Development of Relative Stem-taper Curves for Sugi (Cryptomeria japonica D. Don) Plantation in Kagoshima Prefecture, Southwestern Japan

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ABSTRACT

The primary interest of forest owners is the amount of income that will be derived from forest operations. Before cutting operations are carried out, the quality and quantity of the wood yield need to be estimated as accurately as possible. To calculate the profit from a future cutting operation, the upper diameters (example of 4-m above the ground) of the stems of trees in the stand need to be estimated. The aim of this study was to estimate these diameters by applying a relative stem taper curve. The equation was developed based on diameter at breast height (DBH) data in order to eliminate the effect of root spread. The curve equation is a third-order polynomial based on data from 571 sugi (Cryptomeria japonica D. Don) trees measured between 1996 and 2004; the equation fit the data well ($R^2>0.99$). There are more than 60 local varieties of sugi, and relative stem taper curve equations were developed for 8 of these varieties. By applying the relative stem taper curves, forest managers can estimate the upper stem diameter and log yield before cutting trees.

Keywords: diameter at breast height (DBH), log yield, relative stem taper curve, sugi (Cryptomeria japonica D. Don), upper diameter estimation

INTRODUCTION

Japan has agreed to meet a target of the absorption of 13 Mt of CO$_2$ through forest carbon sinks during the first 5-year commitment period (2008-2012) of the Kyoto Protocol. Tree cutting is an important part of meeting this goal, and cutting operations will be implemented in 550,000 ha every year for 6 years (2007-2012), for a total of 3.3 million ha (Forest Agency of Japan, 2009).

The Forest Agency of Japan (2009) reported that many forest owners are not promoting appropriate forest improvement, such as cutting, because of a decline in wood prices. Most forest contractors generally wait to be asked to conduct forest operations by forest owners. In recent years, to promote forest operations such as cutting, the Forest Agency of Japan (2009) has enacted measures that will integrate forestry operations from a proactive approach, in an effort to remind forest owners of the importance of cutting and cutting operations. As part of these measures, forest operation plans are devised and contain current status photos of the forest, estimated costs of the proposed forest operations, and estimated total sales of timber yielded by the proposed forest operations.

With regard to these measures, the primary interest of forest owners is the amount of income that will be derived from forest operations. Thus, before cutting operations are carried out, the quality and quantity of the wood yield need to be estimated as accurately as possible.

The stem volume in a target forest stand can be estimated using our previously developed yield table (Nagahama and Kondoh, 2006a, b). In the Japanese wood auction market, however, price is assigned based on the diameter of the smaller end and stem length, not stem volume. Thus, to calculate the profit from a future cutting operation, the upper diameters (example of 4-m above the ground) of the stems of trees in the stand need to be estimated. At present, before a cutting operation, the upper diameter is visually estimated by the person in charge of surveying all trees to be felled.

For an accurate assessment of a future yield of a cutting operation, (1) a relative stem taper curve is developed for each species, (2) the relative stem taper curve is applied to produce stem taper tables, and (3) these tables are used to calculate the number of logs yielded for each stem length and each smaller-end diameter class. However, few studies of the relative stem taper or stem form have been conducted recently in Japan (Inoue, 2001; Inoue and Kurokawa, 2001), although such studies were actively conducted in previous decades (Kajihara, 1972, 1973a, 1973b, 1974, 1978, 1983, 1984a, 1984b,
1984c, 1985, 1987a, 1987b, 1987c; Osumi, 1959; Ueno, 1978, 1983). Consequently, stem taper tables are rarely used in stem yield surveys in Japan (Fujimoto et al., 1996; Inoue, 2001; Kajihara, 1988, 1992; Kajihara et al., 1996; Tomita et al., 1991; Yokoi, 2004).

The aim of this study was to develop relative stem taper curves that can be used to estimate the ultimate diameters of trees to be felled. We focus on sugi (Cryptomeria japonica D. Don), an important plantation tree species in Japan, at an appropriate stand age for cutting. There are more than 60 local varieties of sugi (Miyajima, 1989). We developed relative stem taper curves for 8 local varieties of sugi based on wood quality survey data from Kagoshima Prefecture, southwestern Japan.

**MATERIALS AND METHODS**

We used the data gathered during a wood quality survey conducted from 1996 to 2004 at progeny test plantations in Kagoshima Prefecture. The purpose of the survey was to assess the wood quality of clones of elite trees of selected local varieties and to gather fundamental wood quality data with regard to the wood's suitability as construction material. The following eight local varieties were planted as rooted cutting of sugi adapted in Kagoshima Prefecture in 1970’s: Measa, Obiaka, Tanoaka, Tosaaka, Haara, Hiki, Kijin, and Yabukuguri.

In our study, the data of the eight local varieties of sugi was analyzed. The survey method followed that described in the Guideline of Wood Quality Survey on Progeny Test Plantations (Forest Tree Breeding Center, 1996). An outline of the survey and maps of the study area are presented in Table 1 and Fig. 1, respectively.

The wood quality survey was conducted in mature experimental plots of sugi of stand age >25 years. Three trees per clone were surveyed, such that the number surveyed in each plot was three times the number of clones. The local variety of each tree was noted. The diameter at 0.2 m above the ground and diameter at breast height (DBH; generally set at 1.2 m above the ground in Japan) were measured.

After the surveyed trees were felled, diameter was measured each with a distance of 2 m between the stem above the DBH position (i.e. at a height of 3.2 m, 5.2 m, 7.2 m ...). In addition, tree height was measured to the nearest 0.1 m.

In total, 571 mature sugi trees were surveyed and 4253 diameters were measured. In each survey year, data were measured in the same experimental plot and the stand age was uniform across each plot (Table 1). In order to compare the growth of tree height and DBH among the local varieties in each survey year, a Kruskal-Wallis test was conducted.

As previously mentioned, evaluation of upper diameter on stem was aimed mainly in this study. We developed a relative stem taper curve (Behre, 1923) for sugi based on the survey measurements of DBH. Osumi (1959) reported that a third-order polynomial provided an appropriate fit for the relative stem taper curve of sugi. Based on the survey data, we developed a third-order polynomial for the relative stem taper curve:

\[ y = ax^2 + bx + c \]  

(1)

where \( x \) is the relative stem length and \( y \) is the ratio of the diameter in position of relative stem length \( x \) from tree top to DBH, and \( a \), \( b \) and \( c \) are regression coefficients. Thus, a third-order polynomial was applied to the curve in this study. To validate the accuracy of the relative stem taper curve developed in this study, wood quality survey data from 2006 and 2007 were analyzed (138 trees surveyed and 1089 diameters measured). Only six local varieties were surveyed in 2006 and 2007 (Measa, Tanoaka, Tosaaka, Haara, Hiki, and Yabukuguri).

In addition, we analyzed the residual error between the actual diameter and the diameter estimated based on the relative stem taper curve. Logs with a diameter at the smaller end of 14-18 cm and a length >3 m are traded at a relatively high price, as these are the optimal size for timber column material in the Japanese timber market. Therefore, we also performed a similar analysis of the residual error for upper diameters >14 cm.

In this study, the goodness of fit of the relative stem taper curves was analyzed using OriginPro 8J SR2 (OriginLab Co., Northampton, MA, USA), and statistical analysis was performed using SPSS ver. 17 (SPSS Inc., Chicago, IL, USA).

**RESULTS**

Differences in Height and DBH Growth among Local Varieties

The Kruskal-Wallis test revealed significant differences in height growth among local varieties of sugi in 1996, 1997, 1998, 2001, 2002, and 2003 (p<0.05). With regard to DBH growth, significant differences were found in 1996, 1997, 1999, 2000, 2001, 2002 (p<0.05) (Table 1).

Development of Relative Stem Taper Curve

Table 2 was listed on regression coefficient for each relative stem taper curve and the adjusted coefficient of determination (adjusted \( R^2 \)) respectively. Fig. 2 illustrates the relative stem taper curve and the stem form for all sugi trees surveyed, as well as the curves and stem forms. A relative length value of 1.0 corresponds to the DBH position (1.2 m). The adjusted coefficient of determination was >0.99 (Table 2).

Validating the Accuracy of the Relative Stem Taper Curves

We analyzed the residual errors between diameters measured in 2006 and 2007 and those estimated using the relative stem taper curve equations. The numbers of diameters measured, average residual error, standard deviations, and two-sided 95% confidence intervals are listed in Table 3. The narrower the confidence interval, the more precise is the estimate of population parameters (Sokal and Rohlf, 1987). For all sugi trees measured in 2006 and 2007, the average residual error was 0.0 mm and the two-sided 95% confidence interval was 0.5 mm.

Because logs with a diameter of 14-18 cm at the smaller end and length >3 m are traded at a relatively high price, we also analyzed the residual error for trees with upper diameter >14 cm. For the 474 diameters meeting this criterion in 2006
Table 1  Outline of survey data

| Survey year | Watershed area | No. of trees analyzed | Forest age (years) | Local variety | Mean tree height (m) | Standard deviation of tree height (m) | Mean diameter at breast height (cm) | Standard deviation of breast height diameter (cm) | Test statistic of Kruskal-Wallis test of mean tree height | Test statistic of Kruskal-Wallis test of mean diameter at breast height |
|-------------|----------------|-----------------------|-------------------|---------------|---------------------|--------------------------------------|-------------------------------|---------------------------------------------------|--------------------------------------------------|---------------------------------------------------|
| 1996        | Hokkatsu       | 72                    | 26                | Sugi (all analyzed trees) | 15.6             | 2.7                  | 19.0                             | 3.4                                           | 20.151*                                          | 18.481**                                          |
|             |                |                       |                   | Tanoaka        | 13.4              | 2.3                  | 18.7                             | 3.3                                           | 14.231**                                         | 14.100**                                         |
|             |                |                       |                   | Tosaaka        | 15.7              | 1.7                  | 19.5                             | 2.6                                           |                                                  |                                                  |
|             |                |                       |                   | Haara          | 16.3              | 2.8                  | 18.4                             | 3.4                                           |                                                  |                                                  |
|             |                |                       |                   | Kijin          | 13.2              | 2.6                  | 15.4                             | 2.7                                           |                                                  |                                                  |
|             |                |                       |                   | Basabuguri     | 18.4              | 2.4                  | 22.0                             | 2.8                                           |                                                  |                                                  |
| 1997        | Aira           | 54                    | 26                | Sugi (all analyzed trees) | 16.3             | 1.9                  | 19.7                             | 3.2                                           |                                                  |                                                  |
|             |                |                       |                   | Obika          | 17.3              | 1.4                  | 22.0                             | 2.7                                           |                                                  |                                                  |
|             |                |                       |                   | Tanoaka        | 16.3              | 1.5                  | 19.3                             | 1.7                                           |                                                  |                                                  |
|             |                |                       |                   | Haara          | 16.2              | 1.8                  | 19.1                             | 3.0                                           |                                                  |                                                  |
|             |                |                       |                   | Kijin          | 14.3              | 1.9                  | 16.6                             | 2.7                                           |                                                  |                                                  |
| 1998        | Nansatsu       | 72                    | 26                | Sugi (all analyzed trees) | 11.5             | 2.7                  | 13.5                             | 2.8                                           |                                                  |                                                  |
|             |                |                       |                   | Mesua          | 11.8              | 2.3                  | 14.7                             | 2.3                                           |                                                  |                                                  |
|             |                |                       |                   | Tosaaka        | 9.5               | 2.5                  | 14.3                             | 2.9                                           |                                                  |                                                  |
|             |                |                       |                   | Haara          | 11.3              | 2.7                  | 15.3                             | 3.2                                           |                                                  |                                                  |
|             |                |                       |                   | Kijin          | 13.2              | 2.8                  | 16.2                             | 3.0                                           |                                                  |                                                  |
| 1999        | Nansatsu       | 67                    | 26                | Sugi (all analyzed trees) | 12.0             | 1.8                  | 17.7                             | 3.5                                           |                                                  |                                                  |
|             |                |                       |                   | Mesua          | 12.1              | 1.6                  | 18.1                             | 2.7                                           |                                                  |                                                  |
|             |                |                       |                   | Obika          | 13.5              | 1.7                  | 20.8                             | 3.9                                           |                                                  |                                                  |
|             |                |                       |                   | Tosaaka        | 12.4              | 2.0                  | 19.7                             | 4.0                                           |                                                  |                                                  |
|             |                |                       |                   | Haara          | 11.4              | 1.5                  | 15.5                             | 2.9                                           |                                                  |                                                  |
| 2000        | Osumi          | 63                    | 30                | Sugi (all analyzed trees) | 14.9             | 2.1                  | 23.7                             | 3.6                                           |                                                  |                                                  |
|             |                |                       |                   | Tanoaka        | 15.6              | 1.2                  | 26.1                             | 2.6                                           |                                                  |                                                  |
|             |                |                       |                   | Tosaaka        | 15.5              | 2.0                  | 25.3                             | 1.4                                           | 7.314                                            | 24.161***                                         |
|             |                |                       |                   | Haara          | 16.4              | 1.6                  | 27.4                             | 3.0                                           |                                                  |                                                  |
|             |                |                       |                   | Kijin          | 14.1              | 1.5                  | 23.1                             | 3.1                                           |                                                  |                                                  |
|             |                |                       |                   | Basabuguri     | 14.2              | 2.1                  | 17.5                             | 1.7                                           |                                                  |                                                  |
| 2001        | Aira           | 72                    | 25                | Sugi (all analyzed trees) | 15.7             | 1.7                  | 21.0                             | 3.1                                           |                                                  |                                                  |
|             |                |                       |                   | Mesua          | 14.9              | 0.6                  | 20.0                             | 2.4                                           |                                                  |                                                  |
|             |                |                       |                   | Obika          | 17.6              | 0.8                  | 21.8                             | 2.8                                           |                                                  |                                                  |
|             |                |                       |                   | Tosaaka        | 16.8              | 0.6                  | 22.8                             | 2.0                                           |                                                  |                                                  |
|             |                |                       |                   | Haara          | 15.9              | 1.2                  | 22.7                             | 2.2                                           |                                                  |                                                  |
|             |                |                       |                   | Hiki           | 14.2              | 1.7                  | 18.3                             | 2.7                                           |                                                  |                                                  |
| 2002        | Aira           | 72                    | 25                | Sugi (all analyzed trees) | 15.7             | 1.6                  | 19.3                             | 2.0                                           |                                                  |                                                  |
|             |                |                       |                   | Mesua          | 15.7              | 1.0                  | 19.8                             | 1.6                                           |                                                  |                                                  |
|             |                |                       |                   | Obika          | 14.6              | 1.1                  | 19.4                             | 1.6                                           | 9.541*                                           | 9.829*                                           |
|             |                |                       |                   | Tosaaka        | 16.1              | 1.6                  | 17.8                             | 1.8                                           |                                                  |                                                  |
|             |                |                       |                   | Haara          | 16.6              | 0.9                  | 20.3                             | 0.7                                           |                                                  |                                                  |
| 2003        | Aira           | 48                    | 32                | Sugi (all analyzed trees) | 17.6             | 1.6                  | 20.3                             | 1.8                                           |                                                  |                                                  |
|             |                |                       |                   | Obika          | 18.2              | 1.8                  | 21.0                             | 2.3                                           | 10.718*                                          | 5.373                                           |
|             |                |                       |                   | Tosaaka        | 16.3              | 1.2                  | 19.2                             | 1.6                                           |                                                  |                                                  |
|             |                |                       |                   | Haara          | 18.1              | 1.4                  | 20.6                             | 1.7                                           |                                                  |                                                  |
| 2004        | Osumi          | 51                    | 31                | Sugi (all analyzed trees) | 18.8             | 2.3                  | 25.1                             | 3.3                                           |                                                  |                                                  |
|             |                |                       |                   | Mesua          | 18.7              | 2.5                  | 24.0                             | 5.8                                           | 3.189                                            | 5.520                                           |
|             |                |                       |                   | Tosaaka        | 20.3              | 2.5                  | 28.3                             | 5.8                                           |                                                  |                                                  |
|             |                |                       |                   | Haara          | 19.6              | 1.8                  | 27.5                             | 4.0                                           |                                                  |                                                  |
|             |                |                       |                   | Hiki           | 18.4              | 1.6                  | 23.5                             | 3.4                                           |                                                  |                                                  |

Significance level means ‘***’; \( p < 0.001 \), ‘**’; \( p < 0.01 \), ‘*’; \( p < 0.05 \)

and 2007, the average residual error was 0.3 mm and the two-sided 95% confidence interval was 0.8 mm.

For the six local varieties, we performed separate residual error analyses by comparing the diameters measured in 2006 and 2007 with the relative stem taper curve for all sugi trees (middle columns in Table 3), as well as with the stem taper curve developed for each local variety (rightmost columns in Table 3). In the case of Mesua, the sugi curve provided a better fit (i.e., a narrower two-sided 95% confidence interval) than the Mesua curve for all diameters, whereas the opposite was found when analyzing only those diameters >14 cm. For the varieties Tanoaka, Tosaaka, and Haara, the two-sided 95% confidence intervals were the same for the sugi curve and the individual variety’s curve for all diameters and only those diameters >14 cm. In the case of Hiki, the sugi curve provided a better fit than the Hiki curve for all diameters and for only those diameters >14 cm. For the local variety Yabukuguri, the Yabukuguri curve provided a better fit than the sugi curve for all diameters, whereas the opposite was found for diameters >14 cm.

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Fig. 1 (a) Map of the Japanese archipelago. The patchwork on Honshu (the largest island) shows the distribution of administrative prefectures and the Kyushu District. (b) The study area of Kagoshima Prefecture within the Kyushu District. (c) The five watershed areas in the study area.

Table 2  Regression coefficient of relative stem taper curve ($y = ax^3 + bx^2 + cx$) and the adjusted coefficient of determination (adjusted $R^2$)

| Local varieties       | Regression coefficient of relative stem taper curve | Adjusted coefficient of determination (Adjusted $R^2$) |
|-----------------------|-----------------------------------------------|---------------------------------------------------|
| Sugi (all surveyed trees) | 0.4585, -0.9764, 1.0168 | 0.9972                                           |
| Measa                 | 0.3390, -0.7833, 0.9438 | 0.9977                                           |
| Obiaka                | 0.4692, -0.9520, 0.9905 | 0.9971                                           |
| Tonoaka               | 0.4491, -0.9598, 1.0053 | 0.9970                                           |
| Tosaaka               | 0.4184, -0.9094, 0.9861 | 0.9973                                           |
| Haara                 | 0.5923, -1.1744, 1.0810 | 0.9979                                           |
| Hiki                  | 0.4039, -0.9154, 1.0089 | 0.9971                                           |
| Kijin                 | 0.5059, -1.0792, 1.0743 | 0.9984                                           |
| Yabukuguri            | 0.7174, -1.4191, 1.2923 | 0.9984                                           |
Fig. 2  Measured diameter data and relative stem taper curves for sugi (all measured trees) and for eight local varieties: Measa, Obiaka, Tanoaka, Tosaaka, Haara, Hiki, Kijin, and Yabukuguri. In each graph, the tree end is represented by the point of origin, the x-axis shows relative stem length, and the y-axis shows the relative radius calculated from the diameter measured on felled trees. In each equation, \( x \) is the relative stem length and \( y \) is the ratio of the diameter in position of relative stem length \( x \) from tree top to DBH.

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DISCUSSION

Differences in Height and DBH Growth among Local Varieties

In this study, height and DBH growth differed significantly among local sugi varieties in six of the survey years. Miyajima (1989) identified more than 60 local varieties of sugi in Kyushu District, Japan, according to characters such as leaf morphology. To achieve forest management objectives, Okada (1984) noted that sugi varieties are selected based on larger tree growth increment, disease resistance, and better wood quality. Because we found significant differences in height and DBH growth, the stem forms of the surveyed local varieties likely also differed.

Relative Stem Taper Curves

This aim of this study was to develop equations that would allow the estimation of upper diameter of sugi stems based on measurements that can be made at ground level. Following Behre (1923), our relative stem taper curves were based on DBH and trunk height from the breast height position. Kajiwara (1972) and Osumi (1987) noted several problems with stem taper curves based on the method of Behre (1923). First, root spread affects DBH as the tree stem grows and it is difficult to eliminate this effect from actual DBH measurements. Second, only diameters above breast height can be estimated using Behre’s method, and the shape of the butt-end cannot be analyzed. These problems might arise when stem volume is estimated using a relative stem taper curve (e.g., Inoue, 2001; Inoue and Kurokawa, 2001; Kajiwara, 1972, 1973a, 1973b, Osumi, 1959), but they should not affect the estimation of upper diameter.

Other researchers developed relative stem taper curves based on trunk height from the ground to the tree top and the diameter at 0.9 of total trunk height (hereinafter \( d_{0.9} \)) (Hohenadle, 1922; Inoue, 2001; Inoue and Kurokawa, 2001; Kajiwara, 1972, 1973a, 1973b; Osumi, 1959; Prodan, 1944, 1951). Before forest cutting or clearing operations in Japan, complete tree tallies are usually conducted. Although researchers have used \( d_{0.9} \), it is difficult to use this metric in the field for tree tallies because \( d_{0.9} \) is measured at such a high position. As a result, this parameter is most useful in destructive sampling (i.e., after cutting), and is difficult to use in the field to predict whether a stand of trees is sufficiently valuable to justify cutting. Kajiwara (1993) also noted that relative stem taper curves based on \( d_{0.9} \) are rarely used because the position of the basis diameter changes with tree as the height increases over time.

Osumi (1959) noted that the basis diameter could be measured at any height on the stem. In this study, DBH was adopted as the basis diameter for developing relative stem taper curves because this parameter can be measured directly. The curves developed in this study could be applied
to estimate diameters at positions higher than breast height on
the stem.

The relative stem taper curves developed in this study
were third-order polynomials, as Osumi (1959) noted that such
an equation provides a good fit for sugi stem-form data. Our
findings also show this, as the coefficient of determination ($R^2$)
was >0.99 for all nine relative stem taper curves developed for
sugi and its local varieties (Fig. 2).

In our analysis of the accuracy of the relative stem taper
curve, the average residual error between estimated and
measured diameters was <1.0 cm for the sugi curve, as well
as the curves for the individual varieties. Because logs must
have an upper diameter >14.0 cm to be suitable timber column
material in Japan, we also analyzed only those trees meeting
this criterion. In this case as well, we found that the average
residual error was <1.0 cm for all seven curves analyzed. In
the field, logs with an upper diameter >14 cm are sorted in
2-cm increments. Estimating diameter using the relative stem
taper curves developed in this study might be useful in the
field because the residual error of the estimates are <1.0 cm.

Sugi is an important forestry species in Japan. Because
forest tree breeding projects have been conducted in Japan
for only about 50 years, there is little information regarding
the stem form of sugi local varieties. This study revealed
significant differences in height and DBH growth among sugi
varieties in even-aged stands, suggesting that the stem forms
of these eight varieties differ as well. Therefore, we developed
separate relative stem taper curves for each local variety.
In the case of sugi trees that have not been identified to the
variety level or local varieties for which no relative stem taper
curve has been developed, the sugi curve (Fig. 2) is the best
choice for estimating upper diameter.

In the case of Measa, the sugi curve provided a better fit
than the Measa curve for all diameters, whereas the opposite
was found for diameters >14 cm (Table 3). Thus, when
estimating upper diameter with regard to market suitability of
the timber, the Measa curve should be used.

For the varieties Tanoaka, Tosaaka, and Haara, the two-
sided 95% confidence intervals were the same for the sugi
curve and the individual variety curve for all diameters
and only those diameters >14 cm (Table 3). In addition, the
average residual error for each variety was <1.0 cm. The
confidence interval suggests greater reliability when the
standard deviation is lower, because of the way the confidence
interval is calculated (Sokal and Rohlf, 1987). For Tanoaka
and Haara, because the variety curve has a smaller standard
development that of the sugi curve, estimation of the upper
diameter in these varieties should use the variety curve. For

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Fig. 3 Flow chart of forest operation planning based on stem upper diameter estimation

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For Yabukuguri, the variety curve provided a better fit than the sugi curve for all diameters, whereas the opposite was found for diameters >14 cm (Table 3). Thus, when estimating upper diameter of Yabukuguri with regard to market suitability of the timber, the sugi curve should be used. In the case of Hiki, the sugi curve provided a better fit than the Hiki curve for all diameters and only diameters >14 cm (Table 3), so the sugi curve is the best choice for this variety.

In Fig. 2, relative radius on Yabukuguri in 0.1 to 0.6 on relative stem length, was larger than the radius among other varieties of sugi on this study at the t-test significantly (p<0.05). Stem taper of Yabukuguri might be nonpaperness compared to that of the other local varieties of sugi.

In relative radius on Kijin, the t-test on the same analysis in case of Yabukuguri, revealed significant differences among other variety of sugi except Yabukuguri from 0.1 to 0.6 on relative stem length (p<0.05). Stem taper of Kijin might be also nonpaperness compared to that of the other local varieties of sugi.

At the position of 0.25 on relative radius, relative stem length of Yabukuguri alone was smaller than the position of 0.3 (Fig. 2). If relative radius at the position of 0.3 on relative stem length was larger than 0.25 at an unidentified local variety of sugi stem, the variety of the stem might be Yabukuguri. On the other hand, at the position of 0.35 on relative stem length of Measa and Tanaoka, relative radius was short of 0.25. So, if relative radius at the position of 0.35 on relative stem length was smaller than 0.25 at an unidentified local variety of sugi stem, the variety of the stem could be Measa or Tanaoka.

Forest Operation Planning based on Upper Stem Diameter Estimation

In existing stem taper tables, numerous tables are compiled and present a wide range of tree heights and DBH values. However, the upper diameter at a particular stem height cannot be directly obtained from these tables. Therefore, we have formulated a system that allows the diameter at a particular stem height to be easily estimated (Fig. 3). Only diameters higher than breast height can be estimated using this system.

By using this system before conducting cutting or cutting operations, the yield volume can be predicted. The proceeds of sales from the operation can be calculated by multiplying the predicted log yield by the wood market price. The profit can then be calculated by subtracting the operation cost from the proceeds of sales. By simulating the operation profit using this system, the forest manager could provide the forest owner with a proposal or quotation for each forest operation.

For the transportation of dried wood, timber column materials exceeding 16.0 cm in upper diameter are needed in view of the shrinkage that occurs when logs are dried. The estimation system developed in this study would allow for the easy identification of those trees with an upper stem diameter exceeding this 16.0-cm limit.

In future research, we will develop a relative stem taper curve for hinoki (*Chamaecyparis obtusa* Sieb. et Zucc.), which has a higher log price than that of sugi, to allow for more accurate estimates of that species’ upper stem diameter, as well as the profits to be earned from logging operations in hikoki forests.

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