, independent of the changes in tree age.

On the Shichitaro Ridge, tree height as compared with tree age is exceedingly low. Besides, the tree height here tends to change smoothly in step with altitudes. This leads us to expect that a factor suppressing the growth in elongation of trees is more influential in Shichitaro than in Osawa. We must admit the following possibilities at the same time. In the Shichitaro Ridge Series, there are a good deal of variations in the changing pattern of tree age affected by altitudes. In addition, communities are scattered in the form of individual islands, and there exists A-horizon which contains plenty of roots under the surface sediments. Considering these factors together, we can assume the possibility that, as already pointed out in the previous section, communities once established were destroyed by the secondary accumulation of eruptives, and only a modicum of organisms could survive in the sediments. In such a case, original communities must have been well developed in succession, considering the fact that *Abies veitchii* is preserved in a patch up to the 2550-meter altitude. Regarding the Shichitaro Ridge Series, therefore, the object of our analysis will have to include materials that may possibly be buried in the sediments.

Concerning the changes of tree age affected by altitudes, as observed on Osawa right bank, we can make two assumptions: 1) the higher the altitude, the shorter the ecological longevity of *Larix leptolepis*; and 2) the higher the altitude, the later the invasion of *Larix leptolepis*. The first assumption may become no real because there are no withered or damaged trees that ought to co-exist necessarily. Therefore, the changes of tree age affected by altitudes should be regarded as something that primarily indicates a time lag in *Larix leptolepis* trees' invasion period, that is to say, the process of a rise in the altitude of a tree limit. If we view Fig. 9 from this angle, we can figure out that the tree limit must have been continuing to rise at an average speed of 2 meters per year from the altitudes of 2600 to 2900 meters, at least during the period between 250 and 110 years ago, and then ceased to rise at the altitude of 2900 meters, remaining there for the past 110 years. Group B, shown in Fig. 11, is composed of trees whose height will not increase even if their age lengthens. Trees plotted on the extreme right of Figure 9 are exactly those at the greatest age in each altitude zone. In this case, what constitutes the former (Group B) corresponds to the latter (the oldest trees in each altitude). This is suggestive of the fact that trees constituting Group B were something of a frontier which once formed a tree limit and made the forest zone rise. We presume that what corresponds to Group A, which is depicted in the tree age/height scatter diagram, was capable of being established only under the protection of these trees (Group B).

If such a tree limit did actually rise and then cease to rise, then what factors caused it to do so? In order to answer all these questions, we will probably need further evidence of regeneration and more data regarding the history of this location.

Distribution of buried larch seeds

Is the difference in the size of a seed bank between OA and SA attributable to the difference in the quantity of seed supply? Or, is it attributable to the difference of soil conditions receiving the seeds? Currently available data alone are not enough to answer this question. At both OA and SA, seeds are almost uniformly distributed in the back ground more than 3 meters away from crowns. However, a great difference was found close to crowns. So at least it would be reasonable to assert that there is a great difference in the quantity of seeds supplied from mother trees. Behind this assertion, we must admit that there is a difference in environmental conditions symbolized by the difference of altitudes between 2700 and 2800 meters. Within the same Shichitaro Ridge Series, on the other hand, there is an established seed bank whose size remains basically unchanged from its size at 2700 meters, even though the altitude descends to 2650 and 2550 meters. This fact suggests that with the altitude zone of 2700 to 2800 meters as a border, there is a large difference in environmental conditions that affect the productivity of seeds. This altitude zone corresponds exactly to the elevation where the forest limit is located. A forest limit is supposed to involve not only a difference in growth form but also a difference in productivity.

Based on these considerations, we compared the quantity of seedlings between OA and SA, and found that the causes seemed somewhat different, although the quantity was very small in both locations. At OA, seed output itself is poor, which seems to have some bearing on the small quantity of seedlings. At SA, seed output is rich, but seedlings are not established. Why is it difficult for seedlings to be established at SA? Most probably because the movement of scoria is quite active there, causing the location to be extremely unstable. This is also the case with SB and SC, where seedlings are not well established. The quantity of buried seeds and the soil conditions are alike at SB and SC, although their altitudes are different. Therefore, the background situation causing the growth limit of trees is totally different between OA and SA.

If seedling is impossible as a form of propagation even with the presence of seeds, it is inevitable that propagation depends solely on layering. This is the reason that young trees are incapable of expanding their growth territory to higher altitudes *i.e.* a ceiling on the ascent of a tree limit, as observed in both series. In the Osawa Right Bank Series, this ceiling phenomenon has been present for nearly 110 years. It seems that, before then, the tree limit altitude had been ascending and the growth territory expansion had been outstanding.

In those days, seedling was probably the most dominant form of propagation. There might have been a great change in environmental conditions 110 years ago, when the tree limit reached its present ceiling. Was the difference so great as to compel trees to change their system of propagation? Or was the altitude a condition which forced them to change their system? In order to discuss these questions exhaustively, we will have to look into records that contain a longer span of historical data.

Time series change in the tree ring width

Considering the fact that the inequalities in the time series change of the tree-ring width commonly appeared in a certain period regardless of the difference in altitudes, we believe that they were affected by ordinary environmental fluctuations rather than micro-climatic or micro-topographic phenomena. The transitional period, when the tree limit altitude switched from an ascent to a stop as mentioned before, corresponds to the period from around 1870 to around 1880.

In order to reveal the practical factors responsible for the formation of these inequalities, we paid attention to the period after 1933, during which we can make a comparison with the meteorological data of Fuji-san Weather Station (on the summit of Mount Fuji) and Kawaguchi-ko Weather Station (on the base of Mount Fuji). Including the 9 practical examples given in Fig. 13, 15 cases are selected from each altitude zone ranging from 2550 to 2880 meters. Regarding these cases, the secular changes of each tree-ring width index which were laid to overlap are shown in the upper column of Fig. 14. Although there are some periods with dispersion (such as the latter half of 1930), this graph is acceptable because it includes nearly all periods showing both minimum and maximum indices. The mean values of these indices are shown in the middle column of Fig. 14. Comparing these values with the years characterized by a cool summer, we find

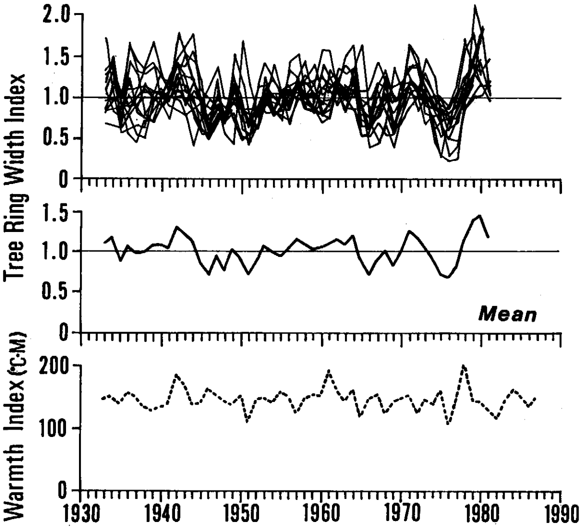

Fig. 14 Secular changes of Tree Ring Width Index and Warmth Index upper: overlapping the 15 samples of TRWI, middle: mean of the 15 samples, bottom: Warmth Index corresponding to 2800-meter altitude (after Oka, 1992)

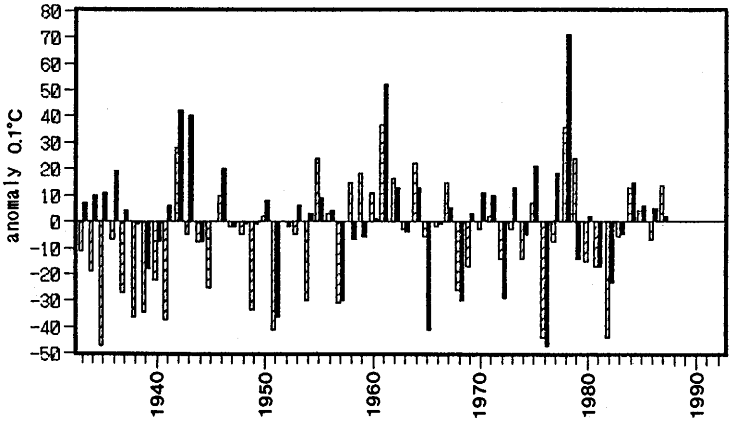

Fig. 15 Interannual variations of temperature anomalies in summer (June-Sept.) at Mount Fuji (black) and Lake Kawaguchi (hatch)

that there are both years of favorable growth (such as 1980, 1971, and 1964) and of unfavorable growth (such as 1976, 1969, and 1966). These disparities may have resulted not only from the variety of growth-controlled factors but also from a difference in the scales (a vertical extent, in particular) of phenomena causing a cool summer.

Fig. 15 shows the secular changes of temperature anomalies in summer (June-Sept.) at the summit station (35°21′N, 138°44′E, 3772 m.a.s.l.) and the base station (35°30′N, 138°46′E, 860 m.a.s.l.) of Mount Fuji from each of normal temperature (1951-1980). The directions of the anomalies at both stations are not always the same, as indicated by opposite ones in 1973, 1977, 1979, 1980, and so on. In these years, the disparity is also observed between the upper air and the ground surface air temperature based on the aerological data from Tateno station (36°03′N, 140°08′E) (Fig. 16). In 1977 and 1980, for instance, despite the extremely low ground surface air temperature, 700 mb surface air temperature is not so much lower than the normal value (1961-1980). In 1973 and 1979, despite high ground surface temperatures, the upper air temperature was not so high. On the other hand, in the cool summer of 1976 and the hot summer of 1978, both upper and ground surface air temperatures based on the aerological data of Tateno show the same tendency as the summit and base of Mount Fuji. Therefore, the temperatures of both summit and the base of Mount Fuji have not always behaved locally; the disparity between them may be due to the vertical fluctuation of cold air causing cool summers. Comparatively stable upper air temperature depends entirely upon the July and August temperatures according to the vertical profiles of their standard deviations from 1961 to 1980 (Fig. 16).

The temperature at an elevation corresponding to 2800 meters on the northwestern slope of Mount Fuji was estimated from the temperatures of summit and base of Mount Fuji (Fig. 17). The mean value of Warmth Index (WI) (Kira, 1971) calculated from these estimated temperatures, which rise more than 5°C from June through September, is 14.9°C·M, less than the value of 17.7°C·M obtained by Aoyama and Oka's method (Aoyama and Oka, 1989). The relationship between the time series change of the thermal condition, including the WI value and temperatures in June, July, August, and September at 2800-meter level, and the secular change of TRWI (Tree Ring Width Index) was examined. For the examination, average indices of 15 cases based on 15-year and 31-year moving averages and average indices of 3 cases which are more than 200 yrs. old were adopted. The results of comparison are shown in Table 2. Values

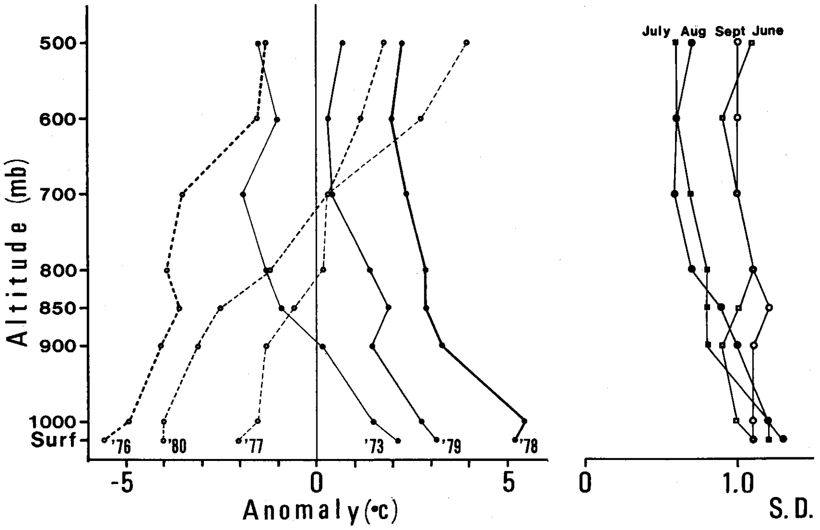

Fig. 16 Anomalies and standard deviations of summer (June-Sept.) temperature at Tateno normal value: 1961-1980

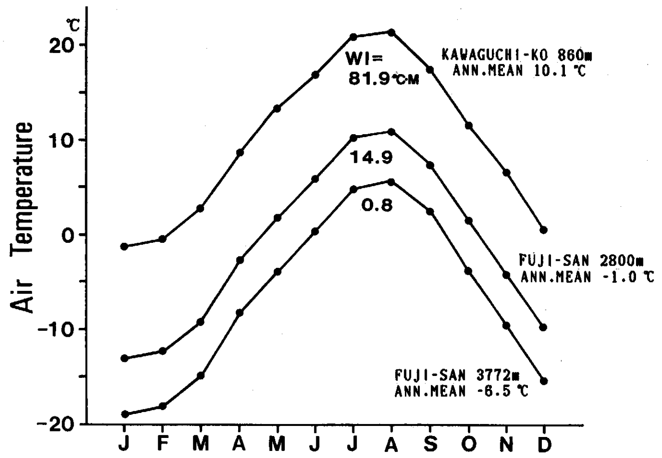

Fig. 17 Estimated temperature at 2800-meter altitude on the northwestern slope of Mount Fuji based on the temperatures of its summit and base

Table 2 Correlation coefficient between Tree Ring Width Indices and Temperatures (after Oka, 1992)

		June	July	Aug.	Sept.	Wl
15yr	A(15)	0.1670	0.1993	0.1256	0.2214	0.3264*
	B(3)	0.1689	0.1982	0.0824	0.1486	0.2652
31yr	A(15)	0.1231	0.2340	0.0806	0.2194	0.2842
	B(3)	0.0954	0.3197*	0.0721	0.2150	0.3548*

* : significant at 0.05 lebel

that had a significant correlation at the 5 % level include: WI and TRWI denoting the average of 15 cases based on the 15-year moving averages; WI and the mean temperature of July and TRWI denoting the average of 3 cases based on the 31-year moving averages. The secular changes of this 15-case average WI are shown in the lower column of Fig. 14. Except for some instances where the position of inequalities shows a little deviation, TRWI and WI can be seen to have a pretty good relation to each other intuitively.

By the way, how are snow cover conditions related to thermal ones? Fig. 18 shows how the snow melts away on the mountaintop from May through July in terms of the large and small values of WI after 1965. A clear-cut distinction arises depending on whether the WI value is large or small. In the case of a high index, even the deepest snow cover is normally less than 2 meters thick and disappears by mid-June. In the case of a low index, on the other hand, the deepest snow cover sometimes reaches 3 meters thick and will not melt away completely until early July. However, there are some exceptions to this. In 1965, for example, it snowed lightly and the thaw occurred earlier than usual, yet the temperature was low in summer. On Mount Fuji, snow tends to fall heavily when a low passing along south coast of Japan develops rather than when the northwesterly monsoon blows. Therefore, a deep snow cover at least will not occur in a severe winter. As suggested by Yamakawa (1989), a winter-type pressure pattern was not necessarily

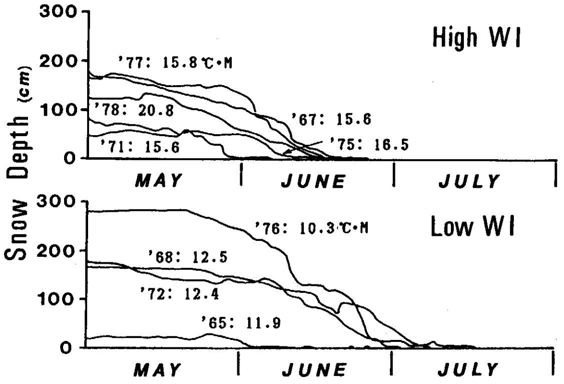

Fig. 18 Changes of snow depth on the summit of Mount Fuji from May through July in terms of the large and small values of WI after 1965 (after Oka, 1992)

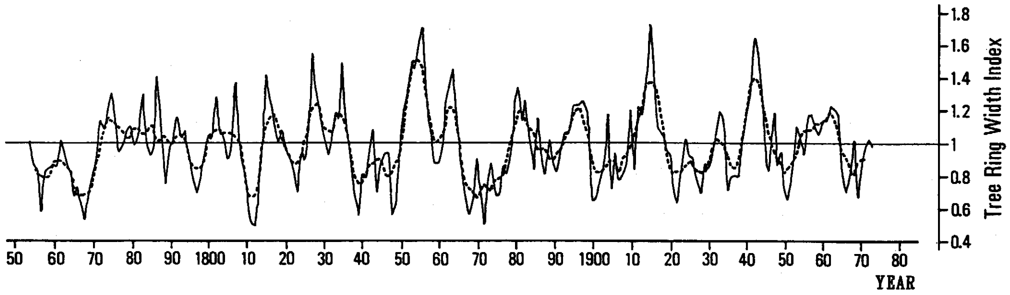

Fig. 19 Secular changes of TRWI of *Larix leptolepis* on the western slope of Mount Fuji solid line: average index of 3 samples whose annual rings are more than 200 years old; broken line: 5-year moving average of this average index (after Oka, 1992)

prevailing (namely, it was not a severe winter) during the cold period (1906-1920). Consequently, a cool summer tends to be followed by a winter with heavy snowfall on Mount Fuji.

Fig. 19 shows the average index of three samples whose tree rings are more than 200 years old. In this case, the indices were standardized on the basis of a 31-year moving average, so as not to cancel a relatively long cycle of fluctuations. As is evident from Table 2, these indices are closely related to WI. Reviewing the overall secular change of these indices, we can grasp a certain characteristic tendency. With the time around 1880 as a turning point, a disparity can be seen in the magnitude of minimum values of the periods before and after that time. Indices below 0.6 do not appear after 1880, but they do appear frequently before then. With thermal conditions being added to this secular change of indices, we can understand that an exceedingly low temperature occurred during the summer seasons before 1880. Around 1870, 1840 and 1810, in particular, the temperature went to the lowest extremes. According to Fig. 18, moreover, there was probably a large volume of unmelted snow in these periods.

In addition, a more important phenomenon is perceptible. These periods characterized by a frequent occurrence of smaller indices correspond to the time when the tree limit altitude was ascending. At least by the time these specific periods came to an end, the tree limit must have reached its present 2900-meter altitude. We postulate the following: the tree limit altitude was ascending during the period when low temperatures occurred frequently in summer, that is to say, when the absolute value of index often diminishes; the tree limit altitude ceased to ascend during the period when moderate temperature prevailed, that is, when the index fluctuates rather moderately.

Consideration of climatic causes of fluctuations in tree limit altitudes

The change of tree ages affected by altitudes in the Osawa Right Bank Series implies that the time of larch invasion varied according to altitudes. Larches invaded the altitude of 2900 meters nearly 110 years ago and have been remaining there ever since. This indicates that the tree limit altitude had been rising continuously before that time and then about 110 years ago ceased to rise. Without exception, old trees in each altitude zone are exceedingly short and they should play a pioneer role in the formation of a tree limit.

Regarding the factors causing fluctuations in a tree limit, there are possibilities that the standstill of a limit at an altitude of 2900 meters is not only caused by climatic change but also affected by soil stabilization and climatic growth limit. The Osawa Right Bank Series has less restrictions in soil condition, and therefore the forest vegetation is developed up to an altitude of 2900 meters which is equivalent to WI 15°C·M in terms of thermal condition. Additionally, a large discontinuity in tree height is recognizable at an altitude of 2800 meters. This discontinuity represents the growth limit of tall trees, that is, the forest limit. The discontinuity does not appear in the distribution of tree ages and therefore seems to be affected by environmental conditions. These facts lead us to assert that both tree and forest limits in the Osawa Right Bank Series are the result of a climatic growth limit being reached.

Seedling was active below the altitude of 2600 meters, and barely perceptible up to 2800 meters, but no seedling was observed at 2900 meters. This fact also leads us to assert that, with the 2900-meter altitude as a growth limit, larches are maintaining an equilibrium in the current climatic environment. If this assertion is true, then tree limits at lower altitudes on other slopes must be still increasing their altitude today. If on the contrary, the ceiling of tree limits is prevailing on other slopes since nearly 110 years ago in the same way as observed in Osawa, then undoubtedly more extensive environmental changes have a lot to do with the fluctuations of tree limit altitudes.

The changes of tree age at different altitudes are shown, utilizing the data on age of larches (Saito, 1971) observed around the forest limit all over Mount Fuji. Fig. 20 depicts only those located in the neighborhood of the tree limit. Here we notice an interesting tendency. The ages of trees constituting the tree limit vary widely below the 2600-meter altitude, whereas they concentrate in two age groups, *i.e.* 51-100 and 101-150 years old, above that altitude (attention: this information was obtained about 20 years ago). These data suggest that a tree limit reaching altitudes of 2700 to 2800 meters was formed during the period from 70 to 170 years ago and at that altitude the tree limit stopped ascending. According to the results of the author's tentative survey conducted on

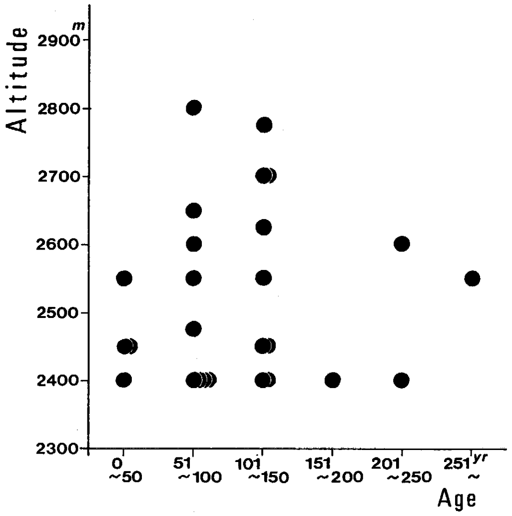

Fig. 20 Changes of tree age at different altitudes on Mount Fuji
These data are quoted from Saito (1971).

the right bank of Busseki Nagashi which lies between Osawa and Shichitaro, the maximum age near the tree limit was 120 years old at an altitude of 2650 meters and then dropped sharply to 40 or 50 years old at 2685 meters. This fact demonstrates that the example in Osawa, which are based on more detailed information, are not exceptional cases at all. Consequently, there arises a greater possibility that fluctuations in tree limit altitudes can be caused by more extensive environmental changes.

As already pointed out, larches grow sporadically around 2900 meters, although their seedlings do not tend to occur there. This suggests that the system of seedling must have been guaranteed when the larch invaded this area as a pioneer, and, thereafter, a change in environmental conditions, which compelled larches to change their system of propagation, must have been present. Then, what change did occur after these larches were established around the altitude of 2900 meters?

As already stated in the previous section, the latter half of the 19th century, when larch seedling was established at an altitude of 2900 meters, was a transitional epoch in terms of the secular change of Tree-Ring Width Indices. With the time around 1880 as a turning point, there were specific periods of low growth (periods distinctly characterized by the lowering of temperatures) before then, but such periods did not arise so conspicuously after that time. The epoch comprising low growth periods, that is, low temperature periods, corresponds to the epoch when the establishment of larches was increasing and the altitude of tree limits was rising. The low temperature periods provided an advantageous condition for larch seedlings to accomplish their establishment.

What are the implications of this phenomenon? According to the meteorological data, we find that low temperatures in summer are more or less connected with the extension of a snow cover period. The unmelted snow remaining in early July on this mountaintop can be regarded as a factor that promotes the establishment of seedlings by preserving a more humid environment during the period of seedling. These circumstances must have been more prevalent in the low temperature periods before 1880. Seeds remain under an exceedingly desiccated condition during their hibernation. Without water supply, they cannot grow even if sunshine and temperature conditions are satisfactory. It is conceivable that, under the dry soil conditions of Mount Fuji, the low temperature accompanying the remaining snow could guarantee a supply of water necessary for germination and seedling, thereby creating a favorable environment that promotes soil stabilization.

In order to figure out these trends, we will have to not only make a detailed study concerning both merits and demerits of the snow cover and low temperature for the growth of larches but also more firmly support our interpretation regarding the secular change of TRWI. In addition, an intensive survey will have to be conducted on other slopes using the same method as on the western and northwestern slopes. Including the possibility that the ascent of the tree limit until nearly 110 years ago had no immediate relation to climatic factors, further investigations remain to be done.

5. Conclusion

The tree limit on Mount Fuji ranges from 1400 to 2900 meters, depending on the slope. The Osawa right bank on the western slope has fewer restrictions of soil conditions and therefore allows forest vegetation to reach a high altitude (around the WI15 altitude) in terms of the Warmth Index value. The tree height (community height) on the Osawa right bank shortens as the altitude increases, creating a large discontinuity around the 2800-meter altitude. This is exactly the growth limit of tall trees, that is, the forest limit. From these phenomena, we may conclude that forest vegetation can be established up to a reasonable altitude, if the elevation of a mountain is high enough. We also notice that, at this reasonable altitude, trees composing the forest tend to get shorter, as they are affected by environmental factors, even though there are no creeping pine growing there.

Concerning the altitudinal change of tree ages, it is clear that the maximum age in particular decreases as the altitude increases. This relationship suggests the history of forest establishment, depicting the process of tree limit ascension. On the Osawa right bank, the tree limit attained the 2900-meter altitude nearly 110 years ago, and has remained there ever since. The factors causing this were investigated on using data from the secular change of tree ring width. As a result of this investigation, it is concluded that the time period during which a tree limit ascends is identical to the time period during which low-growth periods occur frequently. Considering that thermal conditions have some bearing on tree ring width, it is probable that tree limit ascension occurs in the time period during which low-temperature periods frequently occur. Based on this probability, it may be assumed that a supply of water accompanied by the extension of a snowfall season during the low-temperature period was a favorable condition for the establishment of seedlings, which defines the ascent of a tree limit.

Subjects for a future study are as follows.

1) The tree limit of Mount Fuji is composed mainly of *Larix leptolepis* with physiognomical similarity to *Pinus pumila*. This feature of the tree limit of Mount Fuji should be investigated by examining the homogeneity and heterogeneity between "elfinwood" and "krummholz" (Holtmeier, 1981) that comprise the transitional zone included in the forest limit zone.

2) In the process of forest development, the larch's growth territory expands in the time period during which low-temperature periods frequently occur. This appears to be a contradiction. In order to solve this problem, future studies should consider the secular change of tree-ring width, including a standardization method and a comparison with a standard curve thereby produced, as well as evaluating of the effects on seedling of low-temperature conditions and adequate soil moisture conditions brought about by the extension of the snow cover period.

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