Turkish Journal of Agriculture and Forestry
http://journals.tubitak.gov.tr/agriculture/
Research Article
Turk J Agric For
(2013) 37: 488-494

doi:10.3906/tar-1209-80

Site index conversion equations for mixed stands of Scots pine (*Pinus sylvestris* L.) and Oriental beech (*Fagus orientalis* Lipsky) in the Black Sea Region, Turkey

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Received: 27.09.2012 • **Accepted:** 22.12.2012 • **Published Online:** 16.07.2013 • **Printed:** 02.08.2013

Abstract: The site index conversion equations are important for estimating the site index of one tree species from the site index of another tree species in mixed stands. In this study, data were obtained from 162 sample plots in mixed stands of Scots pine (*Pinus sylvestris* L.) and Oriental beech (*Fagus orientalis* Lipsky) from the Black Sea Region in the north of Turkey. The breast height ages and height of the site trees were measured and the site index was estimated by these data. Geometric linear regression was used to estimate the parameters of a linear model relating to site indices of Scots pine and Oriental beech species. The correlation between the site indices of Scots pine and Oriental beech was 0.818, indicating a good fit to the linear model. Validation procedure showed that conversion equations were suitable for the studied mixed stands. The conversion equations can be applied to mixed species stands with inconsistent stratification or in stand conversion situations for an accurate and reliable evaluation of forest quality.

Keywords: Mixed stands, Oriental beech, site index conversion equations, Scots pine

1. Introduction

To successfully meet the increasing demand for high quality wood on a sustainable basis, more intensive management is required so that various land use activities do not disrupt the productive potential of the site and the continued growth of the forest. Measurement of site productive capacity is very significant for forestry, because it shows the maximum amount of the principal forest product, wood, which might be available in that forest on that site (West 2009). The productivity of a site for tree growth is usually evaluated on a stand basis (Pretzsch 2009). Information on site quality is often needed to facilitate planning and decision making. Each site should be identified for its productive potential and management decisions should be made accordingly. Site productivity is also a significant parameter for forest growth and yield modeling (Bravo and Montero 2001). Therefore, site productivity has always been a vital consideration in forest management and ecological research (Wang et al. 1994).

Various methods of estimating potential site quality are available. The effect of site quality on tree growth is generally accounted for by using a site index, which can be defined as the average total height of unrestrained free-to-grow trees (dominant or co-dominant trees) in even-aged stands at specific index ages (Vanclay 1994). The site index is a principal factor included in yield models and is a quantitative measure of all the effective factors of a site, such as climatic, biotic, physiographic, and edaphic factors. The site index is based on height–age curves of dominant or co-dominant trees, which must be unsuppressed and undamaged so that the growth reflects the potential productivity of the site (Nigh 2002). This would be the case when height and age data are missing for one species, or if the trees of a species have some early suppression or are not in the dominant or upper co-dominant layer in mixed stands (Nigh and Kayahara 2000). Where one species is harvested and substituted for another species in mixed stands, the site index of the exchange species is also required for planning goals. At that rate, site index conversion equations should predict the site index of one species from the site index of another species in mixed stands (Carmean 1975; Hägglund 1981; Steele and Cooper 1986).

Scots pine (*Pinus sylvestris* L.) and Oriental beech (*Fagus orientalis* Lipsky) are 2 of the most economically and ecologically important forest tree species for Turkey, with a wide range of commercial uses. Scots pine grows in Turkey (38°34′N to 41°48′N and 28°00′E to 43°05′E),

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from Eskişehir in the west to the country's border in the east, occupying the northern part of the country (Anşin and Özkan 2006). Scots pine occupies about 1,241,083 ha in Turkey, growing mainly in the Black Sea coastal mountains (General Directorate of Forestry 2008). Scots pine grows from sea level up to 2700 m (mainly 1000–2500 m) in Turkey. Oriental beech grows naturally in Turkey and is located in the Black Sea, Marmara, Aegean, and East Mediterranean regions, as well as in many other regions of the world (Davis 1982). Oriental beech forests in Turkey cover 1,810,079 ha and compose nearly 8.5% of the country's total forest area (General Directorate of Forestry 2008). The mixtures of these tree species, resulting in diverse forest structure and biodiversity, are widespread in the north of Turkey. Based on a 2008 inventory by the General Directorate of Forestry, the total forest area of Turkey is 21,363,215 ha, of which 9,622,882 ha (45.04%) is mixed stands and 2,350,133 ha (24.42%) of the mixed stand is coniferous and deciduous mixed stand, of which 32,927 ha (1.40%) is mixed stand of Scotch pine and Oriental beech (General Directorate of Forestry 2008).

The mixed stands of Scotch pine and Oriental beech have many biologically and ecologically positive features compared to pure Scotch pine and pure Oriental beech stands. These mixed stands provide proper conditions for the production of higher-quality, longer, and more well-formed stems; enable an increase in harvest due to having different species; provide mull humus soil composition by accelerating decomposition of soil litter; supply an optimal utilization of soil potential and habitat via different root systems; and are more resistant to wind, snow, and ice damage owing to their diversity, structure, and species combinations (Atay 1990; Duchiron 2000).

Early studies about mixed stands of Scotch pine and Oriental beech, which are a mix of coniferous and deciduous trees and intolerant and tolerant trees, were carried out in Germany (Bonnemann 1939, in Pretzsch 2009). In recent years, studies about the planning of mixed stands have become popular, resulting in an increasing trend in these studies worldwide. Changes in silvicultural planning approaches from pure stands to mixed stands increase the need for growth models to determine the effects of silvicultural activities applied in mixed stands. The management of mixed stands of these species is increasingly important for foresters in Turkey. A crucial factor for the sound management of these stands is knowledge of the growth at the individual tree level of each different species. The objective of this study is to develop a site conversion equation for mixed stands of Scots pine and Oriental beech in the Black Sea Region in the north of Turkey.

2. Materials and methods

The study area is located in the Black Sea Region in the north of Turkey, spanning the regional administrative forest districts of Zonguldak, Kastamonu, Sinop, Ankara, and Amasya. This study area ranges in latitude from 40°15′28″N to 41°46′15″N and in longitude from 32°28′02″E to 37°32′56″E (Figure 1). The mean annual temperature is between –5.8 and 14.6 °C, and the minimum and maximum temperatures are 8.4 °C and 22.67 °C, respectively. The climatic regime is a typical Black Sea climate characterized by a mild winter, a cool summer, and relatively homogeneous precipitation with totals as high as 1000 and 1250 mm. The study area is characterized geomorphologically by high mountainous land with moderate and very steep slopes. The altitudes above sea level range from 704 to 1755 m. The mixed stands selected in this area were even-aged, naturally regenerated, and uniformly stocked stands (55%–97% tree layer cover), without any historical evidence of damage such as fire or storms.

Data were obtained from 162 temporary sample plots with ranging stand ages, site index, density, and

Figure 1. Map showing the locations of the regional administrative forest districts in which mixed Scots pine-Oriental beech were studied in the north of Turkey.

mixture percentage in mixed stands of Scots pine (*Pinus sylvestris* L.) and Oriental beech (*Fagus orientalis* Lipsky) (Kahriman 2011). The data were taken from the previous work of Kahriman (2011). The plot size ranged from 0.06 to 0.12 ha, depending on stand density, in order to achieve a minimum of 25–30 trees per species in sample plots. In each plot, some stem analyses were carried out on at least 2 trees, 1 for Scots pine and 1 for Oriental beech dominant or co-dominant trees. Thus, stem analysis data was obtained from 381 stem analyses of 187 Scots pine and 194 Oriental beech trees. These data were measured during the period between August 2007 and September 2009 (Kahriman 2011).

In this study, sample plots were located subjectively to cover the range of site indices of both species and all the different stand structure and mixture proportions, well disturbed over pine and beech species ratios. The studied mixed stands of Scots pine and Oriental beech were also selected to have uniform stratification, where both species were in the upper stratum, such that site trees of both species were in the plot.

In each sample plot, height and age measurements were obtained from dominant and co-dominant trees (the 100 dominant and co-dominant highest trees per hectare concept, for example, requires the measurements of the 4 highest trees on a 0.04 ha plot) for pine and beech species trees separately, with each tree having been free-growing with no obvious evidence of growth abnormalities or damages. Trees were bored with an increment borer to determine age at breast height, with total height measured by a digital hypsometer with 0.1 m precision. Dominant height is calculated as the average height of these dominant or co-dominant trees, and dominant age is the average breast height age of the dominant height trees of the species in these mixed stands. The mean dominant height and dominant age for sample plots were 24.0 m and 89.8 years for Scots pine and 21.3 m and 80.1 years for Oriental beech species, respectively.

When estimating site index for 2 species after height and age measuring, the generalized algebraic difference approach (GADA) site index models developed by Kahriman (2011) were used in this study. The best site index model results were obtained with a GADA derived from the base model of Hossfeld for both species (Kahriman, 2011). The best site index models results were as follows:

$$h_0(SI) = \left[54,132 + \frac{h - 54,132}{1 - \frac{-18,264 \cdot h}{t^{1,4979}}}\right] \Big/ \left[1 + \frac{-18,264 \cdot \frac{h - 54,132}{1 - \frac{-18,264 \cdot h}{t^{1,4979}}}}{t_0^{1,4979}}\right] \quad \text{for pine} \qquad (1)$$

$$h_0(SI) = \left[63,6517 + \frac{h - 63,6517}{1 - \frac{-7,6526 \cdot h}{t^{1,2677}}}\right] \Big/ \left[1 + \frac{-7,6526 \cdot \frac{h - 63,6517}{1 - \frac{-7,6526 \cdot h}{t^{1,2677}}}}{t_0^{1,2677}}\right] \quad \text{for beech} \qquad (2)$$

where t is the age of the stand (years), t_0 is the reference age (100 years), and h is the dominant height (m). We performed a separate nonlinear regression analysis to develop the curve of the site index for both Scots pine and oriental beech species, using a nonlinear least squares technique in SPSS (SPSS 2003). SPSS uses the Levenberg–Marquard algorithm to obtain the final parameter estimates.

2.1. Geometric mean regression line methods

Site index conversion equations were first presented by Doolittle (1958), Foster (1959), Carmean and Vasilevsky (1971), Carmean (1975, 1979), Hägglund (1981), Steele and Cooper (1986), and Vanclay (1992). In these studies, simple linear models and conventional least squares define functional relationships between the site indices of associated tree species. In these models, 2 regression equations are required to make predictions: the first to predict the site index of species A from the site index of species B, and the other for the inverse (B from A).

The geometric mean regression (GMR) line, which is a simple linear model, was used to develop a compatible site index conversion system for species in mixed stands (Nigh 1995). The GMR line in Eqs. (3) and (4) characterizes the relationships between the site indices of 2 species growing in mixed stands.

$$SI_{Sp} = m \cdot SI_{Ob} + b + \varepsilon \qquad (3)$$

$$SI_{Ob} = m \cdot SI_{Sp} + b + \varepsilon \qquad (4)$$

SI_{Sp} is the site index at breast height age 100 for Scots pine, SI_{Ob} the site index at breast height age 100 for Oriental beech, m the slope parameter, b the intercept parameter, and ε an error term.

The parameters m and b of the site index conversion equation were estimated using GMR (Ricker 1973; Nigh 1995). The parameters of the GMR, m and b, were estimated from the following equations (Nigh 1995):

$$\hat{m} = sign(r) \cdot \frac{S_Y}{S_X} \qquad (5)$$

$$\hat{b} = \overline{Y} - \hat{m} \cdot \overline{X} \qquad (6)$$

where r is the correlation coefficient for the site index pairs; sign (r) is +1 if r is positive, –1 if r is negative, and 0 if r is 0; S_Y and S_X are the standard deviations of the dependent and independent variables, respectively; and $\overline{Y}$ and $\overline{X}$ are the means of the dependent and independent variables, respectively ($Y = SI_{Ob}$, $X = SI_{Sp}$). The correlation coefficient shows the strength of the relationship. Formulae for the 95% confidence intervals for the GMR parameters, $\hat{m}$ and $\hat{b}$, are given in Eqs. (7) and (8) (Rayner 1985), respectively:

$$\left[\hat{m} \cdot \sqrt{\frac{1 - Q}{1 + Q}}, \hat{m} \cdot \sqrt{\frac{1 + Q}{1 - Q}}\right] \quad (7)$$

$$\hat{b} \pm t_{n-2,0.975} \cdot \sqrt{\frac{(S_Y)^2}{n} \cdot (1 - r) \cdot \left(2 + \overline{X}^2 \cdot \frac{1 + r}{(S_X)^2}\right)} \quad (8)$$

where $t_{n\text{-}2,0.975}$ is the 0.975th quantile of Student's t distribution with $n - 2$ degrees of freedom, n is the number of observations, and

$$Q = t_{n-2,0.975} \sqrt{\frac{1 - r^2}{r^2 \cdot (n - 2)}} \quad (9)$$

The error in the predicted site index for both Scots pine and Oriental beech was determined (actual site index – predicted site index by refitted model), and the mean and standard deviation of the errors for both species were computed. The errors were tested for normality with the Kolmogorov–Smirnov test (Lilliefors 1967; Dallal and Wilkinson 1986) and for bias with a t-test (Nigh and Kayahara 2000).

3. Results

The means and standard deviations of the 2site indices for Scots pine and Oriental beech species and the correlation between the mare presented in Table 1. Table 2 shows the results of the GMR for models (3) and (4) fit to Scots pine and Oriental beech species data. This table includes the parameter estimates $\hat{b}$ and $\hat{m}$ and their 95% confidence intervals. The mathematical equivalence of fitted models (3) and (4) can be easily demonstrated by inverting one model and noticing that the parameters are the same (with tolerance for rounding errors) as the parameters in the complementary model (Nigh and Kayahara 2000). The correlation coefficient for site indices of Scots pine and Oriental beech species is 0.818. The correlation between the Scots pine site index and the Oriental beech site index is strong. Figure 2 is a plot of the data points overlaid on the models for the site indices of Scots pine and Oriental beech. This figure shows a definite relationship between the site indices of Scots pine and Oriental beech when they are growing in a mixed stand.

The mean and standard deviation of the errors in the calculated site index for pine were -2.58×10^{-10} and 2.584 m, and for beech they were 4.91×10^{-9} and 2.190 m. The critical values for the D_α test (Kolmogorov–Smirnov) at 95% significance level (P = 0.200 for both trees) are approximately 0.06178026071 and 0.06178026077 for pine and beech, respectively. The Kolmogorov–Smirnov statistic indicates that the errors in an estimated site index are normally distributed.The t-tests show that all models used are unbiased, that is, the mean errors from the models are not statistically significantly different from 0, t-value = -1.076×10^{-9} and 2.851×10^{-8}, P = 0.995 and 0.994 for pine and beech, respectively. Figure 3 shows the distribution of the residuals for Scots pine and Oriental beech site index models, and both models are distributed normally. Both site index models fit the data well and no obvious residual trends were found (Figure 4). Figure 5 shows good performance between the observed and predicted site index for Scots pine and Oriental beech.

Table 1. The means and standard deviations of the 2 site indices for pine and beech species and the correlation coefficient between them.

Species	Means	Standard deviations	Correlation coefficient
Scots pine	25.92	4.28	0.818
Oriental beech	24.26	3.63	

Table 2. Results of the geometric mean regression analysis.

Model	Parameter $\hat{b}$			Parameter $\hat{m}$		
	Estimate	95% Lower CI	95% Upper CI	Estimate	95% Lower CI	95% Upper CI
$SI_{pine} = b + m \cdot SI_{beech}$	−2.7043	−5.2931	−0.1156	1.1802	1.0568	1.3180
$SI_{beech} = b + m \cdot SI_{pine}$	2.2914	1.1553	3.3887	0.8473	0.7587	0.9462

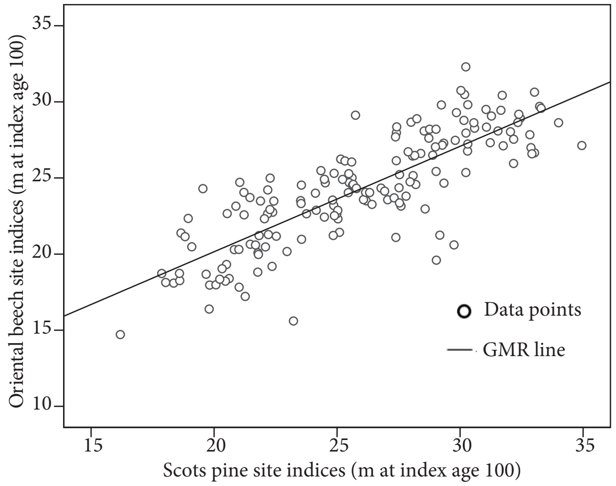

Figure 2. Oriental beech and Scots pine site indices with the fitted geometric regression line.

4. Discussion

This study developed a single set of site index conversion equations predicting the site index of pine trees from the site index of beech trees, and vice versa, in mixed pine/beech stands. These equations are:

$$SI_{Sp} = -2.7043 + 1.1802 \cdot SI_{Ob} \quad (10)$$

$$SI_{Ob} = -2.2914 + 0.8473 \cdot SI_{Sp} \quad (11)$$

These equations were derived using the same data, but with the SI_{pine} and SI_{beech} variables reversed (Table 2). The equations are applied by obtaining the site index for either the pine or beech species. The known site index is then input into either Eq. (10) or (11), depending on whether the site index of pine or beech species is known, to estimate the site index of the complementary species. The conversion equations are designed specifically for mixed species stands. However, they can also be used for stand conversion situations, that is, when a stand of one species is harvested and regenerated with another species. In this situation, species interactions will not be present, and so the estimated site index may be biased (Nigh and Kayahara 2000). The scatter plot (Figure 2) shows that the relationships between site indices for Scots pine and Oriental beech mixtures are linear. This makes the geometric mean line an appropriate model for these species indices.

The simple linear models developed by ordinary least squares technique do not give compatible 2-way predictions. That is, if the site index of species A is x and the predicted site index of species B is y, then using y to predict the site index of species A does not result in a prediction of x. However, the geometric mean line regression technique presents site conversion equations that make compatible prediction equations. This study developed site conversion equations by GMR line for Scots pine and Oriental beech mixtures that can be used for 2-way prediction of site indices. When developing site conversion equations, a GMR line was used because GMR provides a 2-way prediction, but not ordinary least squares. Especially in attempting to predict a species' site index from that of another species, having a 2-way prediction is important for accurate estimation of site indices.

In this study, uniform stratification takes place in mixed stands of Scots pine and Oriental beech, where both species have been in the upper stratum from stand initiation to stand collapse. In this situation, the calculated site index can be used as a measure for site productivity and height growth modeling because appropriate site trees for both species exist. However, in some mixed

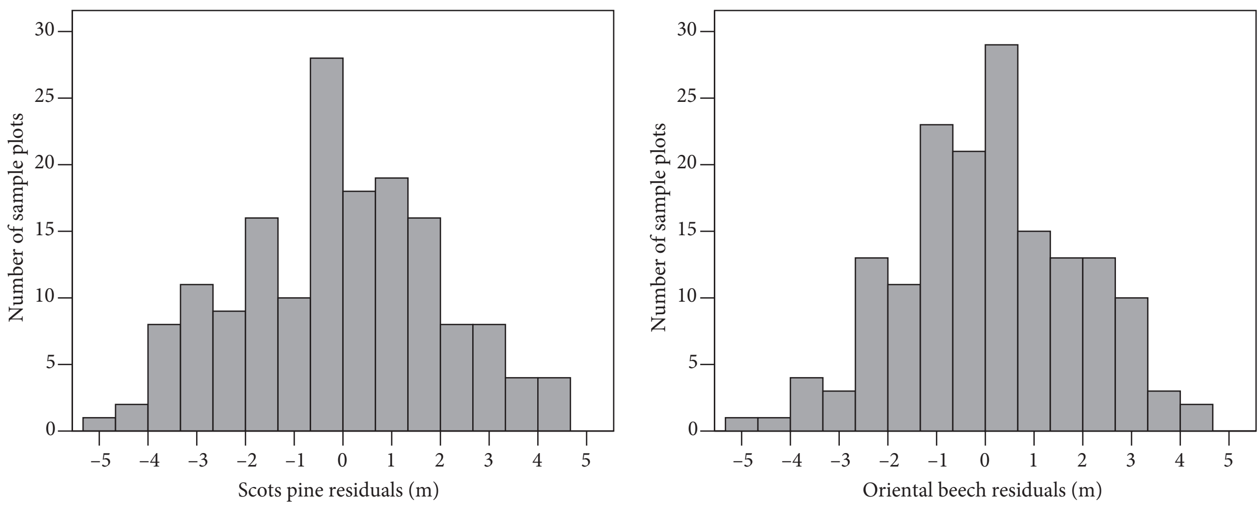

Figure 3. Distribution of the residuals of site index models for Scots pine and Oriental beech.

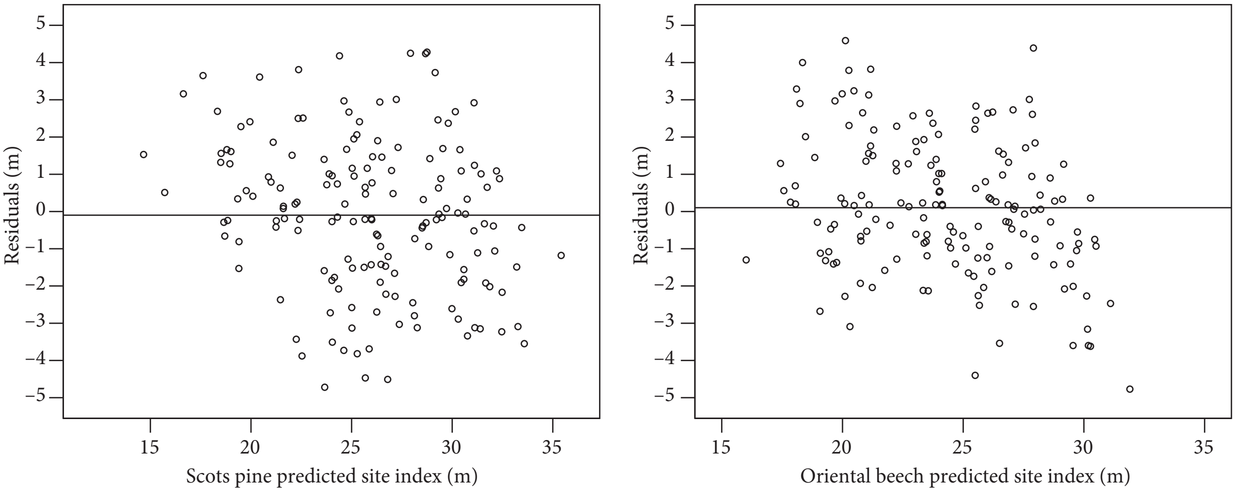

Figure 4. Residuals versus site index prediction for Scots pine and Oriental beech.

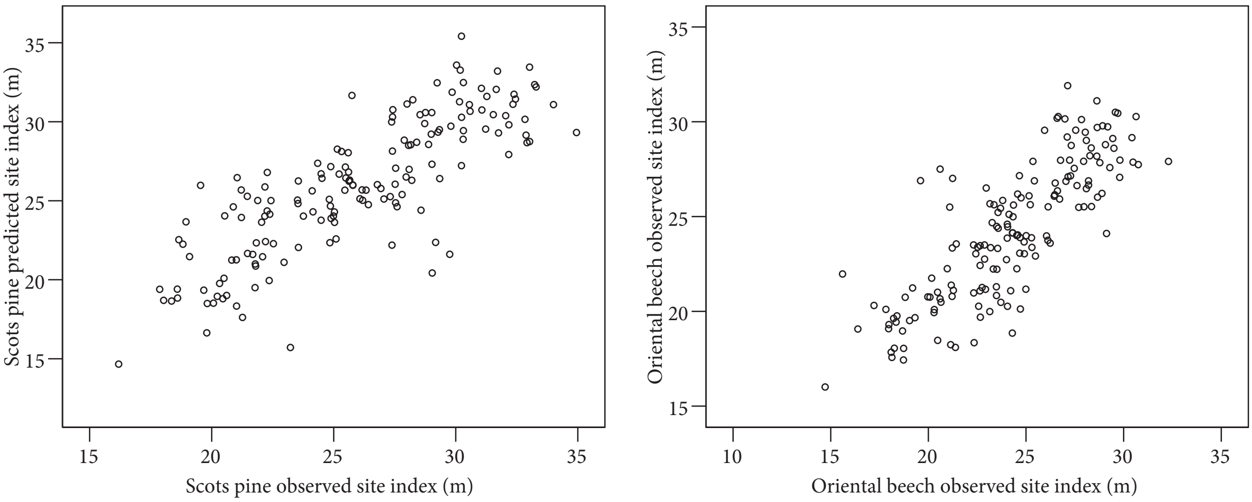

Figure 5. Observed versus predicted site index for Scots pine and Oriental beech.

stands of Scots pine and Oriental beech not contained in this study, inconsistent stratification occurs when one species may be in the upper strata and another species may be in the lower strata. In this situation, the height of one species consistently lags behind the other species. In these stands, a site index may not be an appropriate measure of site productivity for other species, because the dominant species may be suppressing the growth of other species, especially if the trees of one species have some early suppression or are not in the dominant or upper co-dominant layer in mixed stands. Therefore, site index conversion equations developed for mixed stands of Scots pine and Oriental beech with uniform stratification are important to estimate the site index of species in the lower strata from ones in the upper strata for mixed stands of these species with inconsistent stratification. The use of conversion equations for these stands provides accurate and reliable evaluation of forest quality. This knowledge is necessary for effective forest management, because forest planning is, to some extent, based on the ability to assess forest productivity. These conversion equations will be invaluable tools in forest management for these Scots pine and Oriental beech mixed stands.

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