Preliminary Analysis on Site Index of Sugi (Cryptomeria japonica) Planted Forests Using the National Forest Inventory Data in Kyushu Island

Yasushi Mitsuda1*, Fumiaki Kitahara2

Abstract: The objective of this study was to examine the effectiveness of using the Japanese National Forest Inventory (NFI) data in modeling site productivity. We investigated the relationship between the site index of sugi (Cryptomeria japonica) planted forests derived from the NFI data and climatic and topographic factors. The study area was the main island of Kyushu located in the south-west part of Japan. We estimated the site index with the guide curve method using the data set of dominant tree height and stand age of sugi planted stands derived from the NFI data. Solar radiation index, hydrological upslope contributing area, and vertical exposure index were used as topographic factors. Annual mean temperature and annual precipitation were used as climatic factors. Correlation analysis did not detect any significant relationship between estimated site index and topographic and climatic factors. Possible scenarios that may have contributed to the lack of significant correlation, which was contrary to the findings of previous studies, are discussed.

Keywords: climatic factors, guide curve method, topographic factors

1. Introduction

Developing a spatial distribution map of site productivity is one of the most pressing issues in the area of forestry. Local governments across Japan are required to develop a public forest zoning plan that delineates the timber production area and the conservation area in the Japanese public forest planning system (Kawano, 2013). A site productivity map is an essential component for the implementation of reasonable forest zoning (Mitsuda, et al., 2013). Thus, the importance of landscape scale forestry and site productivity map have been increasing.

Data collected from a large area is needed for the development of a site productivity model which can be applied utilized in building a site productivity map for a wide area. Since 1999, the Japanese National Forest Inventory (NFI) has been in progress and provisions were initiated in 2014. This data has been utilized in a mechanistic 4-km grid sampling that provided a spatially unbiased data. The NFI data will be useful for modeling site productivity because of its lack of sampling bias.

Site index, defined as the height of the dominant trees at a specific reference age, is the most commonly used measure of site productivity (e.g., Takeshita et al., 1960; Hägglund, 1981; Davis and Johnson, 1987; Monserud et al., 1990; Wang, 1998). Several papers have previously described the relationships between the site indices of various species and topographic factors derived from digital terrain analysis using digital elevation models (e.g., McNab, 1989; Iverson et al., 1997; Mitsuda et al., 2001; 2007; Minowa et al., 2005). Topographic factors can serve as good predictors of a site index model for a relatively smaller area, whereas climatic factors should be considered in modeling a site index for a relatively wider area. Various studies on sugi (Cryptomeria japonica) site index have been conducted within a relatively small area using topographic variables as explanatory variables, although the effects of climatic factors on the sugi site index have not been extensively examined (e.g., Yamane et al., 1990).

The objective of this study was to examine the effectiveness of the NFI data in modeling site productivity. We investigated the relationship between site index of sugi planted forests derived from the NFI data and climatic and topographic factors. This preliminary analysis will be helpful for future studies that attempt to develop statistical models to predict site index spatial distribution particularly for wide areas. As previous studies revealed, soil factors have large impacts on site productivity (e.g., Monserud et al., 1990). We tried developing a site index prediction model using data from broader area derived from the NFI. Unfortunately reliable data of soil characteristics for the whole study area was absent, therefore soil factors were not considered in this study.
2. Materials and Methods

The study area was the main island of Kyushu, located in the south-west region of Japan, where forestry activity is higher than the other regions, except for Hokkaido. The target tree species was sugi which is the most important planting species in Japan. Approximately 20% of the land area of Kyushu is sugi planted forest; thus, higher forestry activity depends on a large amount of sugi planted forests.

We used the data set of the dominant tree height and stand age of sugi planted stands derived from the NFI data. The NFI was launched in 1999, with approximately 14,000 plots located at each 4-km grid point, and surveyed every 5 years. Since 2014, the Ministry of Forestry have provided the NFI data of the first and second period (1999 to 2003 and 2004 to 2008). We used only the second period data because of its reliability (Kitahara et al., 2010a). Each plot was composed of three concentric circles, with radii of 5.64 (0.01 ha), 11.28 (0.04 ha), and 17.84 m (0.1 ha) and trees larger than 1 cm, 5 cm, and 18 cm in diameter were measured in each circle (Kitahara et al., 2009). Details of the sampling design and field measurements for the NFI data were previously described in Kitahara et al. (2009). We selected plots of pure sugi planted stands and determined the dominant tree height as that of the tallest tree.

We adopted an ordinal guide curve method (c.f., Clutter et al., 1983) to the data set of the dominant tree height and stand age to estimate the site index of each plot of the sugi planted stand. First, we applied upper and lower limits of tree height and age relationship (i.e., height curve) that were derived from our previous study (Mitsuda et al., 2007) to remove data with considerable error from 407 data of sugi pure stands. For plots where stand age was older than the reference age (40 years old), we mitigated the restriction for data screening by adding a 5-m buffer to the upper and lower limits. A total of 320 plots remained after data screening (Figure 1).

![Figure 1. Relationship between the dominant tree height and stand age of the NFI plot of pure sugi planted stands. (Solid lines show height curves of upper and lower limits. Filled and open circles indicate accepted and rejected data through the data screening procedure.)](image)

The remaining plots were classified into 5-year age classes, and the average height and age of each age class were calculated (Figure 2). Three-parameter Richard’s function (Eq.[1]) was applied to the average height and age of each age class, and the parameters of the guide curve were then estimated by nonlinear regression, which was weighted by the number of plots in each age class.

\[ H = A_0(1 - \exp(-k_0 \times t))^{m_0} \]

where \( H \) is the average dominant tree height (m); \( t \) is the average age (in years); and \( A_0 \), \( k_0 \), and \( m_0 \) are parameters of the guide curve. Using estimated parameters of \( k_0 \) and \( m_0 \) as parts of the
Figure 2. Relationship between the average of dominant tree height and the average of stand age for each 5-year interval age class. (Circles indicate the average dominant tree height at the average stand age for each age class. Boxes indicate the site index ranges of 25% to 75% quantiles of each age class. Whiskers indicate the ranges of minimum to maximum site index of each age class. Solid line indicates the guide curve.)

Parameters of height curve of each plot, height curve for each plot was estimated by Eq.[2]:

$$A_i = \frac{H_i}{(1 - exp(-k_0 \times t_i))^{m_0}}$$

where $H_i$ and $t_i$ are dominant tree height and age of $i$th plot, respectively, and $A_i$ is the parameter of the height curve of $i$th plot. Finally, the site index of each plot was estimated as the dominant height of a 40-year-old stand by applying Richard’s function with parameters of $A_i$, $k_0$, and $m_0$ (Eq.[3]).

$$SI_i = A_i(1 - exp(-k_0 \times 40))^{m_0}$$

where $SI_i$ is site index of $i$th plot.

Coefficients of correlation between site index and climatic factors were calculated to explore limiting factors of site index. Solar radiation index (SRI), hydrological upslope contributing area (UCA), and vertical exposure index (VTEX) at a 50-m resolution were used as topographic factors. SRI indicated intensity of solar radiation in relation to soil moisture shortage, and was calculated by solar zenith, azimuth angle and surface zenith, azimuth angle (Smith et al., 1980). UCA indicated soil water supply, which was represented by movement of soil water along topography, and determined by the multiple flow direction algorithm to simulate soil water dynamics (Quinn et al., 1991). UCA was transformed into a logarithm (logUCA) for correlation analysis to remove the effects of the heavy-tailed distribution. VTEX indicated the topographic exposure related to the risk of the forced evapotranspiration by wind, and calculated as the sum of nadir angles in eight directions (Mitsuda et al., 2007). Details of the calculation method of topographic factors were described in (Mitsuda et al., 2007). The topographic factors of each plot were derived from the 50-m resolution digital elevation model published by the Geographic Survey Institute, Japan. Annual mean temperature and annual precipitation at a 1-km resolution were used as climatic factors, because past studies listed these two factors as important climatic factors to predict sugi site productivity (e.g., Zushi, 2007). The climatic factors of each plot were acquired from the average climatic data of a 1-km grid published by the Japan Meteorological Agency.

Furthermore, we calculated coefficients of correlation using the plot where stand age was equal or older than the reference age of site index (i.e., 40 years old), because the data of younger plots could cause larger errors during the estimation of the site index.
Table 1. Coefficients of correlation between site index and topographic and climatic factors.

|          | All data | < 40 | 40 ≤ |
|----------|----------|------|------|
| SRI      | −0.0455  | −0.0809 | −0.0341 |
| logUCA   | −0.0862  | −0.0624 | −0.0948 |
| VTEX     | 0.0426   | −0.0705 | 0.0720 |
| Ann. Mean Temp. | 0.0572 | 0.0228 | 0.0718 |
| Ann. Prec. | −0.0565 | −0.0196 | −0.0686 |

3. Results

The estimated guide curve is shown in Figure 2, and the parameters $A_0$, $k_0$, and $m_0$ were estimated as 25.71, 0.053, and 1.822, respectively. The average, minimum, and maximum of the estimated site index of each plot were 20.44, 10.74, and 28.00, respectively. Compared with the measured site index in our previous study (Mitsuda et al., 2007), values of the estimated site index were within a reasonable range, similar to the measured site index of sugi planted stands. The standard deviation (3.28), 25% quantile (18.25), and 75% quantile (22.76) indicated that most of plots had site indices with relatively small variations.

The relationship between site index and topographic and climatic factors is shown in Figure 3. Table 1 shows the coefficients of correlation between the site index and topographic and climatic factors. All of coefficients of correlation were not statistically significant. The coefficients of correlation between site index and topographic and climatic factors were between −0.0862 and 0.0572 using all data, and between −0.0948 and 0.0720 using data equal or older than 40 years. The highest correlation was observed in logUCA, both with all the data and data equal or older than 40 years; however, its coefficient of correlation was quite low, and showed a negative value, despite the previous observation of a positive correlation (Mitsuda et al., 2007).

4. Discussion

The present study did not detect any significant relationship between sugi site index and topographic and climatic factors, although a strong correlation has been previously reported. Mitsuda et al. (2007) reported relatively high values for the correlation coefficient with SRI, logUCA, and VTEX as −0.615, 0.449, and −0.409, respectively. Other studies have shown that topographic factors were good predictors of site index of sugi planted forests (e.g., Takeshita, 1964; Chen and Abe, 1999; Minowa et al., 2005; Zushi, 2007). In addition, topographic factors were considered as important explanatory variables of site index prediction models for other species (e.g., McNab, 1989; Iverson et al., 1997; Mitsuda et al., 2001). Annual mean temperature was the most representative variable to predict site productivity of sugi planted forest in the northwestern Toyama Prefecture (Zushi, 2007). Takeshita et al. (1967) earlier reported that annual precipitation was an important factor that could be used in predicting site indices of sugi planted forests with wide areas.

Based on the assumption that there is a significant relationship between site index and topographic and climatic factors, we present two reasons why we failed to detect any significant relationship: 1) errors contained in the NFI data and 2) errors in the site index estimation. Kitahara et al. (2009) assessed the measurement of the NFI, and they detected biases in the measurement of tree diameter and height. In addition, Kitahara et al. (2010b) identified position errors in the NFI plots, which indicate that some NFI plots were not established at its designed positions. A stand where a plot was located was confirmed by reading from the forest map and overlaying the designed 4-km grid, and the stand age of each plot was then estimated as that of the stand at the designed 4-km grid point. If a plot established at a position that differed from the designed 4-km grid point, the stand where the plot was located may vary from the expected stand. Therefore, errors in position could cause anomalies in stand age estimation. Errors in size measurement and plot position contained in the original NFI data should not be overlooked.

As stated above, soil factors, which were considered as important factors for modeling site index, were not used as explanatory variables in this study. Several authors have pointed out that
Figure 3. Relationship between site index and topographic and climatic factors of each plot. (Filled and open circles indicate plots where stand age is equal or older and younger than the reference age.)
growth limiting factors varied with site types (e.g., Wang and Klinka, 1996; Curt et al., 2001), thus relationships between site productivity and topographic and climatic factors may change with soil type and geology. The failure in detecting significant relationship between site index and topographic and climatic factors would result from the lack of soil and geology factors. We need to consider the effects of soil characteristics and geology on site productivity in future studies.

Another factor that may have influenced the analysis is the errors in the estimation of the site index of each plot. Data selection by stand age did not improve the result of correlation analysis (Table 1), which suggests that there were errors in the estimation of the site index in both younger and older stand data. Estimating the site index at a stand that is older than the reference should be easier than that using a younger stand; however, estimation errors may also exist in older stands. Therefore, the methodology in estimating site indices may be unreliable, even if errors in size measurement and plot position contained in the NFI data have been identified. The ordinal guide curve method adopted in this study could be responsible for the lack of correlation among variables, as an anamorphic height curve is a strong constraint against estimating site indices (Clutter et al., 1983). Anamorphic height curve was assumed when we applied the ordinal guide curve method (Clutter et al., 1983), whereas polymorphic height curves were detected at sugi planted stands in our previous study (Mitsuda et al., 2007). Therefore, other methodologies in estimating site indices of each plot should be utilized. In our previous study, we proposed a model that combined site index prediction with topographic factors and polymorphic height curve development (Mitsuda, 2014). A model oriented approach, such as this combined model, may be useful for this situation.

These two factors may have affected the results of the present study, and the second factor could be improved by applying other methodologies. We cannot conclude that the NFI data is not available for developing a site index prediction model. Thus we need to continue investigating the effectiveness of the NFI data in modeling site productivity.

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