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Finding Suitable Stands for Clearcutting and Reforestation by Combining GIS Thematic Maps Expressed by Standard Scores: A Case Study in the University of Tokyo Chiba Forest

Takuya Hiroshima*1

ABSTRACT

In this study, suitable sites for clearcutting and reforestation were found by combining GIS thematic maps expressed by standard scores in the case of the University of Tokyo Chiba Forest. The map themes were stand age over rotation age, site quality, accessibility and slope stability, and they were combined after conversion of original units into a common scale of standard scores. Then, planted stands suitable for clearcutting and reforestation were selected considering yarding feasibility. As a result, 18 sub-compartments were selected as candidate stands that had combined scores over 50 in the combined thematic map with stand sizes over 3 ha. Finally, 6 sub-compartments passed the yarding feasibility check to see if there was any obstacle along the sky line of cable logging between the two peaks in the visible area from the neighboring yard. A standard score was useful to set several thematic maps into a common scale when they were combined and to select sub-compartments almost better than an average in all aspects of thematic maps. The suggested method was flexible and could contribute to a wider use of GIS in the field of forest planning.

keyword: GIS, standard score, thematic map

INTRODUCTION

Recently new systems have started such as direct payments of silvicultural subsidies in 2011 and a forest management planning system in 2012. To cope with changes in such systems, forestry officers, planners and researchers in the field of forest planning are required GIS techniques to make silviculture, harvesting and logging strategies considering integration of tending sites and construction of an efficient road network.

In this circumstances, it has become gradually common to make a comprehensive forest management plan using GIS considering a log price, a logging cost, labor requirements, etc. according to stand and terrain conditions, with optimization techniques in some cases, such as zoning of planted forests (Kawata and Matsumura, 2006; Tatsuhara, 2008; Tatsuhara and Dobashi, 2006), harvest scheduling (Lee and Minowa, 2002; Watanabe and Tatsuhara, 2013), logging cost estimation (Toyama and Tatsuhara, 2007), multiple forest function assessment (Wu and Minowa, 2004; Zheng and Nagumo, 1994) and profitability and yield simulation of clearcutting and thinning (Toyama et al., 2012; Yamada and Tatsuhara; 2012). The use of GIS in forest planning is not only for planted forests but also for natural and mixed forests such as landscape managements (Sano et al., 1994; 2009) and those with optimization (Sano et al., 1996; Sano and Sakamoto, 1998). Not such comprehensively but more simply, many studies have used GIS to find suitable sites for forest management such as clearcutting (Hiroshima and Nakajima, 2009), thinning (Moriya et al., 2013), logging (Umezawa et al., 2013), natural vegetation (Nakaya et al., 2014) and so on. This paper is also interested in finding harvestable and reforestable sites using GIS in the study site of the University of Tokyo Chiba Forest.

The University of Tokyo Chiba Forest had planted forests of 825 ha in area with a growing stock of about 238,000 m3 in 2011. The conventional forest management plan was approved for the years from 2010 to 2014, in which clearcutting and thinning were scheduled for the planted forests annually. However, the need for revising the conventional plan arose to receive the new silvicultural subsidies by the direct payment system that required the renewal of the plan in line with the new forest management planning system (The University of Tokyo Chiba Forest, 2012; Toyama et al., 2013). To make the renewal plan, there was the needs for finding clearcutting and reforestation stands for coming 5 years.

Thus, the purpose of this study is to find suitable sites

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for clearcutting and following reforestation using GIS thematic maps such as site quality, accessibility, slope stability and visibility particularly with a common scale of standard scores in the case of the University of Tokyo Chiba Forest.

MATERIALS AND METHODS

Study Area

The University of Tokyo Chiba Forest is located at the southeastern part of the Boso peninsula, Japan, between longitudes of 140°05'33" to 10'10"E and latitudes of 35°08'25" to 12'51"N. The terrain of the Chiba Forest is generally steep, e.g. a mean slope angle of planted stands was 26.4°, and vulnerable to land collapse. Thus cable logging was encouraged for a suitable logging system according to the terrain index (Kato, 1967) in most of the planted forests.

This area belongs to the warm temperate zone that has mean annual precipitation of 2,279 mm with monthly means ranging from 96.7 mm in December to 277.0 mm in September, and that has mean annual temperature of 14.2℃ with monthly means ranging from 4.4℃ in February to 24.2 ℃ in August according to the observations by local weather stations. A soil type is the brown forest.

In this study, targets of clearcutting and reforestation for 5 years were the planted forests. The planted forests of 825 ha in the Chiba Forest had the mean stand age of 69 years old in 2011 and were basically managed under the rotation age of 80 years old.

GIS Data

GIS data used for the following analysis were dominant tree heights and positions of Japanese cedar obtained by an airborne LiDAR (Nakajima et al., 2011), a 10-m grid resolution digital elevation model (DEM), a terrain map in a scale of 1/2,500, a forest type map, a forest road map including logging yards and inventory data for each sub-compartment. The dominant tree height data consisted of 687 tree points at various stand ages from 18 to 102 years old. The DEM covered the elevation from 40 m to 380 m a.s.l. The terrain map was just a background image, which illustrated 2 meters interval contours. The forest type map particularly in planted forest areas consisted of Japanese cedar (*Cryptomeria japonica*), Japanese cypress (*Chamaecyparis obtusa*) and other species in the area ratio of Japanese cedar 6: Japanese cypress 3: others 1. The road network in the forest road map extended over a distance of 23 km (11 m/ha) with 51 logging yards. The inventory data were corresponding to sub-compartment attributes such as stand age, tree species, etc.

By use of these data, thematic maps of stand age over rotation age, site quality, accessibility and slope stability were created and combined after conversion into a common scale of standard scores. In this study, the following Z-score was used as a standard score:

$$Z = \frac{10\,(x-\mu)}{\sigma} + 50 \tag{1}$$

where x: indicators of stand age [years old], a site index [m], a distance from a yard [m] and a safety factor describing thematic maps, μ: means of indicators and σ: standard deviations of indicators. Then, stands suitable for clearcutting and reforestation were selected considering yarding feasibility.

Making Thematic Maps

Planted Stand Age Map over Rotation Age

A stand age map was useful to judge an amount of yield volume and priority of harvesting order. Thus, older stand age leaded to higher suitability for clearcutting. First, planted stands whose age was over the rotation age of 80 years old were extracted. Then, their stand ages were converted into standard scores.

The following several thematic maps were finally all expressed by standard scores. In every map, a higher standard score meant higher suitability for clearcutting and/or reforestation.

Site Quality Map of Japanese Cedar

A site quality map was useful to judge an amount of yield volume. Thus, higher site quality leaded to higher suitability for clearcutting. The site indices of Japanese cedar, as the dominant tree heights at the age of 40 years old, in the Chiba forest were estimated by the following function (Hiroshima and Nakajima, 2009) using the terrain characteristics derived from the DEM (Chen and Abe, 1999; Mitsuda et al., 2001, 2007; Munajati et al., 2009) for each point on the 10-m grid of the dominant Japanese cedar trees:

$$\begin{aligned}&[\text{Site index}] = 0.0167\,[\text{Shaded relief}] + 0.0144\,[\text{Flow accumulation}] - 0.0932\,[\text{Curvature}] + 0.141\,[\text{Distance}\\&\text{from ridge}] + 0.0748\,[\text{Slope angle}] + 11.5\end{aligned} \tag{2}$$

Then the estimated site indices were converted into standard scores. In this study, a site index was calculated only for Japanese cedar to judge site quality all over the Chiba forest area because most sub-compartments in the Chiba forest had Japanese cedars planted in the large parts of the middle to bottom slopes with mixtures of Japanese cypresses planted only along the small parts of ridges.

Accessibility Map

An Accessibility map was useful to judge productivity and profitability of harvesting works. As mentioned above, a cable logging system had been applied in the Chiba Forest, so that buffers were created from the 51 logging yard points where dram machines were assumed to be set. In this case, shorter distance from a yard leaded to higher suitability for clearcutting. Finally, the distances from yards were converted into standard scores.

Slope Stability Map

A slope stability map was useful to judge the possibility that reforested stands successfully got matured. Thus, higher slope stability leaded to higher suitability for reforestation. First, the safety factor of a slope was calculated for each 10-m grid using the stability analysis function of an infinite slope (Mizuta and Seo, 2001; Okimura and Ichikawa, 1985; Shima and Ebisu, 2008) with the parameter values mainly observed in the Chiba Forest:

$$SF = \frac{c + \{(\gamma_{sat} - \gamma_w)h + \gamma_t(H-h)\}\cos^2\alpha\tan\beta}{\{\gamma_{sat}h + \gamma_t(H-h)\}\sin\alpha\cos\alpha} \tag{3}$$

where SF: a safety factor, c = 1.50 (Shuin, 1997): cohesion [tm^{-2}], α: a slope angle of each 10-m grid derived from the DEM [degree], $\beta = 41.8$ (Sugisaki, 2002): an internal friction angle [degree], γ_{sat} = 1.90 (Mizuta and Seo, 2001): saturated soil density [tm^{-3}], γ_w = 1.00: water body density [tm^{-3}], γ_t = 1.70 (Mizuta and Seo, 2001): wet soil density [tm^{-3}], H: surface soil depth of each 10-m grid derived from the DEM (Sakai et al., 2011; Shiraki, 1993) [m], h: groundwater level of each 10-m grid derived from the DEM (Goshima et al., 2008) [m]. Then, the estimated safety factors were converted into standard scores.

Combination of 4 Thematic Maps

The 4 thematic maps were combined with equal weight, i.e. simply averaging 4 standard scores in each 10-m grid. These combined scores also had the mean of 50 and the standard deviation of 10 in their distribution, and a higher score leaded to higher suitability for clearcutting and reforestation considering all 4 aspects of stand age, site quality, accessibility and slope stability. Then, the mean combined scores for sub-compartments were calculated by averaging the combined scores for 10-m grids included in each sub-compartment. Finally, the sub-compartments with their mean combined scores over 50 and their areas over 3 ha were selected as the candidate sites for clearcutting and reforestation. Note that the threshold values of 50 and 3 ha were decided arbitrarily: The former was simply the mean of combined scores easily understood by interest parties as a selection standard in decision making scenes and the latter was based on the lower limit of harvesting sub-compartment size in the Chiba forest considering the efficiencies of following reforestation and tending works.

Check on Yarding Feasibility

Availability of cable logging was examined for the candidate sub-compartments. First, neighboring logging yards to the candidate sub-compartments were selected. Second, a visibility map from each logging yard was created. Third, yarding feasibility was examined by the help of the visibility and terrain map: In visible area from the neighboring yard, the straight line, assuming a sky cable line for logging, was set between the terrain peaks where one peak was set around the harvesting stand and the other peak was set around the yard, and then the vertical cross sectional map of a terrain along the line was checked to see if there was any obstacle between the peaks.

RESULTS

Planted Stand Age Map over Rotation Age

148 sub-compartments were extracted as the planted stands whose age were over the rotation age of 80 years old, which consisted of 39,238 grids in the raster data with the mean of 98 years old and the standard deviation of 11 years old. The standard score expressions were shown in Fig. 1-a by a map and in Fig. 2-a by a histogram. Note that each dot in the map and each frequency in the histogram represented a 10-m grid derived from the DEM. In addition, the standard scores were rounded off to integer values.

Site Quality Map of Japanese Cedar

Using Eq. 2, the site indices of the above 148 sub-compartments were calculated for the corresponding grids with the mean of 16.4 meters and the standard deviation of 5.5 meters. The standard score expressions were shown in Fig. 1-b by a map and in Fig. 2-b by a histogram.

Accessibility Map

The distances from logging yards, i.e. accessibilities, of the above 148 sub-compartments were calculated for the corresponding grids with the mean of 1,052 meters and the standard deviation of 432 meters. The standard score expressions were shown in Fig. 1-c by a map and in Fig. 2-c by a histogram.

Slope Stability Map

The safety factors of the above 148 sub-compartments were calculated by Eq. 3 for the corresponding grids with the mean of 4.3 and the standard deviation of 3.1. The standard score expressions were shown in Fig. 1-d by a map and in Fig. 2-d by a histogram.

Combination of 4 Thematic Maps and Yarding Feasibility Check

The combined map and its histogram were shown in Figs. 1-e and 2-e. There were 18 candidate sub-compartments (Table 1 and bold black and blue polygons in Fig. 1-e) with their mean combined scores over 50 and their area over 3 ha, in which 5 sub-compartments were useless for harvesting because they contained experimental plots, educational facilities, etc. Then, the yarding feasibilities of the rest 13 sub-compartments were checked (Fig. 3 for the example of the sub-compartment 44C11) and 6 sub-compartments (bold blue polygons in Fig. 1-e) of 45C10, 11C1, 44C11, 23C3, 43C3 and 19C6 passed consequently. Among them, 4 sub-compartments of 23C3 in the first year, 44C11 divided into 2 parts in the second and third year, 11C1 in the fourth year and 45C10 in the fifth year were selected as clearcutting and following reforestation stands in the new forest management plan. These 4 sub-compartments were selected in order of the mean combined score and the other stuff such as

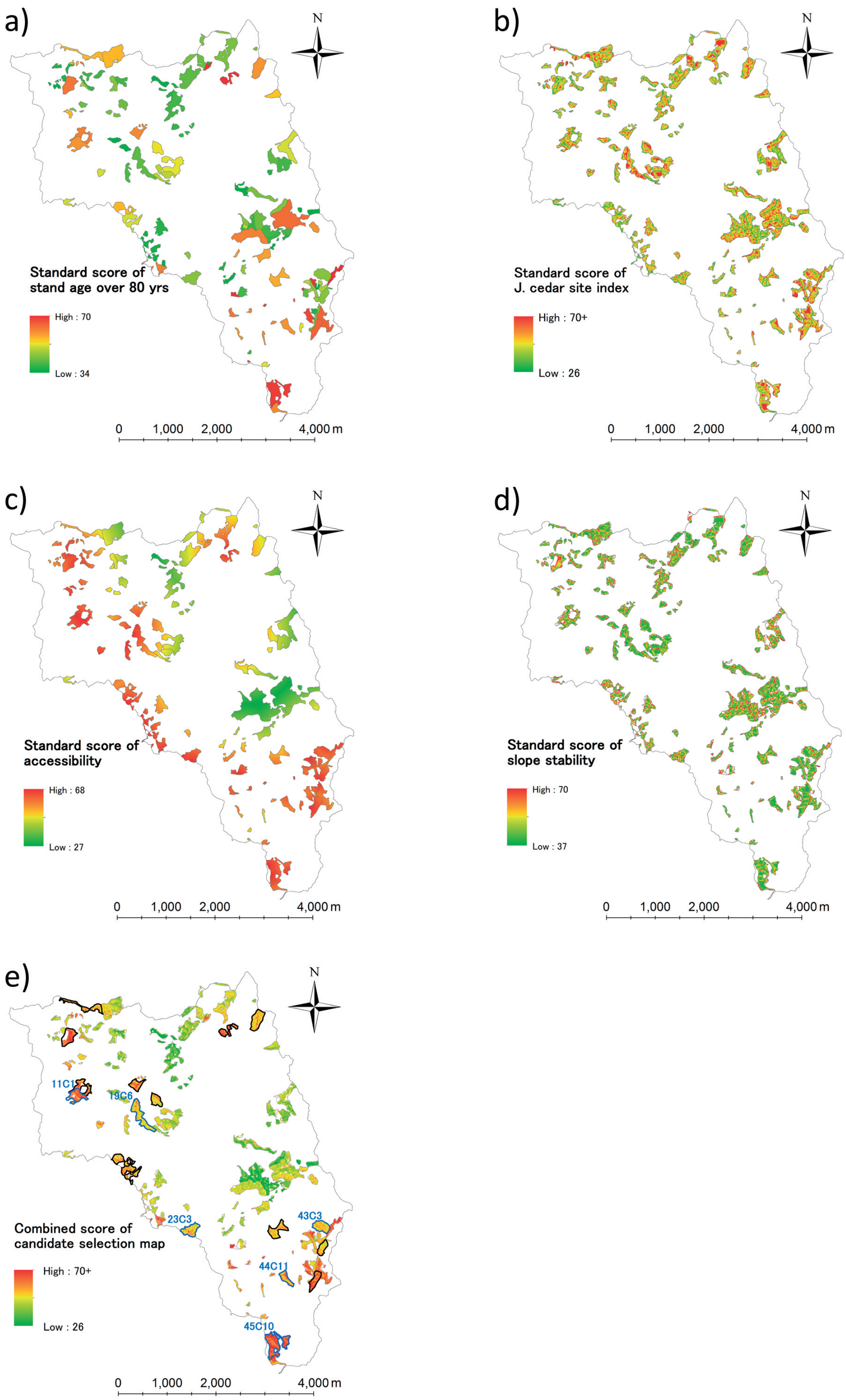

Fig. 1 Thematic maps expressed by a deviation value: a) stand age over the rotation age of 80 years old, b) site index of Japanese cedar, c) accessibility, d) slope stability and e) their combination with equal weight. The bold black and blue polygons represent 18 candidate sub-compartments with their mean combined scores over 50 and their area over 3 ha. Particularly the blue polygons represent finally selected 6 sub-compartments which passed yarding feasibility checks.

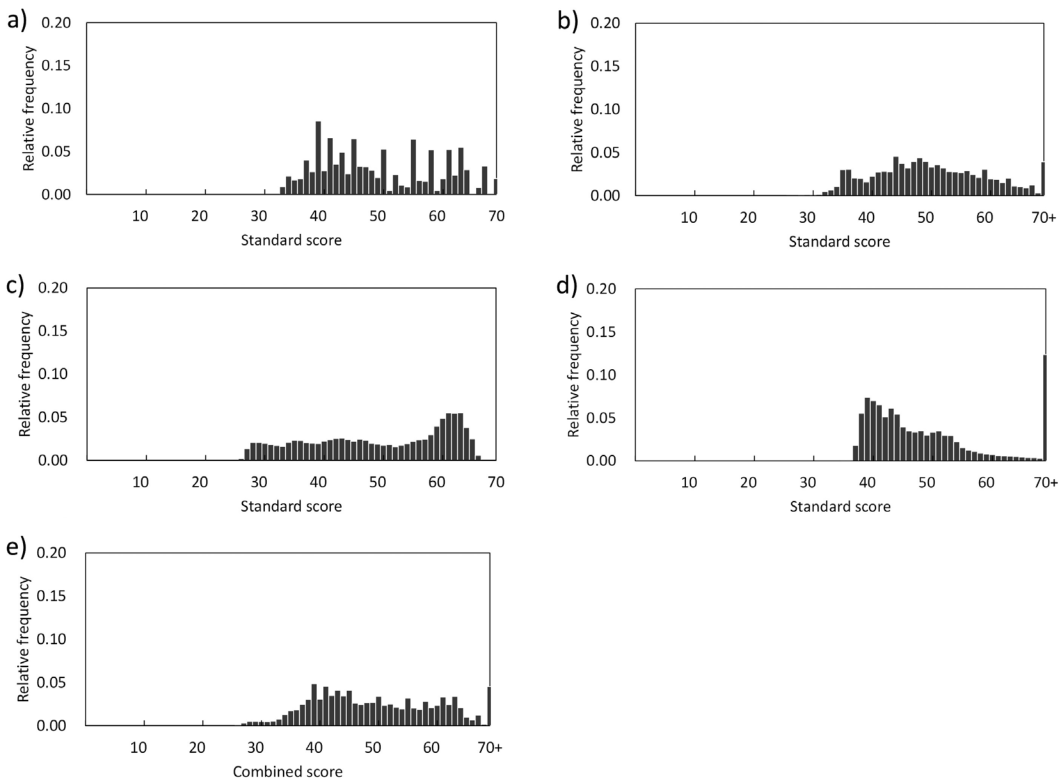

Fig. 2 Histograms of standard scores and a combined score: a) stand age over the rotation age of 80 years old, b) site index of Japanese cedar, c) accessibility, d) slope stability and e) their combination with equal weight.

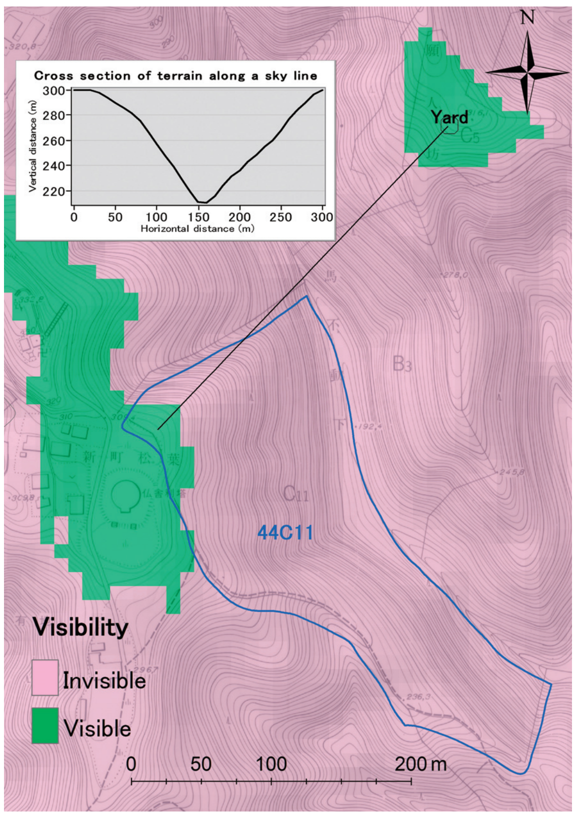

Fig. 3 Yarding feasibility check in the case of candidate sub-compartment 44C11. The black line represents a sky cable line for logging set between the two peaks in the green visible area from the neighboring yard to see if there was any obstacle in the vertical cross sectional map of a terrain along the line as shown in the left-top graph.

Table 1 Combined scores and areas of 18 candidate sub-compartments.

Sub−compartment	Mean (Min, Max) combined score	Area (ha)	Remarks
45C10	57 (52, 67)	12.7	
46C8	56 (52, 66)	4.9	Thinned recently
2C5a	56 (51, 62)	5.1	Incl. exp. plots
27C4	56 (53, 65)	3.8	Incl. exp. plots
11C1	55 (50, 65)	5.5	
10C1	54 (49, 65)	4.1	Incl. facilities
15C5	54 (49, 63)	3.9	
44C11	53 (48, 64)	3.7	
21C	52 (47, 59)	5.9	Incl. exp. plots
20C1	52 (47, 61)	4.3	
6C1	52 (47, 56)	5.2	
39C3	51 (47, 61)	6.2	
28C1	51 (47, 61)	7.2	
46C4	51 (46, 62)	3.6	
23C3	51 (46, 61)	5.8	
43C3	51 (47, 59)	6.0	
18C6	51 (46, 60)	4.2	
19C6	50 (46, 60)	9.0	

harvesting year, a division of a harvesting sub-compartment, etc. depended on the contracts with harvesting companies.

Distributions of Scores in 4 Thematic Maps and Combined Map

In Fig. 2, the distributions of standard scores in 4 thematic maps were different respectively. Note that all these thematic maps extracted only the grids in planted stands over 80 years old. The score distribution of stand age (Fig. 2-a) had roughly two peaks around 43 and 64, and had several spikes that reflected the concentrations of stand ages on several particular ages. The score distributions of a site index, accessibility and slope stability had roughly all single peaks but their skewness were different. The distribution of a site index (Fig. 2-b) did not skewed, which showed old planted stands of the Chiba Forest had generally medium site qualities of Japanese cedar; high quality sites were not many but low quality sites were also not many. The distribution of accessibility (Fig. 2-c) was left-skewed, which showed old planted stands had relatively good accessibility from logging yards. The distribution of slope stability (Fig. 2-d) was right-skewed, which showed old planted stands tended to locate in the places relatively vulnerable to shallow land collapse.

In Figs. 2-a, 2-b, 2-c and 2-d, the percentages of grids with standard scores over 55 were 40%, 32%, 44% and 25% respectively, and these grids were shown as orange to red colors in the maps of Figs 1-a, 1-b, 1-c and 1-d. If the distribution was left-skewed then orange to red parts increased in the map and vice versa.

In Figs. 2-b and 2-d, there were grids with standard scores over 70. The standard scores of 70 were equivalent to the 96 percentile value of 28.3 meters in the case of a site index and 88 percentile value of 10.9 in the case of a safety factor. Particularly in the case of a site index, some grids in the 70+ class had meaninglessly large values such as over 50 meters as a result of extrapolation by Eq. 2 though they had little influences on the combined results considering their few frequencies.

The score distribution of the combined map (Fig. 2-e) had roughly two peaks around 44 and 63 mainly as a result of averaging two peaks (Fig. 2-a), left-skewed (Fig. 2-c) and right-skewed (Fig. 2-d) distributions. The percentages of grids with combined scores over 50, which was the threshold of selecting candidate sub-compartments, was 48%, so that almost half of the grids deserved suitable sites for clearcutting and reforestation in the old planted stands. In this case, the threshold of 50, simply the mean of combined scores, had the percentile of 52% which eventually resulted in 18 candidate sub-compartments over 3 ha enough for harvesting in coming 5 years, but a threshold itself was subject to change owing to score distributions: If candidate sub-compartments were not enough like in case of a right-skewed distribution, a threshold should be lowered. For reference, the thresholds of combined score of 45 and sub-compartment size of 1ha would result in 73 candidate sub-compartments in case of this study.

Details of Selected Sub-compartments

The details of finally selected 4 sub-compartments were shown in Table 2. The table contained mean standard scores, corresponding mean original values of 4 indicators describing thematic maps and resultant mean combined scores. All 4 sub-compartments had mean combined scores over 50 similarly, but their combinations of mean standard scores for the indicators differed: Most standard scores were over 50 but the sub-compartments 45C10, 44C11 and 23C3 partly included the scores under 50. The standard scores of distance from yard tended to be high in all 4 sub-compartments because the percentage of grids with standard scores over 60 was highest among 4 indicators as shown in Fig. 2, which contributed to heighten the combined scores consequently.

In terms of the original values of indicators in 4 sub-compartments, the stand age ranged from 92 years old, no problem to harvest, to 117 years old, the third oldest stand in harvestable planted forests. The site index ranged from 15 meters, classified to the third grade of site class II among Ia, I, II and III of Japanese cedar in the yield table of the Chiba forest (Shiraishi, 1986), to 18 meters, the second grade of site class I. The distance from yard ranged from 301 meters, barely profitable considering stumpage values and cable logging costs in spite of a relatively long logging distance for recent clearcutting site, to 80 meters, so near that timbers around yards would be directly collectable without a cable. The safety factor ranged from 2.8, almost no problem for slope stability, to 4.8, enough stable for following reforestation and tending works.

On the whole, though some indicators were under the standard score of 50 in spite of the resultant combined scores over 50, the original values themselves were in the allowable ranges for clearcutting, logging and reforestation.

Table 2 Mean standard scores, original values and combined scores of finally selected 4 sub-compartments.

Sub-compartment	Stand age		Site index		Distance from yard		Safety factor		Combined score
	Standard score	Original value (yrs. old)	Standard score	Original value (m)	Standard score	Original value (m)	Standard score	Original value	
45C10	67	117	52	18	62	153	47	3.3	57
11C1	58	107	50	16	64	80	50	4.4	55
44C11	58	107	51	17	58	301	45	2.8	53
23C3	44	92	47	15	63	116	52	4.8	51

DISCUSSION

Use of a Standard Score in Combining Thematic Maps

It was convenient to use a standard score as a unit of a thematic map in combining several maps originally expressed by different units. The unit of a standard score was non-dimensional, so once the units of thematic maps such as meter, degree, etc. were converted into a common scale of a standard score, any kind of thematic maps can be combined to enable overall evaluation through the maps.

On the other hand, a standard score should be handled with care particularly in relative comparison among different indicators, areas, etc. In case of this study, the standard score distributions were different among 4 indicators as shown in Fig. 2, so the same standard score of each indicator were not related with the same relative ranking because of different percentiles. For instance, the same standard score of 60 for 4 indicators corresponded to the different percentiles of 76%, 81%, 68% and 77% as mentioned above, so the indicator of site index held the highest relative rank with the largest 81% percentile. In addition, even if all indicators had the same standard score distributions such as a normal distribution, the same standard scores did not necessarily have the same extent of suitability for harvesting. For the hypothetical instance, assuming both a safety factor and distance from yard belonged to normal distributions and the standard scores of 55 with the same percentile of 69% corresponded to the original values of 0.9 and 300 meters respectively, the standard score of 55 for distance from yard was more suitable for harvesting. The reason was that the safety factor under 1.0 meant instable state of slopes unsuitable for harvesting and following reforestation while yarding distance under 500 meters allowed cable logging somehow. Moreover, if one indicator was applied to several areas with different conditions, this case might lead to the same standard scores with different extent of suitability even in the same indicator. For the hypothetical instance, assuming the standard scores of a site index were calculated for compartments A and B in different terrain conditions, the same standard scores of 60 for both A and B would correspond to different original values of such as 20 meters for A and 15 meters for B according to the different standard score distributions, where the former 20 meters classified in the site class I and the latter 15 meters in II resulted in the different suitability for harvesting.

In spite of the above matters with care, it was still convenient to use a standard score in combining several maps considering the following advantages. The mean of 50 and standard deviation (SD) of 10, in case of a Z-score, were common, which leaded to the fact in common that the standard score of 60 represented a mean + 1 SD, 70 represented a mean + 2 SD and so on. It was certain, therefore, for any indicator (here, though the difference of indicator was discussed as an example, the following facts were common in discussing the difference of area, time, etc.) that a higher standard score simply held a better rank in a score distribution, so the increase in selection thresholds of combined scores from 50, 55, 60 and so on enabled the selections of totally better-balanced sub-compartments considering standard scores of all indicators including various cases such as all indicators got higher ranks, some got much higher ranks but some got a little lower ranks, etc. as shown in Table 2. Thus, when we needed to select sub-compartments almost better than an average, it could be settled by selecting the sub-compartments with combined scores over 50 after converting original indicator values into standard scores on condition that original indicator values of selected sub-compartments were all in the allowable ranges for clearcutting, logging and reforestation. The sub-compartments with combined scores over 50 could be regarded as well-balanced taking all indicators into account.

In the end, a standard score should be handled with care in relative comparison among different indicators, areas, etc. However, if the meaning of a standard score and corresponding relative ranking were understood correctly, the use of a standard score was convenient for decision making such as the selection of sub-compartments almost better than an average.

CONCLUTION

In this study, suitable sites for clearcutting and reforestation were found by combining GIS thematic maps of stand age, site quality, accessibility and slope stability expressed by standard scores in the case of the University of Tokyo Chiba Forest. Particularly a standard score was useful to set several thematic maps into a common scale when they were combined, which enabled the selection of well-balanced sub-compartments in all aspects of thematic maps as long as the meaning of a standard score and corresponding relative ranking were understood and handled correctly. The suggested method in this study is flexible and can contribute to a wider use of GIS in the field of forest planning.

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Article

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℃ 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

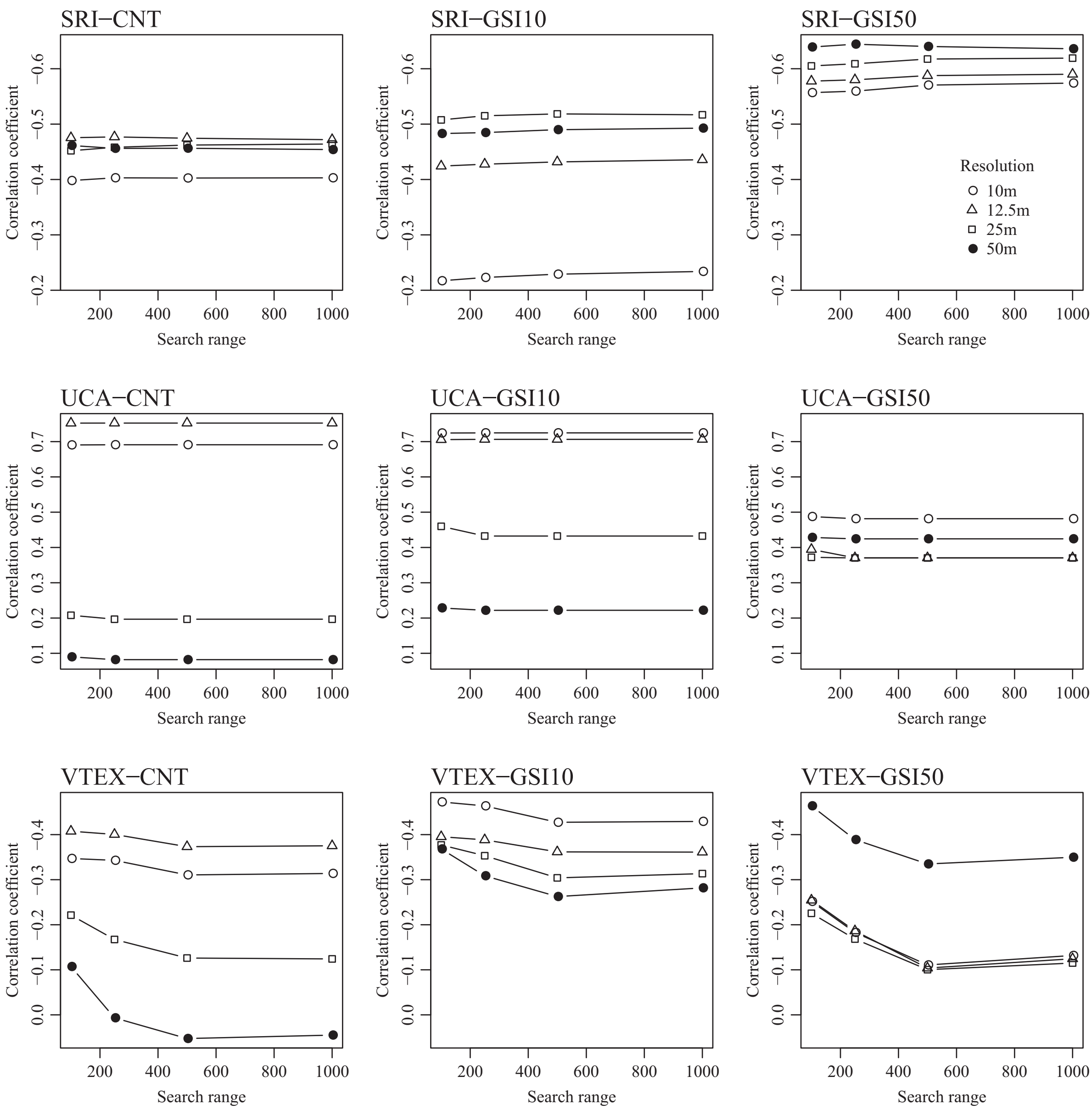

Fig. 1 Correlation coefficients between site index and topographic factors calculated using various search radii and data sources.

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

Source	Resolution	Variables SRI	UCA	VTEX	AIC	R^2	R^2_a	RMSE
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 angel 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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