Modifying the site index model of sugi planted forests in Miyazaki Prefecture considering the effects of DEM quality and scale of digital terrain analysis

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ABSTRACT

The objectives of this study were 1) to modify the site index prediction model for sugi (*Cryptomeria japonica*) planted forests in Miyazaki Prefecture developed in a previous study and 2) to investigate the effects of quality of DEM and the scale of digital terrain analysis on the performances of site index models. The study site was the Tano Forest Science Station, University of Miyazaki. We acquired 18 data sets of site index estimated using stem analysis and global position of each sample site where a sample tree was felled. Three topographic factors, a solar radiation index, a hydrological upslope contributing area index, and a vertical topographic exposure index, were derived from DEMs generated from three data sources (10-m and 50-m interval point data with 3D coordinates and digitized contour map) and at resolutions of 10, 12.5, 25, and 50 m. Several search ranges (100, 250, 500, and 1000 m) were tested. Correlation analysis between site index and topographic factors as well as regression analysis to develop a site index prediction model using topographic factors as explanatory variables revealed that the hydrological upslope contributing area index requires DEMs generated from more informative DEM data sources (10-m interval point data and digitized contour map) and at fine resolution (10 m or 12.5 m); however, these DEMs were unsuitable for solar radiation index. DEMs generated from a less informative DEM data source (50 m interval 3D point data) and at a coarse resolution of 50 m were suitable for the solar radiation index. The effects of search ranges on topographic factors were clear for vertical topographic exposure index but not for the others. The best model developed in this study accepted the solar radiation index derived from the digital contour map based 10-m resolution DEM, the hydrological upslope contributing area index derived from the digital contour map based 12.5-m resolution DEM, and the vertical topographic exposure index derived from the 50-m interval 3D point data based 50-m resolution DEM as the explanatory variables. The descriptive measures of model performance of this best model, namely R^2 , adjusted R^2 , and residual mean squared error, were 0.830, 0.793, and 1.522, respectively. These values indicated that the best model of this study was superior to the previous one developed using only a digital contour map based 12.5-m resolution DEM.

keyword: digital elevation model, digital terrain analysis, scale problem, site index, sugi

INTRODUCTION

Predicting the spatial distribution of site productivity for a target planting species is essential for landscape-scale forest management (Kayahara et al., 1998; Klinka and Feller, 1984; Mitsuda et al., 2003; 2013; Takeshita et al., 1966). Digital terrain analysis (DTA) using a digital elevation model (DEM) can describe topographic features associated with plant

ecophysiological performance, which has been used to provide explanatory variables in modeling site productivity (e. g., Chen and Abe, 1999; Iverson et al., 1997; McNab, 1989; Minowa et al., 2005; Mitsuda et al., 2001; 2007; Munajati et al., 2009; Sturtevant and Seagle, 2004; Zushi, 2007). DTA is highly dependent on DEM quality, which affects the performance of site productivity prediction models. Using DEMs derived from various data sources and generated at various grid resolutions, we attempted to modify the site productivity model of sugi (*Cryptomeria japonica*) planted forests developed in our previous study (Mitsuda et al., 2007). We also investigated the effects of DTA scale on the site productivity model using this model modification procedure. These analyses revealed that site productivity models based on DTA were affected by DEM quality and DTA scale. Our findings will lead to a better understanding of the

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relationship of site productivity of sugi with topography; moreover, they will help in developing better site productivity models for other species and regions.

Topography is a key factor in representing plant responses to the environment and forest management (Takeshita et al., 1966). Site productivity, a concept used for representing a specific tree species' growth suitability for a given site (Davis and Johnson, 1987), has been studied with respect to topography. Site index, defined as the height of the dominant trees at a specific reference age (Davis and Johnson, 1987), is the most commonly used measure of site productivity for a target species (e.g., Davis and Johnson, 1987; Hägglund, 1981; Monserud et al., 1990; Takeshita et al., 1960; Wang, 1998). Various DTA-derived indices that represent topographic features, hereinafter referred to as topographic factors, have been used to develop site index prediction models (e.g., Iverson et al., 1997; Mitsuda et al., 2007; Zushi, 2007). Here we define three points to be considered in DTA: data source, grid resolution, and search range (Wilson et al., 2000). The term "search range" will be further explained in the following section. The value of a specific topographic factor for a specific site varies with respect to these three points; therefore, these points can affect site index model performance. DEM data sources are categorized into three data structures: regular grids, triangulated irregular networks, and line vectors representing contours. Such data sources are employed to generate a raster-type DEM that can be used in DTA. Several square-grid DEM data sources with various grid resolutions have been recently published, and some of them are usually available for a site of interest in Japan. However, a square-grid DEM source consists of summarized data that has lost detailed topographic information. Contour-type DEM data sources that do not lose topographic information can be used by digitizing the contour lines of the original topographic map; however, this is time-consuming and labor-intensive. Thus, it is desirable to examine the effect of DEM data source on DTA in aspects of primary data structure (Van Niel et al., 2004; Wilson et al., 2000).

Scale remains an important but unsolved issue in scientific studies with spatial data, and scale problems defined by grid resolution and search range are important DTA-associated issues (Wilson et al., 2000). Determining a DEM's optimum grid cell size to represent topographic features with respect to target physical phenomena is a common scale problem (Hutchinson and Gallant, 2000; Sharma et al., 2011). Another scale problem is the determination of the optimum range for calculating topographic factors when the geomorphological pattern influences the target process of a site. Typically, algorithms used to calculate topographic factors with raster-type DEMs require an arbitrary value as a parameter (radius or window size) to define the range for searching a geomorphological feature that influences the physical phenomenon in the subject grid cell. Here we refer to the range (a circle or rectangle) defined by the given parameter as the search range.

In our previous study, we developed a site index model for sugi planted forests in Miyazaki Prefecture, Japan using

DTA-derived topographic factors (Mitsuda et al., 2007). Because DEM quality and the DTA scale problem were insufficiently considered in this previous study, we sought to modify the previous site index model while accounting for these two issues. The objectives of this study were 1) to evaluate the potential modification of the site index prediction model for sugi planted forests in Miyazaki Prefecture developed in a previous study and 2) to investigate the effects of quality of DEM and the scale of digital terrain analysis on the performances of site index models. Furthermore, we attempted to ascertain the appropriate DTA scale to represent each topographic feature with respect to site productivity.

MATERIALS AND METHODS

The study site was the Tano Forest Science Station, University of Miyazaki. The university forest (spread across 502 ha) is located in a lowland (approximately 110–300 m a.s.l.) of Miyazaki Prefecture, in a warm-temperate region in southeastern Kyushu Island, Japan, where the natural vegetation is evergreen broad leaved forest. The annual mean temperature and precipitation are 16.5°C and 2800 mm, respectively. The site index data set used here is the same as that used in our previous study (Mitsuda et al., 2007). We felled the dominant tree in 18 sample sites where the stand age was greater than the reference age (40 years), and estimated the height of each dominant tree at the reference age as the site index by implementing Richards' three-parameter equation to the height-age data set derived from stem analysis. After felling, we recorded the position of each felled tree using DGPS (Trimble, Pathfinder ProXR). Thus, we acquired 18 data sets of precisely measured site index and global position of each sample site.

We used three DEM sources: 50-m and 10-m resolution square-grid DEMs published by the Japanese Geographic Survey Institute (GSI, now renamed the Geospatial Information Authority of Japan) and 10-m interval vectorized contour (hereafter, GSI50, GSI10, and CNT, respectively). Using 1:25000-scale topographic maps derived from manual stereoscopic interpretation of aerial photographs, GSI50 and GSI10 were obtained by reading the elevation on 50- and 10-m grids, and these two DEM data sources were treated as points with 3D coordinates at the center of grid cells. The CNT was obtained by digitizing the contour lines of the 1:25000-scale topographic maps of the study area, which maintained complete detailed topographic information of the 1:25000-scale topographic maps, whereas point-type data source (GSI50 and GSI10) lost it.

We interpolated the three data sources to yield raster-type DEMs with resolutions of 10, 12.5, 25, and 50 m by the minimum curve method that fitted a two-dimensional cubic spline surface producing a smoothly varying surface. The four resolutions were set to compare our previous research (Mitsuda et al., 2007) using three of them (12.5, 25, and 50 m resolution), and 10-m resolution square-grid DEM was newly published after the previous research. As various DEMs were used in this study, each DEM was identified by its data source and grid resolution. For example, GSI10-50 denoted a

50-m resolution DEM derived from GSI10.

We focused on three environmental factors, namely solar radiation index (SRI), hydrological upslope contributing area index (UCA), and vertical topographic exposure index (VTEX) because these were selected as the explanatory variables of the best models in the regression analysis in our previous study. The SRI indicates the intensity of solar radiation that causes soil moisture deficiency, and it is proportional to the cosine of the solar incident angle (Smith et al., 1980; Mitsuda et al., 2001; 2007; Zushi, 2007). Solar incident angle is calculated by solar zenith, azimuth angle and land surface zenith, azimuth angle. The solar position with respect to the location of the sample site and time was estimated. The cosine of the solar incident angle was then calculated with respect to the solar position and land surface properties. The UCA reflects the tendency of water to accumulate in a catchment area (Beven and Kirkby, 1979; Mitsuda et al., 2001; 2007; Quinn et al., 1991; 1995). We determined the hydrological contributing area using a multiple-flow-direction algorithm to simulate soil water dynamics and weighted the UCA by slope angle and effective contour length to obtain the UCA used. This UCA was then converted into natural logarithm values and used in subsequent statistical analysis. VTEX is related to wind exposure and indicates the risk of forced evapotranspiration (e.g. McNab, 1993; Mitsuda et al., 2001; 2007; Quine and White, 1998; Takeshita et al., 1966; Yokoyama et al., 2002; Zushi, 2007). The depression angle to the lowest point was recorded for each of the eight main compass directions and then summed as VTEX, similar to Yokoyama's negative openness (e.g. Yokoyama et al., 2002).

We calculated the three topographic factors with search ranges of 100, 250, 500, and 1000 m. For calculating SRI, it was necessary to check whether the solar position at a given site and a given time was higher than the sky line; this was determined using surrounding elevation data within the assigned search range. For calculating UCA, the hydrological contributing area at a given site within the assigned search range was detected. For calculating VTEX, the lowest point for each direction for a given site within the assigned search range was found. As various topographic factors were used in this study, each topographic factor was identified by its index name, its assigned search range, and its DEM. For example, SRI-100_GSI10-50 denoted a SRI calculated with 100-m search range using GSI10-50.

To detect trends in the correlation between the site index of sugi planted forests and each environmental factor with respect to various DEM sources, resolutions and search ranges, we calculated the correlation coefficients between the site index and the three environmental factors derived from each DEM defined by a combination of three sources and four resolutions.

We examined the effects of DEM quality and DTA scale on the performance of the site index model using a step-wise regression analysis. From the candidate models that comprised possible combinations of the three environmental factors, we selected the best linear regression model using Akaike's Information Criterion (AIC). First, we used the topographic factors derived from a DEM with the same source and resolution to construct candidate models. Next we

used the topographic factors derived from DEMs with the same source but of various resolutions. Finally, we used the topographic factors derived from DEMs of all resolutions from all sources. In addition, we used the topographic factors derived from DEMs of all resolutions from GSI10 and GSI50, because of data availability.

RESULTS

Correlation coefficients between the site indices of sugi planted forests and environmental factors are shown in Fig. 1. In general, the site index was negatively correlated with SRIs and VTEXs. Hence, the Y-axes are inverted in the SRI and VTEX plots. The highest correlation coefficient (in absolute value) was 0.752, observed for UCA-250_CNT-12.5. The correlation coefficients were higher for UCAs derived from DEMs generated from more informative DEM sources and in finer resolutions (CNT-10, CNT-12.5, GSI10-10 and GSI 10-12.5). They were lower for those derived from DEMs generated from CNT and GSI10 at coarse resolutions and from GSI50 at all resolutions. In contrast, the correlation coefficients between site index and SRI derived from GSI50 were better (lower) than those derived from CNT and GSI10. There were weaker correlations of site index with VTEXs than with UCAs and SRIs. The changes in correlation coefficients between site index and SRIs and UCAs with change in the search range were small, whereas the correlation coefficients between site index and VTEXs decreased significantly with increase in search range.

The descriptive measures of model performance (AIC, R^2 , R^2_a , and RMSE) of the best linear regression models calculated for the best models of each DEM source and each grid resolution are shown in Table 1. The model performances improved with finer resolution for CNT and GSI10-based models, but worsened with finer resolution for GSI50-based models (Table 1). The accepted explanatory variables were SRI-100_CNT-10 and UCA-100_CNT-12.5 for the best model selected from alternative models of all possible combination of topographic factors derived from DEMs generated from CNT and in all resolutions, which we called here as the CNT best model, SRI-100_GSI10-12.5, UCA-250_GSI10, and VTEX-100_GSI10-10 for the GSI10 best model, and SRI-1000_GSI50-50 and VTEX-100_GSI50-50 for the GSI50 best model (Table 2). The best CNT model and the best GSI10 model adopted 10- or 12.5-m resolution topographic factors, whereas the best GSI50 model adopted only 50-m resolution topographic factors. Among these three best models, the model performance was the finest for the best CNT model, followed by the best GSI10 model, and then the best GSI50 model. The best model among all possible candidates (the all-best model) and the best model among candidates derived from GSI10 and GSI50 (the best GSI model) adopted topographic factors derived from CNT-10, CNT-12.5, GSI-10, or GSI-50 (Table 3). Because UCA-250_GSI 10-10 were accepted in the best GSI10 model, we also calculated the descriptive measures of model performance of the second best GSI model using SRI-1000_GSI50-50, UCA-250_GSI10-10, and VTEX-100_GSI50-50. The AIC of this model was 80.754, indicating that model performance of the

Fig. 1 Correlation coefficients between site index and topographic factors calculated using various search radii and data sources.

Table 1 Best site index model for each DEM source and resolution.

Source	Resolution	Variables			AIC	R^2	R^2_a	RMSE
		SRI	UCA	VTEX				
CNT	10	100	250		83.745	0.711	0.672	1.984
	12.5	100	100		84.095	0.705	0.666	2.003
	25	1000		100	96.339	0.418	0.340	2.815
	50	100		100	96.160	0.424	0.347	2.800
GSI10	10	1000	250		88.559	0.622	0.572	2.268
	12.5	1000	100		89.068	0.611	0.560	2.300
	25	1000		100	96.437	0.415	0.337	2.823
	50	1000		100	97.154	0.391	0.310	2.879
GSI50	10	1000		100	96.810	0.402	0.323	2.852
	12.5	1000			96.376	0.348	0.307	2.979
	25	1000			95.377	0.383	0.345	2.898
	50	1000		100	86.637	0.660	0.615	2.145

Table 2 Best site index model for each DEM source.

Source	Resolution, Search range			AIC	R ²	R ² _a	RMSE
	SRI	UCA	VTEX				
CNT	10, 100	12.5, 100		78.828	0.780	0.751	1.731
GSI10	12.5, 100	10, 250	10, 100	85.556	0.714	0.653	1.974
GSI50	50, 1000		50, 100	86.637	0.660	0.615	2.150

Table 3 Best site index model among models using topographic factors derived from combinations of DEM sources and resolutions.

	Source-Resolution, Search range			AIC	R ²	R ² _a	RMSE
	SRI	UCA	VTEX				
All	CNT-10, 1000	CNT-12.5, 100	GSI50-50, 100	76.199	0.830	0.793	1.522
GSI	GSI50-50, 1000	GSI10-10, 100	GSI50-50, 100	80.744	0.781	0.734	1.727

second best GSI model was almost the same for the best GSI model (80.744). Thus, UCA-250_GSI10-10 can be considered as a good predictor variable for the site index model. Because we used the residual mean estimate (RME) in the previous study calculated as the mean absolute value of estimation error, we also calculated RME for the all-best model and the best GSI model. The values of R^2 , R^2_a , and RME were 0.692, 0.651, and 1.618 for the previous model (Mitsuda et al., 2007), but those values were 0.830, 0.793, and 1.069 for the all-best model and 0.781, 0.743, and 1.376 for the best GSI model. Thus, the all-best model and the best GSI model were superior to the previous model.

DISCUSSION

The suitable DEM data source and grid resolution were different for each topographic factor with respect to its representation of a physical phenomenon (Beven and Kirkby, 1979; Hutchinson and Gallant, 2000; Quinn et al., 1995; Wilson et al., 2000). A high-quality DEM generated from more informative sources (CNT or GSI10) and at fine resolutions (10 m or 12.5 m) was suitable for UCA, whereas a low-quality DEM generated from a less informative source (GSI50) and at coarse resolution (50 m) was suitable for SRI (Fig. 1). Topographic factors indicating microscale phenomena are more sensitive to DEM's capability to represent detailed topography than those indicating macroscale phenomena. Because UCA represents groundwater dynamic flow along a detailed topographical gradient, it can be regarded as a microscale topographic factor, and coarse-resolution DEMs are insufficient to describe groundwater flow influences by microscale topography. Because SRI represents solar radiation intensity determined by solar position, slope angle, and aspect, our results suggest that coarse-scale slope angle and aspect are suitable for evaluating SRI and then SRI can be regarded as a macroscale topographic factor. Coarse-scale slope angle and aspect that represent a macroscale trend in topography are suitable, however, fine-scale slope angle and aspect that are derived from high-quality DEMs are too detailed to represent intensity of solar radiation as a macroscale phenomenon. A fine-scale DEM will not be suitable for SRI because highly detailed topographical information will disturb to indicate this macroscale phenomenon. Thus, a suitable DEM grid resolution as a

determinant factor of DTA scale is determined for a specific topographic factor.

Topographic characteristics of a target area will affect the importance of search range on DTA and development of a site index model. Correlation coefficients between site index and SRI and between site index and UCA saturated for search ranges, while those of VTEX worsened with longer search range in all cases (Fig. 1). The suitable search range for VTEX was obviously 100-m, irrespective of the DEM source and grid resolution. Because VTEX takes into account only the depression angle at the lowest point from each of the eight directions, it can be regarded as ridgeness, and thus, shorter search range was suitable for evaluating ridgeness in a highly undulated land area such as this study area. A longer search range may lead us to overestimate the ridgeness of a site because of a lower point in a further valley bottom beyond some ridges. The shorter search range will work well for SRI and UCA because of the highly undulating land surface of the study area. Although the effects of search range on DTA were not clear in the correlation analysis, our results suggest that search range will also affect DTA and site index modeling. The search ranges of UCA, SRI, and VTEX accepted in the best models developed in the stepwise approach were the same as 1000 m, 100 or 250 m, and 100 m, respectively (Table 1, 2, and 3). Thus, the DTA scale identified by the DEM grid resolution and search range affects the performance of a site index model.

A suitable DEM resolution corresponded to a specific DEM data source used in developing the site index model. As discussed above, UCA requires a fine-resolution DEM; however, the fine-resolution DEMs produced by upscaling from a low-quality source (such as GSI50-10 and GSI50-12.5) were not useful (Fig. 1 and Table 1). In contrast, SRI requires a coarse-resolution DEM, but the coarse-resolution DEMs produced by downscaling from high quality sources (such as CNT-50 and GSI10-50) were not useful (Fig. 1 and Table 1). In the best models developed for each DEM source, fine-resolution topographic factors (10 m or 12.5 m) were accepted for the best CNT and GSI10 models, and coarse-resolution topographic factors (50 m) were accepted for the best GSI50 model. Our result suggests the need to choose an adequate grid resolution for DTA that corresponds to the quality of the original data source. In this case, CNT-10, CNT-12.5, GSI 10-10, and GSI50-50 are recommended. Furthermore,

comparing correlation coefficients between site index and topographic factors derived from CNT-10 and CNT-12.5, 12.5 m resolution was more favorable than 10 m. It may demonstrate the limit of resolution for topographic information contained in the 1:25000-scale topographic maps; moreover, 10 m resolution is too fine to represent topography on the basis of the 1:25000-scale topographic maps for this study area.

The results of stepwise regression analyses revealed that both DEM quality and DTA scale greatly affected the performance of the site index model of sugi planted forests. Although SRI-1000 CNT-10 was accepted in the all-best model, SRI-1000_GSI50, UCA-250_CNT12.5, UCA-250_GSI10, and VTEX-100_GSI50 were superior explanatory variables among UCAs, SRIs, and VTEXs in this study (Table 3). The descriptive measures of model performance (i. e., R^2 , R^2_a , and RME) indicated that the site index model of sugi planted forests developed in the present study was improved using the topographic factors derived from combinations of various DEM sources and various resolutions from the previous model, which used topographic factors produced by the DEM derived from a single data source and generated at fixed resolution. Our results show the importance of taking into account the DEM quality and DTA scale and testing various combinations of topographic factors derived from various DEM data sources, grid resolutions, and search ranges to develop site index models.

We developed a site index model of sugi planted forests for a relatively small area (approximately 500 ha) assuming that climatic condition was uniform within the target area. To develop a site index model for a broad area, we should take into account the climatic factors in the future studies (e.g., Klinka and Carter, 1990; Wang et al., 2004). Furthermore, because of geology is a factor that varies within a broad area and affects the physical and chemical characteristics of soil (Schoenholtz et al., 2000), it should be considered as well.

CONCLUSION

We improved the performance of the site index model of sugi planted forests in Miyazaki Prefecture by selecting explanatory variables from among topographic factors derived from DEMs generated from various sources and at various resolutions and calculated for various search ranges. Our results suggest that searching for suitable combinations of DEM source, resolution, and search range for specific topographic factors will contribute in developing better site index models. Our approach will also increase the awareness of the scales of topographic factors corresponding to each representing phenomenon such as soil water flow, solar radiation, wind flow, and so on, thereby leading to a better understanding of the autecology of target species.

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