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ORIGINAL ARTICLE

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A forest biomass yield table based on an empirical model

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Abstract We report an empirical model for estimating unutilized wood biomass, and its application to *Cryptomeria japonica* D. Don and *Larix kaempferi* in Tohno City, Iwate Prefecture, northeast Japan. Outputs from the model are the quantity of unutilized wood biomass and merchantable volume produced by timber harvest. The unutilized wood biomass is divided into stumps, tops, branches, foliages, small trees, and unutilized stems due to their defects. Inputs to the model are mean diameter at breast height (DBH), mean tree height, trees per unit area, and timber utilization standards. DBH distribution, DBH–height curve, stem form, bark thickness, and relationship of stem biomass to foliage and branch biomass could be described by the proposed model, indicating its validity. The proposed model enables us to develop the forest biomass yield tables modified from the existing stem volume yield tables. The developed forest biomass yield tables indicated that the unutilized wood biomass due to defects accounted for the largest part of the whole unutilized wood biomass, and that the ratio of unutilized parts in stem volume to total stem volume could vary with stand age and site productivity class. Based on a comparison of the developed forest biomass yield tables with those reported previously, we concluded that the proposed model-based forest biomass yield table would be useful for estimating the quantity of unutilized wood biomass.

Key words Unutilized wood biomass · Forest biomass yield table · DBH distribution · Stem form · Empirical model

Introduction

When forests are harvested, a large amount of unutilized wood biomass remains on the harvested sites in the form of tops, stumps, branches, and leaves. This biomass is mostly rotted and decomposed by earthworms, fungi, and bacteria and then is released into the atmosphere as CO_2. Use of this biomass as an energy resource, which is renewable and carbon neutral, is expected to contribute to mitigation of the accumulation of CO_2 in the atmosphere through the displacement of fossil fuel combustion (Marland and Schlamadinger 1997). Despite its importance, little is known about the method of estimating the quantity of unutilized wood biomass left in harvested areas (Harmon et al. 1996; Kunisaki 2002; Kunisaki et al. 2003).

The present study focused on the simple assumption that the unutilized wood biomass was obtained by subtracting the utilized wood biomass from total forest wood biomass. Already, forest mensurationists have developed methods of estimating the quantity of stem volume divided into merchantable and unutilized parts, when a forest was harvested, based on empirical growth models (e.g., Hiwatashi 1986; Iehara and Kurokawa 1990). Hiwatashi (1986) developed a method of estimating the merchantable volume from the stand structure before harvest using a taper curve and bark thickness. This method required the stand structure before harvest as input, which included diameter at breast height (DBH) and tree height of individual trees in the stand. Iehara and Kurokawa (1990) developed a method of estimating the stand structure in a given age and site index for artificial forests of *Chamaecyparis obtusa* using the empirical growth model describing DBH Distribution and DBH–height curve. Then, they estimated the merchantable volume using the estimated stand structure and the method developed by Hiwatashi (1986). The advantage of their method was that only the age and the site index of the forest

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stand were required. Also, the method of estimating the total forest wood biomass by multiplying stem volume (or stem biomass) by a biomass expansion factor has been proposed (e.g., Brown et al. 1999; Fukuda et al. 2003). The combination of these existing methods enables us to estimate the quantity of unutilized wood biomass, although they may need to be slightly modified.

Additionally, to test the feasibility of wood biomass for energy, we have to estimate the quantity of wood biomass not on a stand scale, but on a regional scale. This is because the energy plant needs a large supply of wood biomass every day for effective operation. Usually, the data of forest register has been used to estimate the quantity of stem volume on a regional scale in Japan (Yoshida and Matsushita 1999). Therefore, on a regional scale, estimation of the quantity of unutilized wood biomass based on forest register is one of the most effective methods. Because the forest register data is based on the stem volume yield table, we have to develop a forest biomass yield table to estimate the quantity of unutilized biomass.

Our main objective is to develop forest biomass yield tables for *Cryptomeria japonica* D. Don and *Larix kaempferi* in Tohno City, Iwate Prefecture, northeast Japan. To achieve this purpose, first, we have proposed an empirical model for estimating the quantity of unutilized wood biomass produced by timber harvest. Next, we applied the proposed model to the stands of *C. japonica* and *L. kaempferi* in Tohno City. Thirdly, we developed forest biomass yield tables modified from the existing stem volume yield tables for both species based on the proposed model. Finally, we discuss the characteristics of the developed forest biomass yield tables.

Description of proposed model

Inputs and outputs

Outputs from our model are the quantity of unutilized wood biomass and merchantable volume produced by timber harvest. The wood biomass is divided into stumps, tops, branches, foliages, small tress, and unutilized stems due to their defects such as bending. Inputs to the model are mean DBH, mean tree height, trees per unit area, and timber utilization standards that include the length and the minimum top diameter inside bark of logs, and the stump height.

DBH distribution

DBH distribution was estimated from a Weibull distribution function, a probability density function:

$$g(D) = (c/b)\left\{(D-a)/b\right\}^{c-1}\exp\left[-\left\{(D-a)/b\right\}^{c}\right] \quad (1)$$

where $g(D)$ is the probability density function, D is the DBH, and a, b, and c are the parameters representing the minimum DBH, the range of DBH, and the shape of distribution, respectively. This function can express the shape of any unimodal distribution (Bailey and Dell 1973). Parameters b and c can be mathematically estimated from parameter a, coefficient of variation of DBH (CV), and mean DBH, using the moment method (Nishizawa et al. 1976; Nishizawa 1978); we need to estimate parameter a and CV to estimate the DBH distribution. Parameters a and CV were estimated by using the function of mean DBH D_m:

$$a = \alpha + \beta D_m, \quad (2)$$

$$\mathrm{CV} = \gamma + \delta D_m, \quad (3)$$

where α, β, γ, and δ are constants.

DBH–height curve

The relationship between DBH and tree height was estimated from the dimensionless DBH–height curve of Shiraishi (1981):

$$H/H_m = (D/D_m)^{\varepsilon}, \quad (4)$$

where H and H_m are tree height and mean tree height, respectively, and ε is the parameter representing the form of DBH–height curve. Parameter ε was estimated by using the function of mean tree height:

$$\varepsilon = \zeta + \eta H_m, \quad (5)$$

where ζ and η are constants.

Stem form

Stem form was estimated from a relative stem taper curve. We used a segmented polynomial regression model (Max and Burkhart 1976) to portray stem form, in which neiloid, paraboloid, and cone represent lower, middle, and upper parts of the stems, respectively. The segmented polynomial regression model originally proposed was of the form:

$$\left(\frac{D_h}{D}\right)^2 = \theta_1'\left(\frac{h}{H}-1\right) + \theta_2'\left(\frac{h^2}{H^2}-1\right) + \theta_3'\left(\iota_1' - \frac{h}{H}\right)^2 I_1' + \theta_4\left(\iota_2' - \frac{h}{H}\right)^2 I_2', \quad (6)$$

where D_h is the stem diameter at a distance h from the base of the stem, θ_1', θ_2', θ_3', and θ_4 are constants, ι_1' and ι_2' are inflection points, and I_1' and I_2' are indicator variables defined as:

$I_1' = 1$ if $h/\mathrm{H} < \iota_1$, 0 otherwise,
$I_2' = 1$ if $h/\mathrm{H} < \iota_2$, 0 otherwise.

Equation 6 was modified to be used as a relative stem taper curve, by using relative radius in place of D_h/D, as follows:

$$y^2 = \theta_1 x + \theta_2 x(x-2) + \theta_3 (x-\iota_1)^2 I_1 + \theta_4 (x-\iota_2)^2 I_2, \quad (7)$$

where x is relative height (relative position from the top of the stem expressed in a ratio relative to tree height; i.e., $x = 1 - h/H$), y is relative radius (relative stem radius at position x expressed in a ratio relative to the stem diameter at 0.9 in relative height), θ_1, θ_2, θ_3, and θ_4 are constants, ι_1 and ι_2 are inflection points, and I_1 and I_2 are indicator variables defined as:

$I_1 = 1$ if $x > \iota_1$, 0 otherwise,
$I_2 = 1$ if $x > \iota_2$, 0 otherwise.

Stem diameter outside bark D_h at a given stem height h was calculated by the following equation, when $y = f(x)$,

$$D_h = D/f(1 - H_b/H)f(1 - h/H), \tag{8}$$

where H_b is breast height.

Bark thickness

Bark thickness was estimated from the relationship between the ratio of the diameter inside the bark D_{in} to the diameter outside the bark D_{out} and relative height x. The ratio D_{in}/D_{out} was estimated by using the following function of relative height (Takei 1979):

$$D_{in}/D_{out} = \kappa_1 x + \kappa_2 x^2 + \kappa_3 x^3 + \kappa_4, \tag{9}$$

where κ_1, κ_2, κ_3, and κ_4 are constants. By combining Eqs. 8 and 9, we can calculate D_{in} at a given stem height.

Stem volume and log volume

The stand structure, which included DBH distribution and mean tree height by DBH class, was estimated by using Eqs. 1–5.

Stem volume v_{UL} between any two relative heights, x_U and x_L ($x_U < x_L$), was estimated by using the following equation, with the estimated D and H:

$$v_{UL} = \frac{\pi}{4} D^2 H \int_{x_U}^{x_L} \left\{ \frac{f(x)}{f(1 - H_b/H)} \right\}^2 dx. \tag{10}$$

For example, total stem volume for a tree v was estimated by the following equation:

$$v = \frac{\pi}{4} D^2 H \int_0^1 \left\{ \frac{f(x)}{f(1 - H_b/H)} \right\}^2 dx. \tag{11}$$

The log volume v_L was calculated, after simulation of stem bucking as stated in the next section, in the usual manner according to the Japanese Agricultural Standards (Nagumo and Minowa 1990) as follows:

$$v_L = D_{se}^2 L, \tag{12}$$

where D_{se} is the small-end diameter inside bark and L is log length.

Stand stem volume and stand log volume were calculated by summations over all trees in the stand.

Simulation of stem bucking

Let the logs obtained from a tree be numbered $n = 1,2,3, \ldots, N$ upward from the base of the tree, and $L_L(n)$ be the length of a log of number n cut at distance $H_{lower}(n)$ from the base. Then, we define $H_{upper}(n) = L_L(n) + H_{lower}(n)$, $H_{lower}(n + 1) = H_{upper}(n)$, and $H_{lower}(1) = H_s$, where H_s, is the stump height.

Firstly, the stem diameter inside the bark $D_{H\text{upper}}(n)$ at a tree height $H_{upper}(n)$ was estimated by using Eqs. 8 and 9, and timber utilization standards, which included the length L_{TUS} and the minimum top diameter D_{TUS} of logs, the stump height H_s, and the priority for each log type.

Secondly, if $D_{H\text{upper}}(n) \geq D_{TUS}$, the part of the stem of the tree between $H_{lower}(n)$ and $H_{upper}(n)$ was categorized as "merchantable stem," where $H_{upper}(n)$ was calculated using L_{TUS} with the highest priority of feasible log types. If $D_{H\text{upper}}(n) < D_{TUS}$ and $n = 1$, the tree was categorized as "small tree." If $D_{H\text{upper}}(n) < D_{TUS}$ and $n \geq 2$, the part of stem of the tree between $H_{lower}(n)$ and H was categorized as "top." The volume of "merchantable stem," "small tree," and "top" was estimated by using Eq. 10.

These steps were repeated until $D_{H\text{upper}}(n) < D_{TUS}$ for all log types.

Defects

Although we have so far assumed implicitly that the trees had no defects such as stem and butt bending, these defects decrease log volume and increase unutilized stem volume in the actual stand. Tsukahara et al. (1975) reported that the degree of butt bending increased with increasing age before 35–40 years of age and then reached a constant. Based on their study, we assumed that the length of unutilized stem due to butt bending L_B increased linearly with age T, and then reached a constant value A at 35 years of age, based on the following equations:

$$\begin{cases} L_B = A/35 \cdot T & (T < 35) \\ L_B = A & (T \geq 35) \end{cases} \tag{13}$$

Thus, unutilized stem volume due to butt bending v_{butt} was estimated using the following equation:

$$v_{butt} = \frac{\pi}{4} D^2 H \int_{1-(H_s+L_B)/H}^{1-H_s/H} \left\{ \frac{f(x)}{f(1 - H_b/H)} \right\}^2 dx. \tag{14}$$

Here, we have to replace $H_{lower}(1) = H_s$ with $H_{lower}(1) = H_s + L_B$ in the preceding section. Because stem bending is correlated strongly with butt bending (Japan Forestry Agency 1969), we assumed that unutilized stem volume due to stem bending v_{stem} was related linearly with v_{butt}, and could be estimated using the following equation:

$$v_{\mathrm{stem}} = Bv_{\mathrm{butt}}, \tag{15}$$

where B is a constant. Consequently, the output of log volume was estimated by subtracting the unutilized stem volume due to stem bending estimated by using Eq. 15 from the log volume estimated by our model ignoring the stem bending. Unutilized stem volume due to its defects for a tree v_{defect} was estimated as $v_{\mathrm{defect}} = v_{\mathrm{butt}} + v_{\mathrm{stem}}$.

Conversion of volume into biomass for wood and bark in stem

The wood and bark volume (v_{W} and v_{B}, respectively) in the stem were converted into biomass weight (w_{W} and w_{B}, respectively) using bulk density for each part (d_{W} and d_{B}, respectively) as follows:

$$w_{\mathrm{w}} = d_{\mathrm{w}}v_{\mathrm{w}}, \tag{16}$$

$$w_{\mathrm{B}} = d_{\mathrm{B}}v_{\mathrm{B}}. \tag{17}$$

The d_{W} used in the present study was the mean value of oven-dried weight calculated by Fukuda et al. (2002, 2003). It was 0.319 for *Cryptomeria japonica* D. Don and 0.408 for *Larix kaempferi* (Lamb.) Carr. The value of d_{B} for the species examined in the present study, to our knowledge, has not been reported. In other coniferous tree species, d_{B} was reported to be usually smaller than in wood (Hakkila 1989; Senelwa and Sims 1999; Møller 2000). Therefore, we set d_{B} as 80% of d_{W}, tentatively, as did Møller (2000). Thus, stem biomass w_{S} is calculated as follows:

$$w_{\mathrm{S}} = d_{\mathrm{W}}\left(v_{\mathrm{W}} + 0.8v_{\mathrm{B}}\right). \tag{18}$$

Foliage and branch biomass

Foliage and branch biomass was estimated from the relationship of stem biomass to foliage and branch biomass. We selected a model out of three models for each relationship on the basis of the goodness of fit. The three models were expressed by the following equations.

$$Y = \mu, \tag{19}$$

$$Y = \lambda_1 W_S^{\lambda_2}, \tag{20}$$

$$1/Y = 1\big/\left(\xi_1 W_S^{\xi_2}\right) + 1/\xi_3, \tag{21}$$

where Y is the foliage or branch biomass per hectare, W_{s} is stem biomass per hectare, μ is the mean value of Y, and λ_1, λ_2, ξ_1, ξ_2, and ξ_3 are constants. Equation 19 is the constant regression model; Y always has a constant value μ, independent of stem biomass. Equation 20 is a simple allometric function. Equation 21 is a generalized allometric function (Ogawa and Kira 1977).

Study site

Tohno City, which has an area of 66 038 ha, is located in the middle of Iwate Prefecture, northeast Japan, between the latitudes of 39°11′N and 39°33′N, and between the longitudes of 141°21′W and 141°44′W. The average annual temperature is about 9.8°C. In winter, the temperature may sometimes drop to −15°C, while in summer, it may rise to +30°C. The annual precipitation is about 1000 mm. Most of the forested area consists of granite. The forested area is 52 362 ha, constituting 79.3% of the total area. The area of the artifical forest stand is 31 975 ha; the area occupied by *C. japonica*, *Pinus densiflora*, and *L. kaempferi* is 50%, 25%, and 25%, respectively. The area of the natural forest stand is 20 387 ha, most of which consists of broad-leaved species. The volulme of log production is 27 400 m^3 for coniferous trees, mainly stands of *C. japonica* and *L. kaempferi*, and 3100 m^3 for broad-leaved trees.

Data

To obtain the parameters concerning DBH distribution and the DBH–height curve, we used the data sets collected in Iwate Prefecture by the Forestry Agency and Iwate Prefectural Office to prepare stand density control diagrams (Ando 1968). The data for *C. japonica* and *L. kaempferi* were gathered from 65 and 294 stands, respectively. The data set for each stand included number of trees in each 2-cm DBH class, and tree height for sample trees selected from each 2-cm DBH class, and other data. These data are hereafter called “Data 1.”

To obtain the parameters concerning stem form and bark thickness, we obtained sample trees from four *C. japonica* and six *L. kaempferi* even-aged pure stands, which were commercially thinned, in Tohno City. The stand age ranged from 44 to 58 years for *C. japonica*, from 38 to 52 years for *L. kaempferi*. The total number of sample trees was 42 for *C. japonica* and 42 for *L. kaempferi*. After all sample trees were felled, some sample trees were cut into short logs for shortwood logging, and others were cut into the two main parts of merchantable bole and top for tree-length logging. The height and log length of these trees were measured directly on the stem with a tape to the nearest tenth of a meter. The diameter was measured with a caliper along the stem to the nearest tenth of a centimeter at the ends of each log. If there was unutilized stem due to its defects, the length of that part of stem, diameter at both ends, and defect were recorded. Additionally, diameter was measured at 2-m intervals through the merchantable part of the stem in the sample tree for tree-length logging. Stem diameter at 0.9 relative height was estimated by linear interpolation between measurement points. Bark thickness for 35 *C. japonica* trees and 36 *L. kaempferi* trees of these sample trees was also measured at the ends of each log. These data are hereafter called “Data 2.”

The data set developed by Fukuda et al. (2001a, 2001b) based on reported data was used to obtain the parameters for the relationship of stem biomass to foliage and branch biomass. The data set included biomass of stem, branch, and foliage per hectare. These data are hereafter called “Data 3.”

Parameter estimating

Firstly, from Data 1, the parameter a of Eq. 1 was obtained as a minimum DBH observed in the examined plot, and mean DBH and CV were calculated. Then, these calculated values were fitted to Eqs. 2 and 3. Secondly, Data 1 were fitted to Eq. 4 to obtain the parameter ε. Then, mean tree height and calculated ε for each stand in Data 1 were fitted to Eq. 5. Thirdly, Data 2 were fitted to Eqs. 7 and 9 to obtain the parameters θ_1, θ_2, θ_3, θ_4, ι_1, ι_2, κ_1, κ_2, κ_3, and κ_4. Fourthly, A in Eq. 13 was obtained as mean length of unutilized stem due to butt bending in Data 2. B in Eq. 15 was obtained as the ratio of unutilized stem volume due to stem bending to that due to butt bending in Data 2. Finally, Data 3 were fitted to Eqs. 19–21. Then, the goodness of fit of three models (Eqs. 19–21) was compared using Akaike's information criterion (AIC) (Akaike 1974),

$$\mathrm{AIC} = M\log\left(S/M\right) + 2m \qquad (22)$$

where M is the number of samples, S is the sum of the squares of residuals, and m is the number of constants in the model. We regarded the model having the smallest AIC value as the most appropriate (Sakamoto et al. 1983).

Results and discussion

DBH distribution

Parameter a significantly increased with increasing mean DBH for *Cryptomeria japonica* D. Don and *Larix kaempferi* (Lamb.) Carr. stands (Fig. 1). The relationship between a and mean DBH is described by Eq. 2 [*C. japonica*: $a = -4.9582 + 0.662973D_{\mathrm{m}}$ ($P < 0.01$), *L. kaempferi*: $a = -3.97489 + 0.743634D_{\mathrm{m}}$ ($P < 0.01$)]. Shiraishi and Minowa (1982) reported that parameter a was strongly correlated with mean DBH, and that parameter a could be estimated from the mean DBH. Our findings were consistent with those reported by Shiraishi and Minowa (1982). Coefficient of variation of mean DBH (CV) significantly decreased with increasing mean DBH for *C. japonica* and *L. kaempferi* stands (Fig. 2). The relationship between CV and mean DBH is described by Eq. 3 [*C. japonica*: CV = $0.296373 - 0.00241D_{\mathrm{m}}$ ($P < 0.05$), *L. kaempferi*: CV = $0.313837 - 0.00526D_{\mathrm{m}}$ ($P < 0.01$)]. Yamazaki and Nishizawa (1983) estimated CV from mean DBH in coniferous stands, although they used a function different from ours. They showed that CV dereased with increasing mean DBH, corresponding with our results. Figure 3 shows the change in Weibull parameters with stand age estimated by mean DBH and stand age in stem volume yield table for Tohno district. The parameters were estimated using Eqs. 2 and 3, and the moment method (Nishizawa et al. 1976; Nishizawa 1978). Parameters a and b increased with increasing stand age while parameter c decreased with increasing stand age. The trend of change in the estimated parameters was consistent with those reported previously (e.g., Kinashi 1978; Shiraishi and Minowa 1982; Iehara and Kurokawa 1990), indicating that the Weibull parameters estimated by mean DBH are valid.

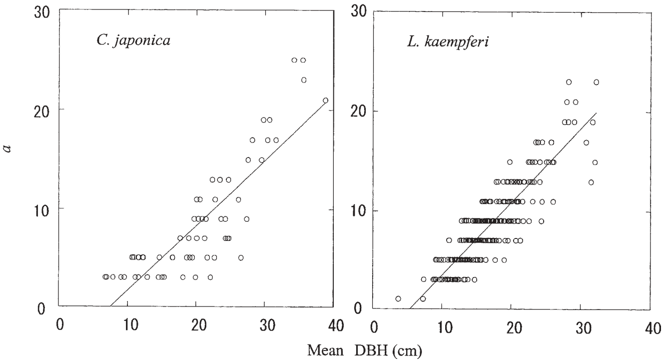


Fig. 1. Relationships between mean diameter at breast height (DBH) and parameter a for *Cryptomeria japonica* D. Don and *Larix kaempferi* (Lamb.) Carr. The *solid lines* indicate the fitted regression equations: $a = -4.9582 + 0.662973D_{\mathrm{m}}$ ($P < 0.01$) for *C. japonica*; $a = -3.97489 + 0.743634D_{\mathrm{m}}$ ($P < 0.01$) for *L. kaempferi*

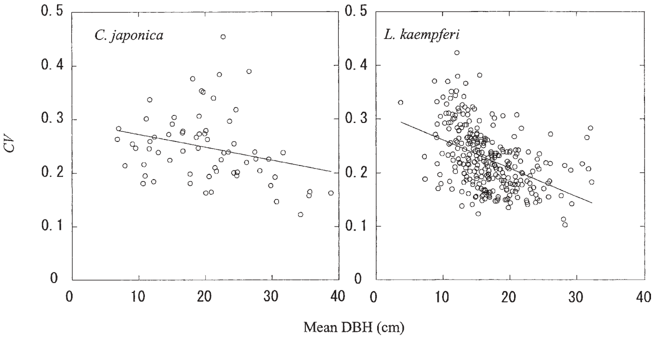


Fig. 2. Relationships between mean DBH and coefficient of variation of DBH (*CV*) for *C. japonica* and *L. kaempferi*. The *solid lines* indicate the fitted regression equations: CV = $0.296373 - 0.00241D_{\mathrm{m}}$ ($P < 0.05$) for *C. japonica*; CV = $0.313837 - 0.00526D_{\mathrm{m}}$ ($P < 0.01$) for *L. kaempferi*

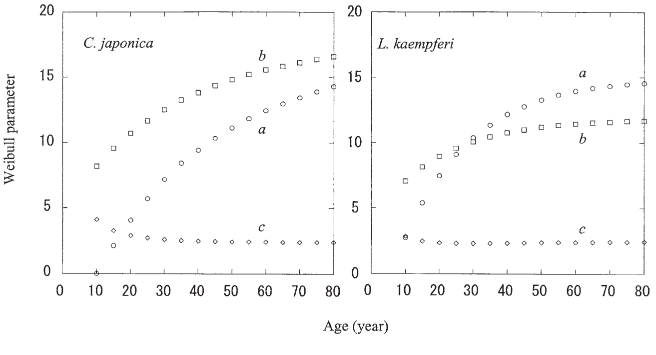


Fig. 3. Changes in Weibull parameters a, b, and c with age for *C. japonica* and *L. kaempferi*

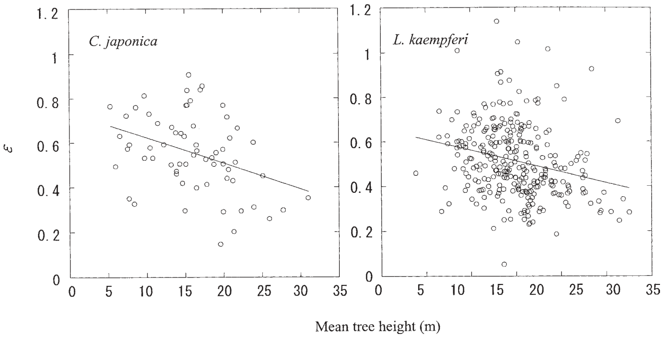


Fig. 4. Relationships between mean tree height and ε for *C. japonica* and *L. kaempferi*. The *solid lines* indicate the fitted regression equations: $\varepsilon = 0.7648 - 0.0127H_m$ ($P < 0.01$) for *C. japonica* and $\varepsilon = 0.6565 - 0.0096H_m$ ($P < 0.01$) for *L. kaempferi*

DBH–height curve

Parameter ε significantly decreased with increasing mean tree height for *C. japonica* and *L. kaempferi* stands (Fig. 4). The relationship between ε and mean tree height is described by Eq. 5 [*C. japonica*: $\varepsilon = 0.7648 - 0.0127H_m$ ($P < 0.01$), *L. kaempferi*: $\varepsilon = 0.6565 - 0.0096H_m$ ($P < 0.01$)]. The trend of the DBH–height curve in even-aged pure stands is usually apparent (Nagumo and Minowa 1990; Schreuder et al. 1993). With aging, it moves upward to the right, when the longitudinal and abscissa axes are tree height and DBH, respectively. In addition, the curve is steep for a young crop and nearly flat for an old crop. In the dimensionless DBH–height curve (Eq. 4) of Shiraishi (1981), the increase in mean tree height and mean DBH explain the former phenomena, and parameter ε explains the latter phenomena; ε is large for low age and small for advanced age. The good consistency between our results and the general trend supports the validity of the parameter ε as estimated by mean tree height.

Stem form, bark thickness, and defects

Figure 5 shows the relationship between relative height and relative diameter. The stem taper is described by Eq. 7 [*C. japonica*: $y^2 = 17.29x + 8.68x(x - 2) - 8.46(x - 0.07)^2I_1 + 2737.86(x - 0.97)^2I_2$ ($P < 0.01$), *L. kaempferi*: $y^2 = 9.53x + 4.71x(x - 2) - 4.83(x - 0.14)^2I_1 + 660.83(x - 0.97)^2I_2$ ($P < 0.01$)].

Figure 6 shows the relationship between the ratio of the diameter inside the bark D_{in} to the diameter outside the bark D_{out} and relative height x. Change in D_{in}/D_{out} with relative height is described by Eq. 9 [*C. japonica*: $D_{in}/D_{out} = 0.04x - 0.04x^2 + 0.01x^3 + 0.96$ ($P < 0.01$), *L. kaempferi*: $D_{in}/D_{out} = 0.34x - 0.45x^2 + 0.20x^3 + 0.87$ ($P < 0.01$)]. The comparison between both curves indicated that D_{in}/D_{out} for *L. kaempferi* was smaller than that for *C. japonica* at any relative height. This finding is in agreement with the results of a study by Takei (1979).

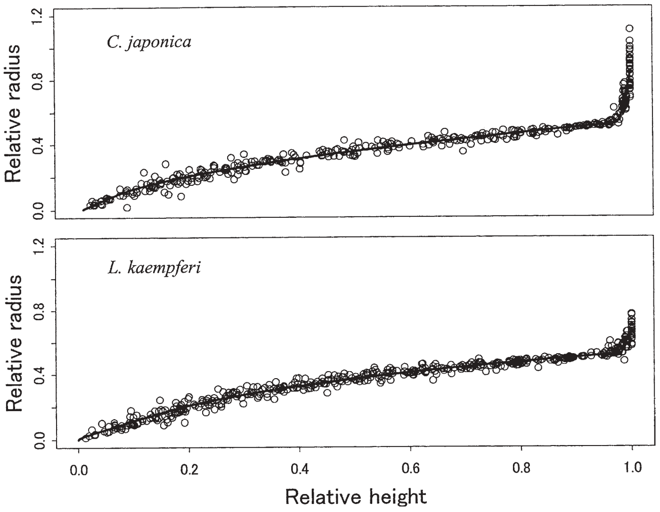


Fig. 5. Relationships between relative height and relative diameter for *C. japonica* and *L. kaempferi*. The *solid lines* indicate the fitted regression equations: $y^2 = 17.29x + 8.68x(x - 2) - 8.46(x - 0.07)^2I_1 + 2737.86(x - 0.97)^2I_2$ ($P < 0.01$) for *C. japonica* and $y^2 = 9.53x + 4.71x(x - 2) - 4.83(x - 0.14)^2I_1 + 660.83(x - 0.97)^2I_2$ ($P < 0.01$) for *L. kaempferi*

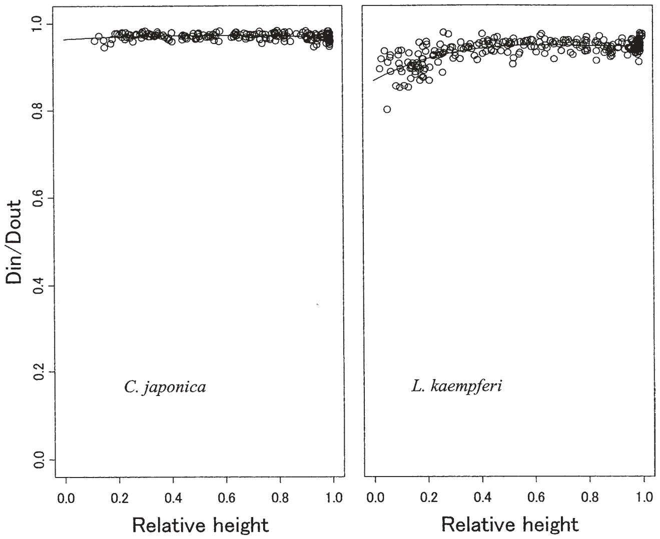


Fig. 6. Relationships between relative height and D_{in}/D_{out} for *C. japonica* and *L. kaempferi*. The *solid lines* indicate the fitted regression equations: $D_{in}/D_{out} = 0.04x - 0.04x^2 + 0.01x^3 + 0.96$ ($P < 0.01$) for *C. japonica* and $D_{in}/D_{out} = 0.34x - 0.45x^2 + 0.20x^3 + 0.87$ ($P < 0.01$) for *L. kaempferi*

The values of A obtained in Eq. 13 were 1.05 for *C. japonica*, and 0.72 for *L. kaempferi*. Similarly, the obtained B values in Eq. 15 were 0.66 for *C. japonica*, and 0.58 for *L. kaempferi*. These results suggest that the quantity of unutilized biomass due to defects in *C. japonica* was larger than in *L. kaempferi*.

Relationship of stem biomass to foliage and branch biomass

Figure 7 shows the relationship of the foliage and branch biomass to stem biomass. We could not obtain parameters in Eq. 21 for the relationships of stem biomass to foliage and branch biomass in *L. kaempferi* stands, although we repeatedly ran the nonlinear regression with different initial values. Thus, we regarded Eq. 21 as an incompatible model for *L. kaempferi* stands. On the basis of the values of AIC, the relationship between foliage and stem biomass is described by Eq. 21 [$1/Y = 1/(1.30W_S^{1.06}) + 1/24.75$] for *C. japonica*, and by Eq. 19 ($Y = 2.95$) for *L. kaempferi* (Table 1), and the relationship between branch and stem biomass by Eq. 20 (*C. japonica*: $Y = 0.24W_S^{0.79}$; *L. kaempferi*: $Y = 2.90W_S^{0.32}$) for both species (Table 1).

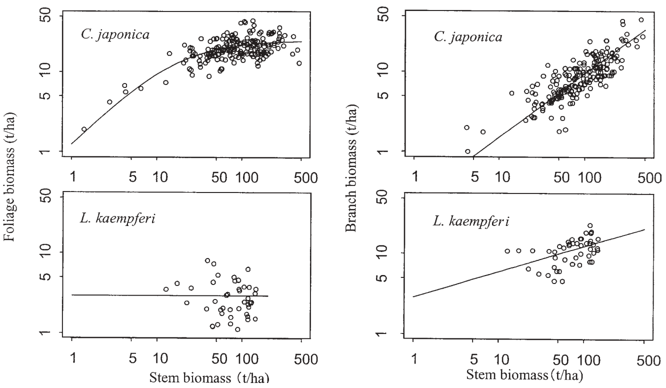


Fig. 7. Relationships of stem biomass to foliage and branch biomass for *C. japonica* and *L. kaempferi*. The *solid lines* at *left* indicate the fitted regression equations for foliage: $1/Y = 1/(1.30W_S^{1.06}) + 1/24.75$ for *C. japonica* and $Y = 2.95$ for *L. kaempferi*. The *solid lines* at *right* indicate the fitted regression equations for branch: $Y = 0.24W_S^{0.79}$ for *C. japonica* and $Y = 2.90W_S^{0.32}$ for *L. kaempferi*

Development of forest biomass yield table based on proposed model

Inputs to the model are mean DBH, mean tree height, stand density, and timber utilization standards, which include the length and the minimum top diameter inside the bark of the log, and the stump height. Although timber utilization standards need to be determined using the data from the harvested site or from an interview with the forester, mean DBH, mean tree height, and stand density can be estimated by the existing stem volume yield table. Therefore, we can easily make a forest biomass yield table by modifying the existing stem volume yield table based on the proposed model. Table 2 shows the forest biomass yield table developed from stand dimensions in the stem volume yield table for *C. japonica* in the Tohno district. Here, we used the timber utilization standards obtained from an interview with the forest owners' association in the Tohno district (Table 3). Figure 8 shows the change in forest wood biomass with stand age in the developed forest biomass yield table

Table 1. Constants and AIC values of regression curves between branch and stem biomass, and foliage and stem biomass

	$Y = \mu$		$Y = \lambda_1 W_S^{\lambda_2}$			$1/Y = 1/(\xi_1 W_S^{\xi_2}) + 1/\xi_3$			
	μ	AIC	λ_1	λ_1	AIC	ξ_1	ξ_2	ξ_3	AIC
Cryptomeria japonica D. Don									
Branch vs stem	9.83	2467.08	0.24	0.79	3217.27	0.31	0.74	582.28	4219.25
Foliage vs stem	20.12	2369.30	8.76	0.19	3173.73	1.30	1.06	24.75	
439.22									
Larix kaempferi (Lamb.) Carr.									
Branch vs stem	11.28	245.78	2.90	0.32	338.24	–	–	–	–
Foliage vs stem	2.95	274.45	4.73	−0.11	376.35	–	–	–	–

AIC, Akaike's information criterion

Table 2. Forest biomass yield table for *Cryptomeria japonica* D. Don in Tohno

Age (years)	Log volume (m^3/ha)	Stump (t/ha)	Defects (t/ha)	Top (t/ha)	Small tree (t/ha)	Branch (t/ha)	Foliage (t/ha)
10	0.09	1.41	0.01	0.01	11.61	1.88	11.07
15	35.64	2.74	3.83	5.17	8.62	4.12	17.29
20	85.48	3.95	9.12	10.48	4.18	6.37	19.95
25	147.68	4.91	14.51	8.42	1.89	8.38	21.21
30	202.92	5.67	19.86	9.58	0.79	10.16	21.92
35	247.93	6.35	25.55	10.66	0.27	11.82	22.39
40	309.87	6.98	27.94	8.83	0.09	13.31	22.71
45	362.31	7.52	29.98	9.13	0.02	14.63	22.94
50	408.04	7.95	31.64	8.61	0.00	15.78	23.10
55	454.73	8.33	33.13	7.47	0.00	16.80	23.22
60	488.60	8.63	34.36	8.33	0.00	17.69	23.32
65	527.99	8.89	35.43	6.73	0.00	18.47	23.40
70	563.36	9.12	36.37	6.89	0.00	19.16	23.46
75	594.11	9.32	37.22	7.35	0.00	19.76	23.51
80	623.32	9.47	37.86	5.85	0.00	20.28	23.55

This table was developed for the site that had average productivity; the site index was II

Table 3. Timber utilization standards in Tohno

	Stump height (m)	Priority	Length of log (m)	Minimum top diameter inside bark (cm)
Cryptomeria japonica D. Don	0.23	1	3.65	30.0
		2	3.65	18.0–28.0
		3	4	12.0–16.0
		4	4	8.0–10.0
Larix kaempferi (Lamb.) Carr.	0.23	1	4	16
		2	4	8–14

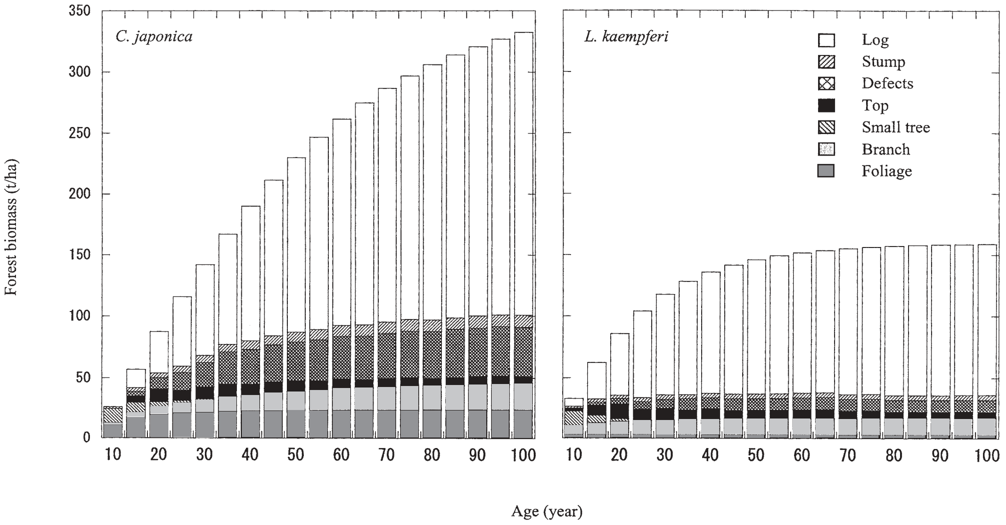


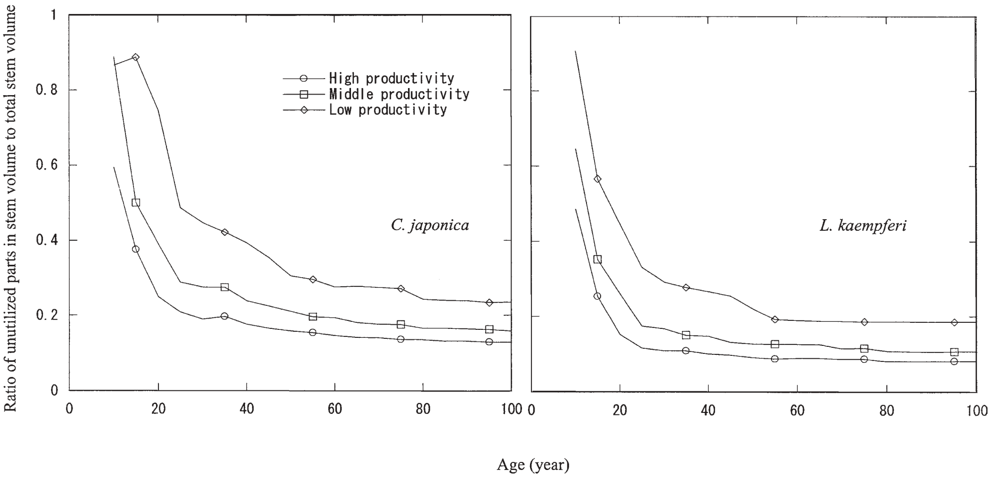
Fig. 8. Changes in forest biomass with stand age for *C. japonica* and *L. kaempferi*

for both species. The difference in total unutilized wood biomass with the species increased with increasing stand age after 20 years. The total unutilized wood biomass for *C. japonica* became about twice that for *L. kaempferi* after middle age. The unutilized wood biomass due to defects accounted for the largest part of the whole wood biomass for both species. This biomass may be a promising energy resource, because they are actually skidded from the harvested area to the landing area under tree length logging.

Foliage biomass in *C. japonica* increased with increasing stand age at an early stage before 30 years of age, and then reached a constant value. Foliage biomass in *L. kaempferi* always had a constant value. Generally, the foliage biomass in a unit land area reaches a maximum at an early stage, and then decreases somewhat to reach a constant level (Kira and Shidei 1967). Our forest biomass yield table may underestimate the foliage biomass for both species at the middle stage, and may overestimate the foliage biomass for *L. kaempferi* at an early stage. Lack of data for *L. kaempferi* at an early stage and the function type of the proposed model may have generated this error between our results and the general trend. To correct the estimating error, we should collect the data at an early stage and reanalyze the relationship between foliage and stem biomass in the future. However, because the harvest is mainly conducted after the middle stage, we consider that our biomass yield tables are applicable for estimating the quantity of unutilized wood biomass.

Figure 9 shows the changes in the ratio of volume in unutilized parts of stem to total stem volume with stand age for *C. japonica* and *L. kaempferi* with low, middle, and high site productivity. The unutilized parts included the volume of tops, small trees, and unutilized stems due to their defects. The ratio decreased with increasing stand age at the early stage, and then reached a constant value for both species. The stands with high site productivity reached constant values earlier than those with low site productivity. The constant values were different for each site productivity class for both species; the values were about 0.13, 0.16, and 0.24 for high, middle, and low site productivity, respectively, in *C. japonica*, and about 0.08, 0.11, and 0.19, respectively, in *L. kaempferi*. Accordingly, our results indicate that the ratio of unutilized parts in stem volume to total stem volume can vary with stand age and site productivity class. The values obtained were smaller than the value, 0.30, in thinned stands of *C. japonica* in Sumita Town next to Tohno City reported by Kunisaki et al. (2003). The discrepancy between the results reported by Kunisaki et al. (2003) and our results may be caused by the difference in species, stand age, and site productivity, and the difference between clear cutting and thinning. In the present study, we could not clarify the factors affecting the difference because of lack of data.

Fig. 9. Changes in ratio of volume in unutilized parts of stem to total stem volume with stand age for *C. japonica* and *L. kaempferi*



Characteristics of proposed forest biomass yield table

In the present study, we proposed an empirical model for estimating the quantity of unutilized wood biomass produced by timber harvest. There have been many reports on most of the submodels we used in the present study. The results of these reports have been integrated partially to the method to estimate stand structure and log volume for forest management (e.g., Hiwatashi 1986; Iehara and Kurokawa 1990), or to quantify the forest carbon budgets (Fukuda et al., 2003). However, the results of these reports have so far not been integrated to the model to estimate unutilized wood biomass. Because most of the reported methods of estimating log volume ignored defects, these methods could not be used to estimate the unutilized wood biomass. Thus, we proposed a simple submodel to describe the effect of the defects. This enables us to estimate the unutilized wood biomass, although the submodel needs to be examined with more data in the future.

Although many authors have studied the stem volume yield tables, only a few forest biomass yield tables have been reported in Japan (Tsujimoto 1963; Sekiya 1964; Research Group on Forest Productivity 1966; Kunisaki 2002). Tsujimoto (1963) and Sekiya (1964) developed stem biomass yield tables for *Pinus luchuensis* and *Pinus densiflora*, respectively. However, their yield tables were limited to stem biomass. The Research Group on Forest Productivity (1966) developed a yield table with stem, foliage, and branch biomass for *C. japonica*, but the quantity of unutilized wood biomass could not be estimated. Kunisaki (2002) developed a regression model for estimating residuals after harvest (see also Kunisaki et al. 2003) and developed an unutilized wood biomass yield table with unutilized stem, foliage, and branch biomass. This yield table enables us to estimate the quantity of unutilized wood biomass, and has application to not only clear cutting but also to thinning practice. Therefore, this yield table is useful for estimating the quantity of unutilized wood biomass. However, this yield table does not provide the merchantable volume. On the other hand, our model-based yield table can provide merchantable volume as well as unutilized biomass. This characteristic of our yield table allows us to estimate the quantity of unutilized biomass in the forest from statistical data of the merchantable volume actually produced.

Moreover, it is desirable to estimate the quantity of the wood biomass according to the tree parts, because the difficulty and the cost of yarding of unutilized wood biomass differ with each part. The method we proposed here can be used to estimate the wood biomass divided into several parts, and our yield table should be useful for economic analysis.

In addition, our method using the existing stem volume table requires less effort to develop the forest biomass yield table. This is because two of the three data sets used to estimate the model parameters in the present study (Data 1 and Data 3) were obtained from previous surveys and reports. This indicates that our method could be successfully applied throughout Japan. Therefore, our model-based forest biomass yield table can be considered one of the most useful tools for estimating the quantity of the unutilized wood biomass to test the feasibility of wood biomass as an energy resource.

Conclusions

We proposed an empirical model for estimating unutilized wood biomass, and applied it to *Cryptomeria japonica* D. Don and *Larix kaempferi* (Lamb.) Carr. in Tohno City, Iwate Prefecture, northeast Japan. The proposed model could adequately describe DBH distribution, the DBH–height curve, stem form, bark thickness, and the relationship of stem biomass to foliage and branch biomass. Forest biomass yield tables were modified from existing stem volume yield tables using the proposed model. We discussed the characteristics of the developed forest biomass yield tables, and conclude that our method of developing the forest biomass yield table can be applied throughout Japan, and that the developed tables will be useful for estimating the quantity of the unutilized wood biomass. Application of these forest biomass yield tables to test the feasibility of wood biomass as an energy resource in Tohno City has been reported separately (Kuboyama et al. 2004).

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