Evaluation of stem taper models fitted for Japanese cedar (Cryptomeria japonica) in the subtropical forests of Jeju Island, Korea

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Abstract
This study was conducted to evaluate the performance of the five stem taper models in predicting the diameter over bark at any given height (d) and total volume of Japanese cedar (Cryptomeria japonica) D.Don in the subtropical forests of Korea. The four fit statistics used in this study were standard error of estimate (SEE), mean bias (E), mean absolute bias (MAB), and coefficient of determination (R²). For the lack-of-fit statistics, SEE, MAB, and E of the five models in predicting d in the different relative height classes and in predicting the total volume in the different diameter at breast height (D) classes were determined. Results of the model evaluation indicated that the Kozak88 stem taper model had the best performance in most of the fit statistics followed by Kozak02 stem taper model. The Kozak88 model also provided the best performance in the lack-of-fit statistics having the best SEE, MAB, and E in predicting d in most of the relative height classes. This model consistently performed well in estimating the total volume of Japanese cedar in the different D classes as compared to other stem taper and volume models. These stem taper equations could serve as a management tool for forest managers to accurately predict the d, merchantable stem volumes, and total stem volumes of the standing trees of Japanese cedar in the southern plantation of Korea.

Introduction
Japanese cedar (Cryptomeria japonica) is native to Japan (Cheng et al. 2009) and considered as one of the most commercially important conifers in Asia (Yoon et al. 2009). It is the most common plantation species in Japan, covering approximately 45% of the total plantation area and 20% of the total forested area (Japan FAO Association 1997; Konopka et al. 2007; Yashiro et al. 2010). This species was introduced in the different countries in East Asia such as Taiwan and Korea. In Taiwan it covers 10% of the total plantation area and is thus considered one of the most important coniferous species in forest plantations (Cheng et al. 2013). In Korea Japanese cedar was one of the species used for the afforestation in 1920 and was also planted in the southern-most province; Jeju, during the 1970’s afforestation. Approximately 40,000 ha were planted using Japanese cedar in Korea (Korea Forest Research Institute 2006). Furthermore, according to Lim et al. (2013), it is one of the most used coniferous species in the southern forest plantation of Korea along with Korean pine (Pinus koraiensis), Japanese ypress (Chamaecyparis obtusa), and Japanese larch (Larix leptolepis). To sustainably manage the Japanese cedar forest in the southern part of Korea, an accurate tool in acquiring merchantable and total volume estimates is needed.

Several authors (Figueiredo-Filho et al. 1996; Kozak 2004; Sharma and Zhang 2004; Jiang et al. 2005; Rojo et al. 2005; Trincado and Burkhart 2006; Yang et al. 2009; Li and Weiskittel 2010; Ozcelik et al. 2011, Subedi et al. 2011; Li et al. 2012) recommended a stem taper equation as one of the most useful tools to accurately predict the stem diameter at any given height (d), merchantable and total volume. Most of the stem taper models use total height (H), diameter at breast height (D), and height of d above the ground (h) as predictor variables (Berhe and Arnoldsson 2008; Hjelm 2013) because these are commonly measured during forest inventories (Brooks et al. 2008). The most commonly used stem taper equations are usually classified into segmented polynomial and variable exponent (Berhe and Arnoldsson 2008; Li et al. 2012; Gómez-Garcia et al. 2013). The former uses different sub-functions for various parts of the stem (Kozak 1988; Rojo et al. 2005) with an assumption that a tree has three geometric shapes (a neiloid frustum at the bottom, a paraboloid frustum at the middle, and cone frustum at the top) (Husch et al. 1982; Corral-Rivas et al. 2007; Yang et al. 2009; Li and Weiskittel 2010) while the latter assumes that the form of the tree changes continuously along the stem (Corral-Rivas et al. 2007; Yang et al. 2009; Li and Weiskittel 2010; Heidarsson and Pulkka 2011; Li et al. 2012; Hjelm 2013). In comparison to the traditional stem volume models, Kozak (2004) explained that a stem taper equation is better because it can estimate d, merchantable height to any top diameter and from any stump height, volume of a stem log at any length and at any height from ground in addition to merchantable and total stem volume.

In Korea there are limited studies that deal with stem taper equation modeling. Stem taper models were fitted for the major Korean tree species which are Pinus koraiensis, Pinus densiflora, Pinus rigida, Larix kaempferi, Quercus acutissima, and Quercus mongolica (Son et al. 2002). However, prior to this study, a stem taper equation has not been developed specifically for Japanese cedar grown in Korea. One of
the major limitations of the stem taper model is that it is species specific (Sharma and Zhang 2004; Subedi et al. 2011; Li et al. 2012); thus, using a stem taper model developed for other species will have an inaccurate estimate of \( d \) and volume for Japanese cedar. Furthermore, most of the stem taper studies in Korea focused only on evaluating the accuracy of stem taper models in predicting \( d \) and did not evaluate the predictive capability of stem taper models in estimating total stem volume. Developing stem taper models for this commercially important species could help forest managers develop a more efficient forest inventory, which is essential for sustainable forest management. Thus, the objective of this study was to develop stem taper models for Japanese cedar in Korea and to evaluate the performance of these stem taper models in predicting \( d \) and total stem volume.

**Materials and methods**

**Study site**

This study was conducted in the southernmost province of South Korea, between 126°08'43"-126°58'20"E and 33°11'27"-33°33'50"N (Lee et al. 2009). Jeju province has a total land area of 184,840 ha and c. 48% (88,874 ha) of this island has forest cover (Korea Forest Service 2012). The mean annual temperature (MAT) is 15.40 °C. In addition, the mean annual minimum temperature is 3.20 °C and the maximum annual temperature is 29.80 °C. The mean annual precipitation (MAP) is 1560.80 mm (Korea Meteorological Administration 2014).

**Stem taper models**

A total of 120 Japanese cedar trees were harvested for the measurement of \( D \) (in cm), \( H \) (in m), \( d \) (in cm), and \( h \) (in m). Before felling, \( D \) and \( d \) in 0.2 m (stump height) were measured for each tree while \( H \) and \( h \) from 2.3 m up to the top of the tree with 1 m interval were measured after felling. Furthermore, \( D \) and \( d \) were measured using standard diameter tape and \( H \) and \( h \) were measured using meter tape. The mean \( H \) was 20.40 m with a range of 9.00 to 26.80 m and the mean \( D \) was 32.60 cm with a range of 9.80 cm to 55.90 cm, as shown in Table 1. The scatter plot of relative diameter (\( d/D \)) against relative height (\( h/H \)) was created as shown in Figure 1 to visually examine the data as suggested by Corral-Rivas et al. (2007) and Gómez-García et al. (2013).

The stem taper models used in this study were the models published by Kozak in 1988 (referred hereafter as Kozak88) and in 2004 (referred hereafter as Kozak01 and Kozak02). Furthermore, the stem taper model developed by Lee et al. (2003) for Pinus densiflora in Korea (referred hereafter as Lee03) and a modification of the Lee03 model (referred hereafter as Mod Lee03) published by Berhe and Arnoldsson (2008) for Cupressus lusitanica plantations in Ethiopia were also used. The mathematical forms of these candidate models are shown in Table 2. The parameters of these models were estimated using the Statistical Analysis System Non-linear (SAS NLIN) procedure (SAS Institute Inc. 2004).

**Model evaluation**

Kozak (2004) recommended the following fit statistics: standard error of estimate (\( SE_E \)), mean bias (\( E \)), mean absolute bias (\( MAB \)), and coefficient of determination (\( R^2 \)), to be used for evaluation and comparison of stem taper models. These were determined as follows:

\[
SE_E = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n-k}}
\]

and in 2004 (referred hereafter as Kozak01 and Kozak02). Furthermore, the stem taper model developed by Lee et al. (2003) for Pinus densiflora in Korea (referred hereafter as Lee03) and a modification of the Lee03 model (referred hereafter as Mod Lee03) published by Berhe and Arnoldsson (2008) for Cupressus lusitanica plantations in Ethiopia were also used. The mathematical forms of these candidate models are shown in Table 2. The parameters of these models were estimated using the Statistical Analysis System Non-linear (SAS NLIN) procedure (SAS Institute Inc. 2004).

**Table 1. Summary of observed statistics of the data used in the development of stem taper models for Japanese cedar in southern Korea.**

| Variable     | n  | Mean   | Minimum | Maximum | SD  |
|--------------|----|--------|---------|---------|-----|
| Total height | 120| 20.40  | 9.00    | 26.80   | 4.20|
| DBH          | 120| 32.60  | 9.80    | 55.90   | 9.80|

Note: SD = standard deviation; \( n \) = number of sampled trees.

**Table 2. Five stem taper equations selected as candidate models for Japanese cedar in southern Korea.**

| Model code | Mathematical form \(^1\) | Reference |
|------------|----------------------------|-----------|
| Kozak88    | \( \hat{d} = a_1D^{a_2}h^{b_1}X^{b_2} \) | Kozak 1988 |
| Kozak01    | \( \hat{d} = a_1D^{0.5}h^{1.2}X^{0.3} \) | Kozak 2004 |
| Kozak02    | \( \hat{d} = a_1D^{0.5}h^{1.2}X^{0.3}+b_1h^{1.2}X^{0.3} \) | Kozak 2004 |
| Lee03      | \( \hat{d} = a_1D^{b_1}h^{b_2}X^{b_3} \) | Lee et al. 2003 |
| Mod Lee03  | \( \hat{d} = a_1D^{b_1}h^{b_2}X^{b_3} \) | Berhe and Arnoldsson 2008 |

Notes: "\( D \) is diameter at breast height (cm), \( H \) is the tree total height (m), \( h \) is the height from the ground (m), \( Z \) is proportional height from the ground (\( h/H \)), \( \hat{d} \) is the predicted diameter outside bark at \( h \) (cm), and \( a_1, b_1, b_2, b_3 \) are the estimated parameters.

\(^2\) The \( p \) for Japanese cedar in this study was 0.22, which is within the range of the suggested value (0.1–0.3) given by Kozak (2004).
\[ E = \frac{\sum_{i=1}^{n}(Y_i - \bar{Y})}{n} \]  
\[ MAB = \frac{\sum_{i=1}^{n}|Y_i - \bar{Y}|}{n} \]  
\[ R^2 = 1 - \frac{\sum_{i=1}^{n}(|Y_i - \bar{Y}|)^2}{\sum_{i=1}^{n}(|Y_i - \bar{Y}|)^2} \]

where \( Y_i \) = observed variable; \( \bar{Y}_i \) = predicted variable; \( \bar{Y} \) = observed mean of the variable; \( k \) = the number of estimated parameters; and \( n \) = number of observations.

To determine further which model is most suitable, Kozak and Kozak (2003) recommended using lack-of-fit statistics. In this evaluation, one or more evaluation statistics must be determined for the various subgroups of the independent variable. In this study, the SEE, \( E \), and MAB of the candidate models in predicting \( d \) in the different relative height classes (0.10 interval) were determined. This study also assessed the applicability of stem taper models in accurately estimating stem volume (m\(^3\)). According to Li and Weiskittel (2010), a stem taper model should not only predict \( d \) but it must also estimate stem volume accurately. Thus, the performance of five stem taper models in estimating the total volume of Japanese cedar was also evaluated. Both the observed and predicted total volumes were calculated using the Smalian formula (Clutter et al. 1983) as done in the different stem taper studies (Kurinobu et al. 2007; Berhe and Arnoldsson 2008; Li and Weiskittel 2010; Li et al. 2012). For the observed volume, the measured \( d \) was used to calculate the volume of the different log sections and these were summed up to determine the total stem volume of each tree. For the predicted volume, the \( d \) were first predicted starting from 0.2 m up to the top of the tree at 1 m intervals, and the volumes in each log section were determined and summed up to acquire the total volume. Finally, the \( SEE, E, \) and MAB of the five models in the different D classes (10 cm intervals) were determined.

### Results and discussion

Stem taper models (Kozak88, Kozak01, Kozak02, Lee03, and Mod Lee03) were fitted to Japanese cedar in the southern part of Korea and their parameters were estimated as shown in Table 3. The overall performance of these models was evaluated using four statistical criteria (SEE, \( E \), MAB, and \( R^2 \)) as shown in Table 3. To determine the best model, rank analysis was employed. In this method, the model that had the lowest values for \( SEE \) and \( MAB \) had the best rank while a value near to 0 and 1 was considered best for \( E \) and \( R^2 \), respectively. The ranks of each model in the four performance criteria were summed and the model with the lowest value was considered the best stem taper model for Japanese cedar in Korea. Results of rank analysis indicated that the Kozak88 model had the overall best performance in predicting \( d \), having the best \( SEE \) (1.5126), \( MAB \) (1.0460 cm), and \( R^2 \) (0.9959), and having the second best \( E \) (0.0160 cm). This model was followed by the Kozak02 model having the best \( E \) with –0.0060 cm and having the second rank for \( SEE \) (1.5234), \( MAB \) (1.0490 cm), and \( R^2 \) (0.9958). The Lee03 model was considered the poorest among the candidate models in this study having the lowest rank in three statistical criteria (\( SEE \): 2.1822, \( MAB \): 1.5170 cm, and \( R^2 \): 0.9914).

To evaluate further, lack-of-fit statistics were used and the results indicated that the Kozak88 model provided the best performance in predicting \( d \), having the best \( SEE, E, \) and \( MAB \) in most of the relative height classes (Table 4). This model was followed by Kozak02 and Mod Lee03, respectively, while the Lee03 model consistently provided the poorest performance in predicting \( d \). Furthermore, the performance of the candidate stem taper models to accurately predict total stem volume of Japanese cedar was also assessed using lack-of-fit statistics, as shown in Table 5. The Kozak88 model showed again its superiority among the candidate models having the best \( SEE, E, \) and \( MAB \) in most of the D classes in predicting the total stem volume. The Kozak02 model again

| Parameter and fit statistics | Kozak88 | Kozak01 | Kozak02 | Lee03 | Mod Lee03 |
|-----------------------------|--------|--------|--------|-------|----------|
| \( a_1 \)                   | 0.7683 | 1.3946 | 0.9759 | 1.9034 | 2.2673   |
| \( a_2 \)                   | 1.2363 | 0.9892 | 0.8589 | 0.8885 | 0.8896   |
| \( a_3 \)                   | 0.9922 | 0.1737 | 0.3628 | 3.7015 | 1.6992   |
| \( b_1 \)                   | 2.1374 | 0.5105 | 0.3628 | 3.7015 | 1.6992   |
| \( b_2 \)                   | 0.0214 | 0.2523 | 0.5613 | 5.5723 | 2.3628   |
| \( b_3 \)                   | 2.9157 | 0.0418 | 0.3388 | 2.8764 | 1.4579   |
| \( b_4 \)                   | 0.6183 | 0.1350 | 0.0060 | 0.0540 | 0.0210   |
| \( b_5 \)                   | 0.0320 | 0.2497 | 0.0060 | 0.0540 | 0.0210   |
| \( b_6 \)                   | 0.0320 | 0.2497 | 0.0060 | 0.0540 | 0.0210   |
| \( \bar{Y} \)               | 1.5126 | 1.8596 | 1.5234 | 2.1822 | 1.7785   |
| MAB                         | 1.0460 | 1.3420 | 1.0490 | 1.5170 | 1.2590   |
| \( E \)                     | 0.0160 | 0.1350 | 0.0060 | 0.0540 | 0.0210   |
| \( R^2 \)                   | 0.9959 | 0.9938 | 0.9958 | 0.9914 | 0.9943   |
| Rank                        | 1      | 4      | 2      | 5      | 3        |
came second in accurately predicting the total stem volume of Japanese cedar.

Several studies have shown that the Kozak88 stem taper model can provide accurate estimates of the total stem volume for various species in different countries. Huang et al. (2000) concluded that the Kozak88 stem taper model is flexible, easy to use, and readily adaptable to any species. This was proven by Klos et al. (2007) who also used the Kozak88 model for the estimation of stem form and volume of Japanese cedar. Using the Kozak88 model, the best three stem taper models in this study (Kozak88, Kozak02, and Lee03) were predicted and compared to the observed stem profile (Figure 2).

The stem taper models in this study can be applied in the estimation of stem form and volume of Japanese cedar. Using the best three stem taper models in this study (Kozak88, Kozak02, and Lee03), the stem profiles of three Japanese cedar trees were predicted and compared to the observed stem profile (Figure 2). Another application of this study is in the volume prediction of Japanese cedar. The d in the different h should be predicted first using the best model (Kozak88) in this study. Using the Smalian formula, the volume of the different log section can be determined and summed up for the total stem volume estimation. For instance, the total stem volume of a Japanese cedar with a DBH of 32 cm and total height of 20 m can be estimated. The d starting from the stump height (0.20 from the ground) to the H with intervals of 0.50 m can be predicted as follows:

\[ Z_1 = \frac{0.20}{0.20} = 0.01 \]  
\[ X_1 = \frac{1 - 0.01^{1/2}}{1 - 0.22^{1/2}} = 1.01 \]  
\[ d_1 = 0.7683 \times 32^{1.2363} \times 0.9922^{32} \times 1.01^{2.1574 - 0.017} \times 0.8240\times0.01 - 0.011) \times [2.9157 - 0.01^{1/2}] \times -1.6652\exp0.000\times0.009492\times0.09492\times0.09492 / 20] \]  
\[ d_1 = 44.10 \text{ cm} \]

The d of the next height position (h2 = 0.70 m) can also be predicted as follows:

\[ Z_2 = \frac{0.70}{0.20} = 0.40 \]  
\[ X_2 = \frac{1 - 0.04^{1/2}}{1 - 0.22^{1/2}} = 0.91 \]  
\[ d_2 = 0.7683 \times 32^{1.2363} \times 0.9922^{32} \times 0.91^{2.1574 - 0.04^{1/2}} \times -0.8240(0.01 - 0.011) \times [2.9157 - 0.04^{1/2}] \times -1.6652\exp0.000\times0.009492\times0.09492\times0.09492 / 20] \]  
\[ d_2 = 35.67 \text{ cm} \]
This process must be done at every 0.5 m height position until the 19.70 m. After estimation of \( d \), the volume for each log section can now be determined using the Smalian formula as follows:

\[
\text{Volume}_1 = 0.00007854 \times \left( \left( d_1^2 + d_2^2 \right) / 2 \right) \times L \] (11)

\[
\text{Volume}_2 = 0.00007854 \times \left( \left( 44.10^2 + 35.67^2 \right) / 2 \right) \times 0.5 \] (12)

\[
\text{Volume}_3 = 0.0632 \text{ m}^3 \] (13)

By summing up the volumes from the different sections, the total stem volume of this tree is 0.7272 m³. This process can be done with the aid of a spreadsheet or other computer program as it is relatively easier than a pocket calculator (Li et al. 2012).

The performance of the Kozak88 model in volume estimation was compared to the volume model developed for Japanese cedar by Lee et al. (2001) and to a computer program as it is relatively easier than a pocket calculator (Li et al. 2012). The performance of the Kozak88 model in volume estimation was compared to the volume model developed for Japanese cedar by Lee et al. (2001) and to a computer program as it is relatively easier than a pocket calculator (Li et al. 2012).

**Conclusion**

Based on the fit statistics and lack-of-fit statistics, the performance of the five stem taper models was evaluated. The Kozak88 model provided the best performance in accurately predicting \( d \) of Japanese cedar in the southern part of Korea. This model was followed by the Kozak02 and Mod Lee03 model, respectively. The results of this study also indicated that stem taper models can be used to accurately estimate the total stem volume of Japanese cedar. The Kozak88 model also showed its superiority in total volume estimation as compared to the other stem taper models. This model was also superior when compared to the FREPP computer program and volume model developed by Lee et al. 2001 in accurately estimating the total stem volume of Japanese cedar; thus, this model is recommended for the estimation of \( d \), log volume at any given length, merchantable and total volume of Japanese cedar in Jeju island, Korea.

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**Figure 3.** Mean absolute bias (MAB) in the different diameter at breast height classes of the three methods in estimating the total stem volume of Japanese cedar.
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