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Article

Development of Relative Stem-taper Curves for Sugi (*Cryptomeria japonica* D. Don) Plantation in Kagoshima Prefecture, Southwestern Japan

Takayuki Nagahama [*1] and Hiroshi Kondoh [*2]

ABSTRACT

The primary interest of forest owners is the amount of income that will be derived from forest operations. Before cutting operations are carried out, the quality and quantity of the wood yield need to be estimated as accurately as possible. To calculate the profit from a future cutting operation, the upper diameters (example of 4-m above the ground) of the stems of trees in the stand need to be estimated. The aim of this study was to estimate these diameters by applying a relative stem taper curve. The equation was developed based on diameter at breast height (DBH) data in order to eliminate the effect of root spread. The curve equation is a third-order polynomial based on data from 571 sugi (*Cryptomeria japonica* D. Don) trees measured between 1996 and 2004; the equation fit the data well (R^2>0.99). There are more than 60 local varieties of sugi, and relative stem taper curve equations were developed for 8 of these varieties. By applying the relative stem taper curves, forest managers can estimate the upper stem diameter and log yield before cutting trees.

Keywords: diameter at breast height (DBH), log yield, relative stem taper curve, sugi (*Cryptomeria japonica* D. Don), upper diameter estimation

INTRODUCTION

Japan has agreed to meet a target of the absorption of 13 Mt of CO_2 through forest carbon sinks during the first 5-year commitment period (2008-2012) of the Kyoto Protocol. Tree cutting is an important part of meeting this goal, and cutting operations will be implemented in 550,000 ha every year for 6 years (2007-2012), for a total of 3.3 million ha (Forest Agency of Japan, 2009).

The Forest Agency of Japan (2009) reported that many forest owners are not promoting appropriate forest improvement, such as cutting, because of a decline in wood prices. Most forest contractors generally wait to be asked to conduct forest operations by forest owners. In recent years, to promote forest operations such as cutting, the Forest Agency of Japan (2009) has enacted measures that will integrate forestry operations from a proactive approach, in an effort to remind forest owners of the importance of cutting and cutting operations. As part of these measures, forest operation plans are devised and contain current status photos of the forest, estimated costs of the proposed forest operations, and estimated total sales of timber yielded by the proposed forest operations.

With regard to these measures, the primary interest of forest owners is the amount of income that will be derived from forest operations. Thus, before cutting operations are carried out, the quality and quantity of the wood yield need to be estimated as accurately as possible.

The stem volume in a target forest stand can be estimated using our previously developed yield table (Nagahama and Kondoh, 2006a, b). In the Japanese wood auction market, however, price is assigned based on the diameter of the smaller end and stem length, not stem volume. Thus, to calculate the profit from a future cutting operation, the upper diameters (example of 4-m above the ground) of the stems of trees in the stand need to be estimated. At present, before a cutting operation, the upper diameter is visually estimated by the person in charge of surveying all trees to be felled.

For an accurate assessment of a future yield of a cutting operation, (1) a relative stem taper curve is developed for each species, (2) the relative stem taper curve is applied to produce stem taper tables, and (3) these tables are used to calculate the number of logs yielded for each stem length and each smaller-end diameter class. However, few studies of the relative stem taper or stem form have been conducted recently in Japan (Inoue, 2001; Inoue and Kurokawa, 2001), although such studies were actively conducted in previous decades (Kajihara, 1972, 1973a, 1973b, 1974, 1978, 1983, 1984a, 1984b,

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1984c, 1985, 1987a, 1987b, 1987c; Osumi, 1959; Ueno, 1978, 1983). Consequently, stem taper tables are rarely used in stem yield surveys in Japan (Fujimoto et al., 1996; Inoue, 2001; Kajihara, 1989, 1992; Kajihara et al., 1996; Tomita et al., 1991; Yokoi, 2004).

The aim of this study was to develop relative stem taper curves that can be used to estimate the upper diameters of trees to be felled. We focus on sugi (*Cryptomeria japonica* D. Don), an important plantation tree species in Japan, at an appropriate stand age for cutting. There are more than 60 local varieties of sugi (Miyajima, 1989). We developed relative stem taper curves for 8 local varieties of sugi based on wood quality survey data from Kagoshima Prefecture, southwestern Japan.

MATERIALS AND METHODS

We used the data gathered during a wood quality survey conducted from 1996 to 2004 at progeny test plantations in Kagoshima Prefecture. The purpose of the survey was to assess the wood quality of clones of elite trees of selected local varieties and to gather fundamental wood quality data with regard to the wood's suitability as construction material. The following eight local varieties were planted as rooted cutting of sugi adapted in Kagoshima Prefecture in 1970's: Measa, Obiaka, Tanoaka, Tosaaka, Haara, Hiki, Kijin, and Yabukuguri. In our study, the data of the eight local varieties of sugi was analyzed. The survey method followed that described in the Guideline of Wood Quality Survey on Progeny Test Plantations (Forest Tree Breeding Center, 1996). An outline of the survey and maps of the study area are presented in Table 1 and Fig. 1, respectively.

The wood quality survey was conducted in mature experimental plots of sugi of stand age >25 years. Three trees per clone were surveyed, such that the number surveyed in each plot was three times the number of clones. The local variety of each tree was noted. The diameter at 0.2 m above the ground and diameter at breast height (DBH; generally set at 1.2 m above the ground in Japan) were measured.

After the surveyed trees were felled, diameter was measured each with a distance of 2 m between the stem above the DBH position (i.e. at a height of 3.2 m, 5.2 m, 7.2m …). In addition, tree height was measured to the nearest 0.1 m.

In total, 571 mature sugi trees were surveyed and 4253 diameters were measured. In each survey year, data were measured in the same experimental plot and the stand age was uniform across each plot (Table 1). In order to compare the growth of tree height and DBH among the local varieties in each survey year, a Kruskal-Wallis test was conducted.

As previously mentioned, evaluation of upper diameter on stem was aimed mainly in this study. We developed a relative stem taper curve (Behre, 1923) for sugi based on the survey measurements of DBH. Osumi (1959) reported that a third-order polynomial provided an appropriate fit for the relative stem taper curve of sugi. Based on the survey data, we developed a third-order polynomial for the relative stem taper curve:

$$y = ax^3 + bx^2 + cx \qquad (1)$$

where x is the relative stem length and y is the ratio of the diameter in position of relative stem length x from tree top to DBH, and a, b and c are regression coefficients. Thus, a third-order polynomial was applied to the curve in this study. To validate the accuracy of the relative stem taper curve developed in this study, wood quality survey data from 2006 and 2007 were analyzed (138 trees surveyed and 1089 diameters measured). Only six local varieties were surveyed in 2006 and 2007 (Measa, Tanoaka, Tosaaka, Haara, Hiki, and Yabukuguri).

In addition, we analyzed the residual error between the actual diameter and the diameter estimated based on the relative stem taper curve. Logs with a diameter at the smaller end of 14-18 cm and a length >3 m are traded at a relatively high price, as these are the optimal size for timber column material in the Japanese timber market. Therefore, we also performed a similar analysis of the residual error for upper diameters >14 cm.

In this study, the goodness of fit of the relative stem taper curves was analyzed using OriginPro 8J SR2 (OriginLab Co., Northampton, MA, USA), and statistical analysis was performed using SPSS ver. 17 (SPSS Inc., Chicago, IL, USA).

RESULTS

Differences in Height and DBH Growth among Local Varieties

The Kruskal-Wallis test revealed significant differences in height growth among local varieties of sugi in 1996, 1997, 1998, 2001, 2002, and 2003 ($p<0.05$). With regard to DBH growth, significant differences were found in 1996, 1997, 1999, 2000, 2001, 2002 ($p<0.05$) (Table 1).

Development of Relative Stem Taper Curve

Table 2 was listed on regression coefficient for each relative stem taper curve and the adjusted coefficient of determination (adjusted R^2) respectively. Fig. 2 illustrates the relative stem taper curve and the stem form for all sugi trees surveyed, as well as the curves and stem forms. A relative length value of 1.0 corresponds to the DBH position (1.2 m). The adjusted coefficient of determination was >0.99 (Table 2).

Validating the Accuracy of the Relative Stem Taper Curves

We analyzed the residual errors between diameters measured in 2006 and 2007 and those estimated using the relative stem taper curve equations. The numbers of diameters measured, average residual error, standard deviations, and two-sided 95% confidence intervals are listed in Table 3. The narrower the confidence interval, the more precise is the estimate of population parameters (Sokal and Rohlf, 1987). For all sugi trees measured in 2006 and 2007, the average residual error was 0.0 mm and the two-sided 95% confidence interval was 0.5 mm.

Because logs with a diameter of 14-18 cm at the smaller end and length >3 m are traded at a relatively high price, we also analyzed the residual error for trees with upper diameter >14 cm. For the 474 diameters meeting this criterion in 2006

Table 1 Outline of survey data

Survey year	Watershed area	No.of trees analyzed	Forest age (years)	Local variety	Mean tree height (m)	Standard deviation of tree height(m)	Mean diameter at breast height (cm)	Standard deviation of diameter at breast height (cm)	Test statistic of Kruskal-Walles test of mean tree height	Test statistic of Kruskal-Walles test of mean diameter at breast
1996	Hokusatsu	72	26	Sugi(all analyzed trees)	15.6	2.7	19.0	3.4		
				Tanoaka	13.4	2.3	18.7	3.3		
				Tosaaka	15.7	1.7	19.5	2.6	20.151*	18.481**
				Haara	16.3	2.8	18.4	3.4		
				Hiki	13.2	2.1	15.4	2.7		
				Kijin	18.4	2.4	22.0	2.8		
1997	Aira	54	26	Sugi(all analyzed trees)	16.3	1.9	19.7	3.2		
				Obiaka	17.3	1.4	22.0	2.7		
				Tanoaka	16.3	1.5	19.3	1.7	14.231**	14.100**
				Hiki	16.2	1.8	19.1	3.0		
				Yabukuguri	14.3	1.9	16.6	2.7		
1998	Nansatsu	72	26	Sugi(all analyzed trees)	11.5	2.7	15.5	2.8		
				Measa	11.8	2.3	14.7	2.3		
				Tosaaka	9.5	2.5	14.3	2.9	10.113*	2.313
				Haara	11.3	2.7	15.3	3.2		
				Kijin	13.2	2.8	16.2	3.0		
1999	Nansatsu	67	26	Sugi(all analyzed trees)	12.0	1.8	17.7	3.5		
				Measa	12.1	1.6	18.1	2.7		
				Obiaka	13.5	1.7	20.8	3.9	6.491	16.451**
				Tanoaka	12.4	2.0	19.7	4.0		
				Hiki	11.4	1.5	15.5	2.0		
2000	Osumi	63	30	Sugi(all analyzed trees)	14.9	2.1	23.7	3.6		
				Tanoaka	15.6	1.2	26.1	2.6		
				Tosaaka	15.5	2.0	25.3	1.4	7.314	24.161***
				Haara	16.4	1.6	27.4	3.0		
				Kijin	14.1	1.5	23.1	3.1		
				Yabukuguri	14.2	2.1	17.5	1.7		
2001	Aira	72	25	Sugi(all analyzed trees)	15.7	1.7	21.0	3.1		
				Measa	14.9	0.6	20.0	2.4		
				Obiaka	17.6	0.8	21.8	2.8	36.963***	24.761***
				Tosaaka	16.8	0.6	22.8	2.0		
				Haara	15.9	1.2	22.7	2.2		
				Hiki	14.2	1.7	18.3	2.7		
2002	Aira	72	25	Sugi(all analyzed trees)	15.7	1.6	19.3	2.0		
				Measa	15.7	1.0	19.8	1.6		
				Obiaka	14.6	1.1	19.4	1.6	9.541*	9.829*
				Tanoaka	16.1	1.6	17.8	1.8		
				Haara	16.6	0.9	20.3	0.7		
2003	Aira	48	32	Sugi(all analyzed trees)	17.6	1.6	20.3	1.8		
				Obiaka	18.2	1.8	21.0	2.3	10.718*	5.373
				Tosaaka	16.3	1.2	19.2	1.6		
				Haara	18.1	1.4	20.6	1.7		
2004	Osumi	51	31	Sugi(all analyzed trees)	18.8	2.3	25.1	5.3		
				Measa	18.7	2.5	24.0	5.8		
				Tosaaka	20.3	2.5	28.3	5.8	3.189	5.520
				Haara	19.6	1.8	27.5	4.0		
				Hiki	18.4	1.6	23.5	3.4		

Significance level means '***' ; $p < 0.001$, '**' ; $p < 0.01$, '*' ; $p < 0.05$

and 2007, the average residual error was 0.3 mm and the two-sided 95% confidence interval was 0.8 mm.

For the six local varieties, we performed separate residual error analyses by comparing the diameters measured in 2006 and 2007 with the relative stem taper curve for all sugi trees (middle columns in Table 3), as well as with the stem taper curve developed for each local variety (rightmost columns in Table 3). In the case of Measa, the sugi curve provided a better fit (i.e., a narrower two-sided 95% confidence interval) than the Measa curve for all diameters, whereas the opposite was found when analyzing only those diameters >14 cm. For the varieties Tanoaka, Tosaaka, and Haara, the two-sided 95% confidence intervals were the same for the sugi curve and the individual variety's curve for all diameters and only those diameters >14 cm. In the case of Hiki, the sugi curve provided a better fit than the Hiki curve for all diameters and for only those diameters >14 cm. For the local variety Yabukuguri, the Yabukuguri curve provided a better fit than the sugi curve for all diameters, whereas the opposite was found for diameters >14 cm.

Fig. 1 (a) Map of the Japanese archipelago. The patchwork on Honshu (the largest island) shows the distribution of administrative prefectures and the Kyushu District. (b) The study area of Kagoshima Prefecture within the Kyushu District. (c) The five watershed areas in the study area.

Table 2 Regression coefficient of relative stem taper curve ($y = ax^3 + bx^2 + cx$) and the adjusted coefficient of determination (adjusted R^2)

Local varieties	Pegression coefficient of relative stem taper curve			Adjusted coefficient of detemination (Adjusted R^2)
	a	*b*	*c*	
Sugi (all surveyed trees)	0.4585	-0.9764	1.0168	0.9972
Measa	0.3390	-0.7833	0.9438	0.9977
Obiaka	0.4602	-0.9520	0.9905	0.9971
Tanoaka	0.4491	-0.9598	1.0093	0.9970
Tosaaka	0.4184	-0.9054	0.9861	0.9973
Haara	0.5923	-1.1744	1.0810	0.9970
Hiki	0.4039	-0.9154	1.0089	0.9971
Kijin	0.5059	-1.0792	1.0743	0.9984
Yabukuguri	0.7174	-1.4191	1.2023	0.9984

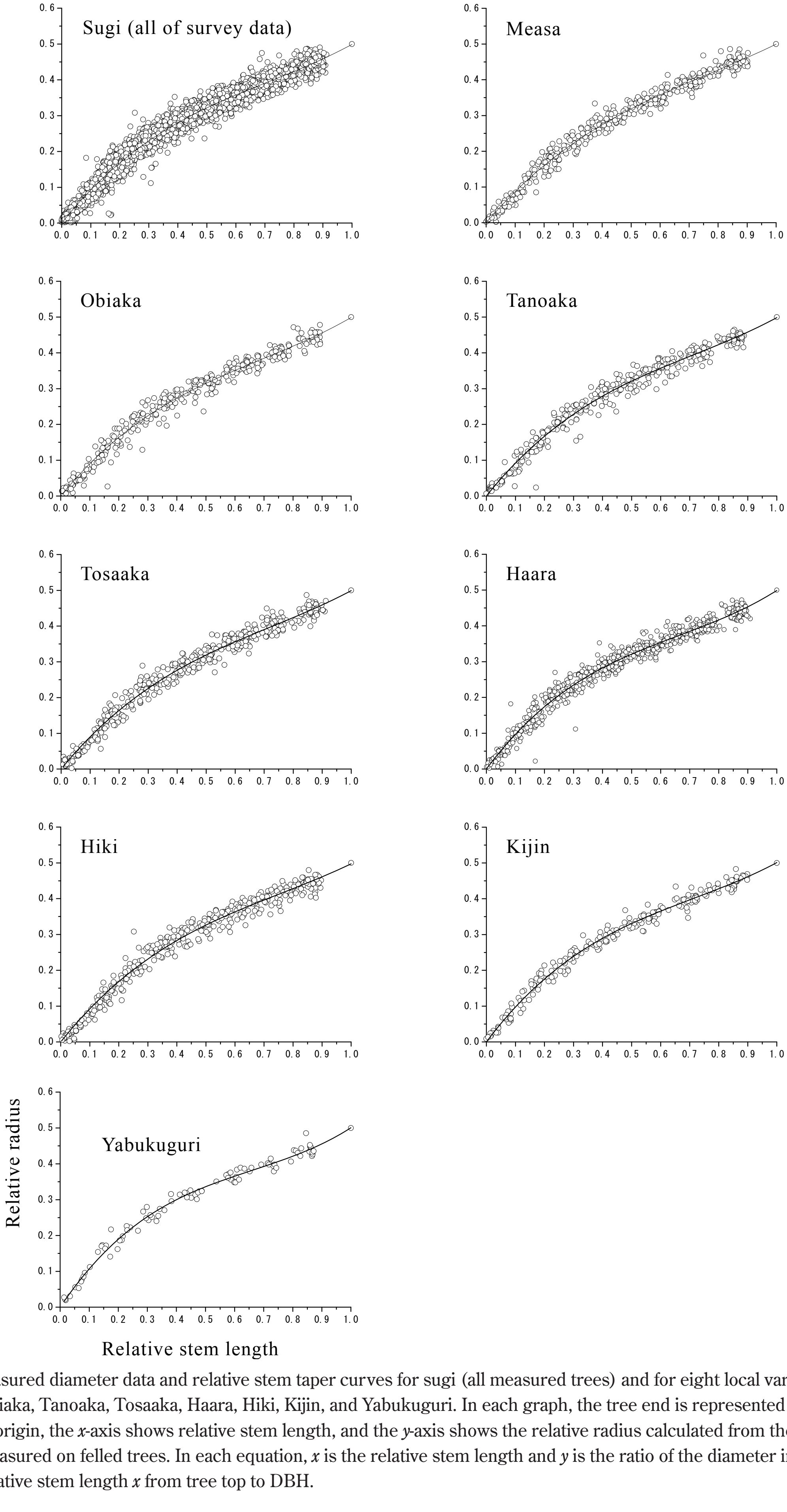

Fig. 2 Measured diameter data and relative stem taper curves for sugi (all measured trees) and for eight local varieties: Measa, Obiaka, Tanoaka, Tosaaka, Haara, Hiki, Kijin, and Yabukuguri. In each graph, the tree end is represented by the point of origin, the *x*-axis shows relative stem length, and the *y*-axis shows the relative radius calculated from the diameter measured on felled trees. In each equation, *x* is the relative stem length and *y* is the ratio of the diameter in position of relative stem length *x* from tree top to DBH.

Table 3 Accuracy validation of relative stem taper curves

Local varieties	Calculated items	Mean residual between measured diameter and that estimated using the sugi curve		Mean residual between measured diameter and that estimated using the variety curve	
		All measured diameters	Measured diameter>14 cm	All measured diameters	Measured diameter>14 cm
Sugi (all surveyed trees)	No.diameters measured	1087.0	474.0		
	Average residual error (mm)	0.0	0.3		
	Standard deviation (mm)	8.8	9.4		
	Two-sided 95% confidence interval (mm)	0.5	0.8		
Measa	No.diameters measured	130.0	36.0	130.0	36.0
	Average residual error (mm)	-4.3	-4.4	-4.9	-3.6
	Standard deviation (mm)	5.4	4.6	5.7	4.3
	Two-sided 95% confidence interval (mm)	0.9	1.6	1.0	1.4
Tanoaka	No.diameters measured	77.0	43.0	77.0	43.0
	Average residual error (mm)	-4.3	-6.3	-4.5	-6.6
	Standard deviation (mm)	6.1	4.3	6.0	4.3
	Two-sided 95% confidence interval (mm)	1.4	1.3	1.4	1.3
Tosaaka	No.diameters measured	86.0	32.0	86.0	32.0
	Average residual error (mm)	-4.3	-4.5	-4.9	-4.5
	Standard deviation (mm)	7.5	6.9	7.5	6.9
	Two-sided 95% confidence interval (mm)	1.6	2.5	1.6	2.5
Harra	No.diameters measured	242.0	129.0	242.0	129.0
	Average residual error (mm)	5.4	6.9	5.2	5.0
	Standard deviation (mm)	8.0	8.1	7.9	8.0
	Two-sided 95% confidence interval (mm)	1.0	1.4	1.0	1.4
Hiki	No.diameters measued	65.0	33.0	65.0	33.0
	Average residual error (mm)	8.7	7.3	9.8	8.7
	Standard deviation (mm)	12.1	9.9	12.4	10.7
	Two-sided 95% confidence interval (mm)	3.0	3.5	3.1	3.8
Yabukuguri	No.diameters measurred	88.0	20.0	88.0	20.0
	Average residual error (mm)	-4.4	-2.5	-1.4	-2.6
	Standard deviation (mm)	4.1	4.0	3.9	4.3
	Two-sided 95% confidence interval (mm)	0.9	1.9	0.8	2.0

DISCUSSION

Differences in Height and DBH Growth among Local Varieties

In this study, height and DBH growth differed significantly among local sugi varieties in six of the survey years. Miyajima (1989) identified more than 60 local varieties of sugi in Kyushu District, Japan, according to characters such as leaf morphology. To achieve forest management objectives, Okada (1984) noted that sugi varieties are selected based on larger tree growth increment, disease resistance, and better wood quality. Because we found significant differences in height and DBH growth, the stem forms of the surveyed local varieties likely also differed.

Relative Stem Taper Curves

This aim of this study was to develop equations that would allow the estimation of upper diameter of sugi stems based on measurements that can be made at ground level. Following Behre (1923), our relative stem taper curves were based on DBH and trunk height from the breast height position. Kajiwara (1972) and Osumi (1987) noted several problems with stem taper curves based on the method of Behre (1923). First, root spread affects DBH as the tree stem grows and it is difficult to eliminate this effect from actual DBH measurements. Second, only diameters above breast height can be estimated using Behre's method, and the shape of the butt-end cannot be analyzed. These problems might arise when stem volume is estimated using a relative stem taper curve (e.g., Inoue, 2001; Inoue and Kurokawa, 2001; Kajiwara, 1972, 1973a, 1973b, Osumi, 1959), but they should not affect the estimation of upper diameter.

Other researchers developed relative stem taper curves based on trunk height from the ground to the tree top and the diameter at 0.9 of total trunk height (hereinafter $d_{0.9}$) (Hohenadle, 1922; Inoue, 2001; Inoue and Kurokawa, 2001; Kajiwara, 1972, 1973a, 1973b; Osumi, 1959; Prodan, 1944, 1951). Before forest cutting or clearing operations in Japan, complete tree tallies are usually conducted. Although researchers have used $d_{0.9}$, it is difficult to use this metric in the field for tree tallies because $d_{0.9}$ is measured at such a high position. As a result, this parameter is most useful in destructive sampling (i.e., after cutting), and is difficult to use in the field to predict whether a stand of trees is sufficiently valuable to justify cutting. Kajiwara (1993) also noted that relative stem taper curves based on $d_{0.9}$ are rarely used because the position of the basis diameter changes with tree as the height increases over time.

Osumi (1959) noted that the basis diameter could be measured at any height on the stem. In this study, DBH was adopted as the basis diameter for developing relative stem taper curves because this parameter can be measured directly. The curves developed in this study could be applied to estimate diameters at positions higher than breast height on the stem.

The relative stem taper curves developed in this study were third-order polynomials, as Osumi (1959) noted that such an equation provides a good fit for sugi stem-form data. Our findings also show this, as the coefficient of determination (R^2) was >0.99 for all nine relative stem taper curves developed for sugi and its local varieties (Fig. 2).

In our analysis of the accuracy of the relative stem taper curve, the average residual error between estimated and measured diameters was <1.0 cm for the sugi curve, as well as the curves for the individual varieties. Because logs must have an upper diameter >14.0 cm to be suitable timber column material in Japan, we also analyzed only those trees meeting this criterion. In this case as well, we found that the average residual error was <1.0 cm for all seven curves analyzed. In the field, logs with an upper diameter >14 cm are sorted in 2-cm increments. Estimating diameter using the relative stem taper curves developed in this study might be useful in the field because the residual error of the estimates are <1.0 cm.

Sugi is an important forestry species in Japan. Because forest tree breeding projects have been conducted in Japan for only about 50 years, there is little information regarding the stem form of sugi local varieties. This study revealed significant differences in height and DBH growth among sugi varieties in even-aged stands, suggesting that the stem forms of these eight varieties differ as well. Therefore, we developed separate relative stem taper curves for each local variety. In the case of sugi trees that have not been identified to the variety level or local varieties for which no relative stem taper curve has been developed, the sugi curve (Fig. 2) is the best choice for estimating upper diameter.

In the case of Measa, the sugi curve provided a better fit than the Measa curve for all diameters, whereas the opposite was found for diameters >14 cm (Table 3). Thus, when estimating upper diameter with regard to market suitability of the timber, the Measa curve should be used.

For the varieties Tanoaka, Tosaaka, and Haara, the two-sided 95% confidence intervals were the same for the sugi curve and the individual variety curve for all diameters and only those diameters >14 cm (Table 3). In addition, the average residual error for each variety was <1.0 cm. The confidence interval suggests greater reliability when the standard deviation is lower, because of the way the confidence interval is calculated (Sokal and Rohlf, 1987). For Tanoaka and Haara, because the variety curve has a smaller standard deviation than that of the sugi curve, estimation of the upper diameter in these varieties should use the variety curve. For

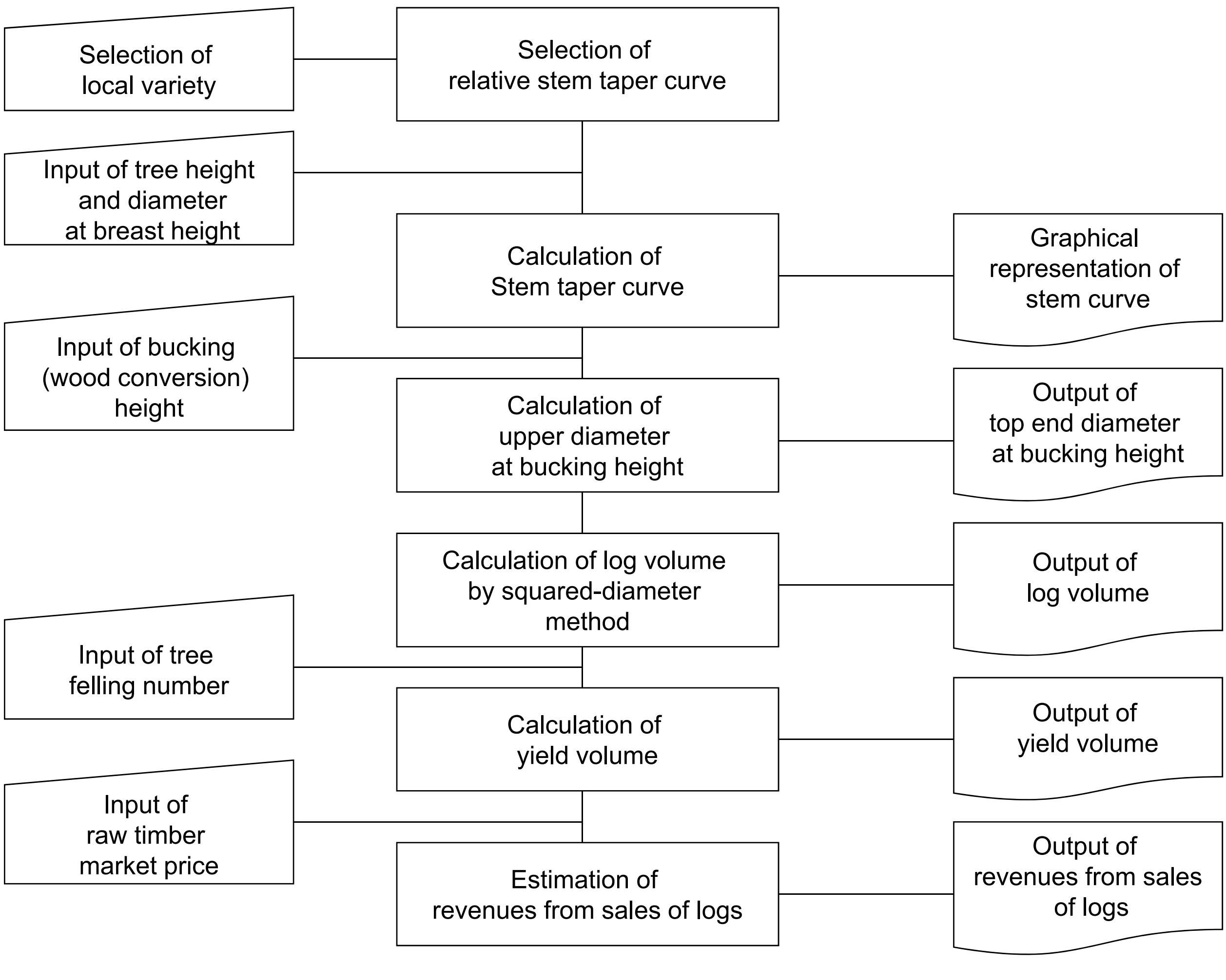

Fig. 3 Flow chart of forest operation planning based on stem upper diameter estimation

Tosaaka, there was no difference in the standard deviations, so either the sugi curve or variety curve would be suitable for estimating upper diameter.

For Yabukuguri, the variety curve provided a better fit than the sugi curve for all diameters, whereas the opposite was found for diameters >14 cm (Table 3). Thus, when estimating upper diameter of Yabukuguri with regard to market suitability of the timber, the sugi curve should be used. In the case of Hiki, the sugi curve provided a better fit than the Hiki curve for all diameters and only diameters >14 cm (Table 3), so the sugi curve is the best choice for this variety.

In Fig. 2, relative radius on Yabukuguri in 0.1 to 0.6 on relative stem length, was larger than the radius among other varieties of sugi on this study at the t-test significantly (p<0.05). Stem taper of Yabukuguri might be nontaperness compared to that of the other local varieties of sugi.

In relative radius on Kijin, the t-test on the same analysis in case of Yabukuguri, revealed significant differences among other variety of sugi except Yabukuguri from 0.1 to 0.6 on relative stem length (p<0.05). Stem taper of Kigin might be also nontaperness compared to that of the other local varieties of sugi.

At the position of 0.25 on relative radius, relative stem length of Yabukuguri alone was smaller than the position of 0.3 (Fig. 2). If relative radius at the position of 0.3 on relative stem length was larger than 0.25 at an unidentified local variety of sugi stem, the variety of the stem might be Yabukuguri. On the other hand, at the position of 0.35 on relative stem length of Measa and Tanoaka, relative radius was short of 0.25. So, if relative radius at the position of 0.35 on relative stem length was smaller than 0.25 at an unidentified local variety of sugi stem, the variety of the stem could be Measa or Tanoaka.

Forest Operation Planning based on Upper Stem Diameter Estimation

In existing stem taper tables, numerous tables are compiled and present a wide range of tree heights and DBH values. However, the upper diameter at a particular stem height cannot be directly obtained from these tables. Therefore, we have formulated a system that allows the diameter at a particular stem height to be easily estimated (Fig. 3). Only diameters higher than breast height can be estimated using this system.

By using this system before conducting cutting or cutting operations, the yield volume can be predicted. The proceeds of sales from the operation can be calculated by multiplying the predicted log yield by the wood market price. The profit can then be calculated by subtracting the operation cost from the proceeds of sales. By simulating the operation profit using this system, the forest manager could provide the forest owner with a proposal or quotation for each forest operation.

For the transportation of dried wood, timber column materials exceeding 16.0 cm in upper diameter are needed in view of the shrinkage that occurs when logs are dried. The estimation system developed in this study would allow for the easy identification of those trees with an upper stem diameter exceeding this 16.0-cm limit.

In future research, we will develop a relative stem taper curve for hinoki (*Chamaecyparis obtusa* Sieb. et Zucc.), which has a higher log price than that of sugi, to allow for more accurate estimates of that species' upper stem diameter, as well as the profits to be earned from logging operations in hikoki forests.

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Article

Spatial and Temporal Analysis of Probabilities for Acquiring Cloud-free Optical Sensor Images Using MODIS Cloud Mask Products 2000-2008 in Southeast Asia

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ABSTRACT

Accessibility to cloud-free optical sensor images is essential for large-area monitoring of land and forest cover changes. In this study, the acquisition probabilities of cloud-free images were analyzed using MODIS cloud mask products from 2000 to 2008 in Southeast Asia. The daily cloud masks were summarized into monthly acquisition probabilities for cloud-free images over the period at a spatial resolution of 1km. The mean annual acquisition probability profiles were extracted averaging nine years' observation. Unsupervised clustering was conducted for zoning of the acquisition probabilities using the mean annual profiles. Annual variations in the acquisition probabilities were examined by the standard deviations calculated for each month and comparisons of the mean annual profiles of the whole period and individual years. The distributions of annual acquisition probabilities in forested areas were different in each country. These results suggested that selection of suitable methods and data allowing for the spatial and temporal differences in the acquisition probabilities is necessary for periodic large-area monitoring.

Keywords: cloud-free image acquisition, large-area monitoring, MODIS cloud mask, Southeast Asia

INTRODUCTION

The IPCC Fourth Assessment Report (AR4) pointed out the possibility that emissions caused by land use change may account for 20% of total emissions of greenhouse gases that cause global warming (Denman et al., 2007). To reduce emissions caused by land and forest cover changes, the REDD-plus (Reducing emissions from deforestation and forest degradation in developing countries, and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks) scheme is now under discussion. REDD-plus is a political framework that aims at stopping deforestation by giving incentives to developing countries that achieve conservation of carbon levels (Angelsen, 2008). Therefore, it is essential to monitor land and forest cover at the national level.

Remote sensing techniques are expected to be an adequate tool for enabling this large-area monitoring in a transparent and cost effective way (Achard et al., 2010). Land and forest cover change monitoring has been conducted using remote sensing in many cases and a national inventory of forest cover is conducted in some countries (GOFC-GOLD, 2012). For example, some Southeast Asian countries has been reporting land and forest cover using medium spatial resolution data such as Landsat TM / ETM+ and SPOT (e.g., Department of Forestry, 2005; Forestry Administration, 2008; Royal Forest Department, 2008). The monitoring is usually conducted based on the manual delineation and interpretation of land cover and forest types by skillful technicians. Optical medium spatial resolution satellite imagery has been utilized because of its data accessibility, coverage, long historical observation and easy data handling. It still has some advantages in terms of cost-effectiveness, spatial resolution and multi-spectral observations (Hansen and Loveland, 2012; Wulder et al., 2012). However, the appearance of clouds is one of the main problems that prevent constant observation using optical sensors from space (Hansen and Loveland, 2012). The image acquisition date or season also have a large effect on the accuracy of change detection and multi-temporal land cover classification (Lunetta and Elvidge, 1999; Franklin and Wulder, 2002). Therefore, it is important to study the probabilities for acquiring cloud-free optical sensor images when considering the utility of optical remote sensing for large-area monitoring.

Cloud-free image acquisition has been studied all over

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the world (e.g., Kontoes and Stakenborg, 1990; Fuller et al., 1994; Asner, 2001; Akiyama and Kawamura, 2003; Sano et al., 2007; Ju and Roy, 2008). Such studies calculated spatial patterns and seasonality of acquisition probabilities using time-series Landsat images and summarized them at the scene level. Therefore, these studies cannot analyze spatial patterns within a scene or annual variations. On the other hand, the Moderate Resolution Imaging Spectrometer (MODIS), onboard the Terra and Aqua satellites, performs daily observations consistently with a wide coverage and a fairly high spatial resolution (Savtchenko et al., 2004). Therefore, it is possible to clarify the spatial patterns and annual variations in probabilities of cloud-free acquisition using the MODIS historical dataset.

In the present study, the targets were in Southeast Asia, where the climate is strongly affected by the Asian monsoon (Lau and Yang, 1997). There is a long dry season, especially in the inland Indochina Peninsular (Lau et al., 1988). This leads to high acquisition probabilities of cloud-free images during the dry season. On the other hand, it is said that the acquisition probabilities are low in the equatorial region and coastal or island areas such as Kalimantan, Indonesia. These facts are empirically known, but there is little quantitative analysis. Therefore, the objective of the present study was to clarify the spatial and seasonal patterns and the annual variations in acquisition probabilities of cloud-free optical images using nine years of MODIS cloud mask data in the Southeast Asian region.

MATERIALS AND METHODS

Study Area

The study area was the Southeast Asian region (Fig. 1). The study area was separated into two parts: 1. Continental Southeast Asian region (N 5° -29°, E 92° -110°) and 2. Insular Southeast Asian region (S 10° -N 8°, E 95° -120°). This study area covered the Southeastern Asian countries such as Cambodia, Lao PDR, Malaysia, Myanmar, Thailand, Vietnam and West Indonesia (hereinafter, referred as Indonesia). As Indonesia and Myanmar are listed in the Global Forest Resources Assessment 2005 (FAO, 2006) as two of ten countries with the largest annual net loss of forested areas from 2000 to 2005, land and forest cover monitoring are very important in this region. Tropical evergreen forests have expanded in equatorial regions such as Kalimantan in Indonesia. The vegetation gradually changes from evergreen forests to seasonal forests caused by strong Asian monsoons at higher latitude and altitude, especially in the inland area of the Indochina Peninsular (Kira, 1991; Blasco et al., 1996).

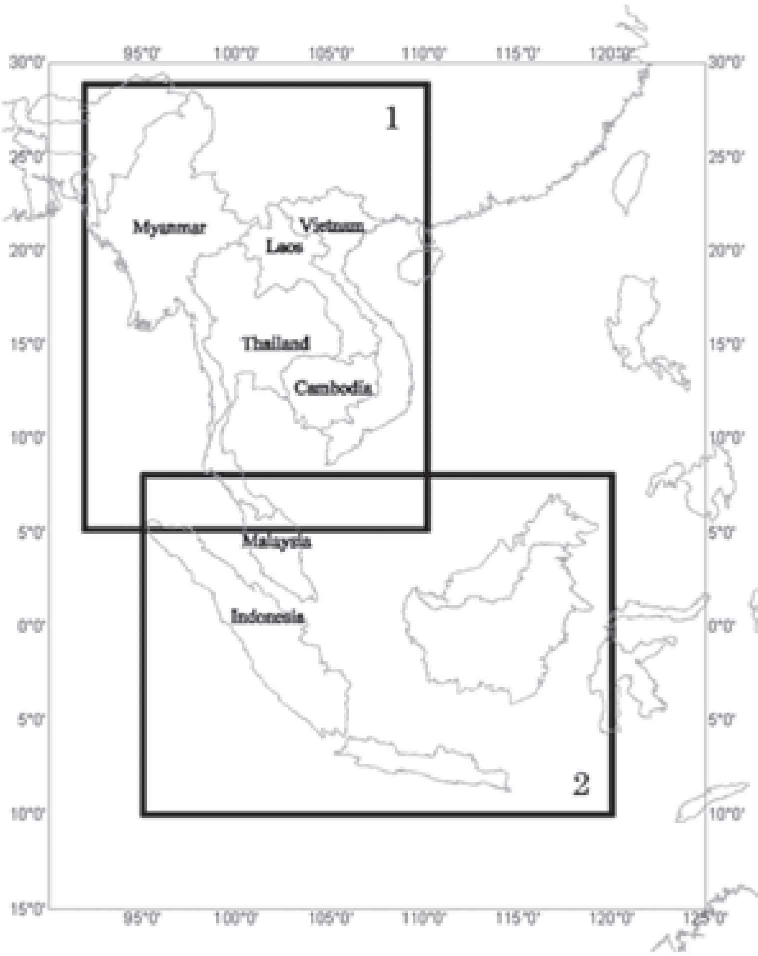

Fig. 1 Study area (1. Continental region (N5-29, E92-110) and 2. Insular islands (S10-N8, E95-120))

Materials

MODIS Level 2 Cloud Mask Product (MOD35_L2, Version Collection 5) (Frey et al., 2008) with spatial resolution of 1 km downloaded from NASA-LAADS (the Level 1 and Atmosphere Archive and Distribution System) were utilized for this study. The geo-projection was conducted using the MODIS Reprojection Tool Swath (MRTSwath) program with additional Geolocation files. The coordinates were set to Lat / Lon WGS 1984. The geo-projection was conducted using the nearest neighbor method to preserve the original discrete data value. Some gaps caused in the projection process were dealt with as deficit pixels at each observation date. MODIS onboard Terra passes the equator at 10:30 am (Savtchenko et al., 2004). The data acquisition time corresponds to those of typical satellites with sun-synchronous orbits. Therefore, only the products of the MODIS onboard Terra satellite were analyzed in the present study. Terra MODIS started observations from the end of February in the year 2000. The analysis period was almost nine years from March 2000 to December 2008. The MODIS sensor has been collecting data constantly, though a lack of data was observed for some short periods over these nine years (NASA-LAADS, 2013).

Calculation of Monthly Acquisition Probability of Cloud-free Images Using MODIS Cloud Mask (MOD35) Products

MODIS cloud mask is created by integrating the results of multiple tests using multiple bands with grouping according to the cloud type (Ackerman et al., 1998). The results are given by four ranks of confidential flags such as 1. Clear, 2. Probably clear, 3. Uncertain / Probably Cloudy, and 4. Cloudy (Frey et al., 2008). Therefore, the end users can inspect the products according to their own interests (Ackerman et al., 1998). This algorithm is conservative in terms of clear sky detection. It means that only very high confidence pixels are designated as clear (Ackerman et al., 1998). In this study, the days with the flag "Clear" were counted as clear days in a monthly summary. "Probably clear" appeared at the edge between clouds and clear sky, but the occurrence frequency was not high. Monthly observation days were summarized by accumulating actually observed days within a month and excluding the days with deficit data. Following this procedure, the monthly cloud-free image acquisition probability was calculated as below.

Monthly acquisition probability (%) =
Total days with clear sky / *Total observation days* x 100

where *Monthly acquisition probability* is a percentage of clear sky occurring each month. *Total days with clear sky* are the number of days observed as "clear" sky in the cloud mask each month. *Total observation days* are the number of days observed by Terra MODIS each month. As a result, 12 scenes of monthly acquisition probabilities for cloud-free image acquisition, corresponding to 12 months, were created. Standard deviation for each month was calculated using nine years of data. This standard deviation value was expected to be a good indicator for showing the intensity in annual variations. The null area mask of GTOPO30 global Digital Elevation Model in the TNT Global Geodata, prepared for user groups of GIS and Image processing software TNTmips (MicroImages, Inc.), was adapted to analyze the land area. All the geospatial analysis and image processing were conducted using TNTmips (MicroImages, Inc.).

Clustering Based on the Differences in Acquisition Probabilities of Cloud-free Images

An averaged monthly acquisition probability profile was created by averaging 9 years of data to minimize the annual variations. To clarify the spatial pattern of the acquisition probability profiles, clustering was conducted. Unsupervised Fuzzy *c*-means clustering was conducted using 12 averaged monthly acquisition probabilities with setting of initial class numbers of 12. Those classes were integrated into 8 classes in the final product by checking the class separability and co-occurrence.

Summary of Probabilities in Forested Area at National Levels

In the REDD-plus scheme, changes in forested areas at the national or sub-national level were the main concerns of monitoring. Therefore, annual acquisition probabilities in forested areas were summarized for each country and compared. The annual acquisition probability was calculated by averaging the nine years' mean monthly probabilities in a 1-km Grid generated within the whole study area. Grid points in forested areas were defined using Global Land Cover 2000 (GLC2000) database (Joint Research Centre, 2003). Changes such as deforestation that occurred during 2000 to 2008 were not considered in this study because our main concern here was to clarify the differences in probabilities among countries. Country attributes were added to the Grid points by using the country boundary vector data in the Global Geodata (MicroImages, Inc.). Frequency distribution of annual acquisition probabilities of cloud-free images was compared by country.

RESULTS

Spatiality and Seasonality of Acquisition Probabilities

The average monthly acquisition probabilities of cloud-free images are shown in Fig. 2. The bright color shows high acquisition probabilities and the dark color shows low acquisition probabilities. This result showed the obvious seasonality in some regions.

Clustering

Fig. 3 shows the results of unsupervised Fuzzy *c*-means clustering using 12 averaged monthly acquisition probabilities. The example of the 9-years' mean probability profile and annual variation at a point in each cluster are shown in Fig. 4. There were areas where the probability was constantly high in the dry season in the inland Indochina Peninsula (e.g. C7). On the other hand, there were areas where the probability was

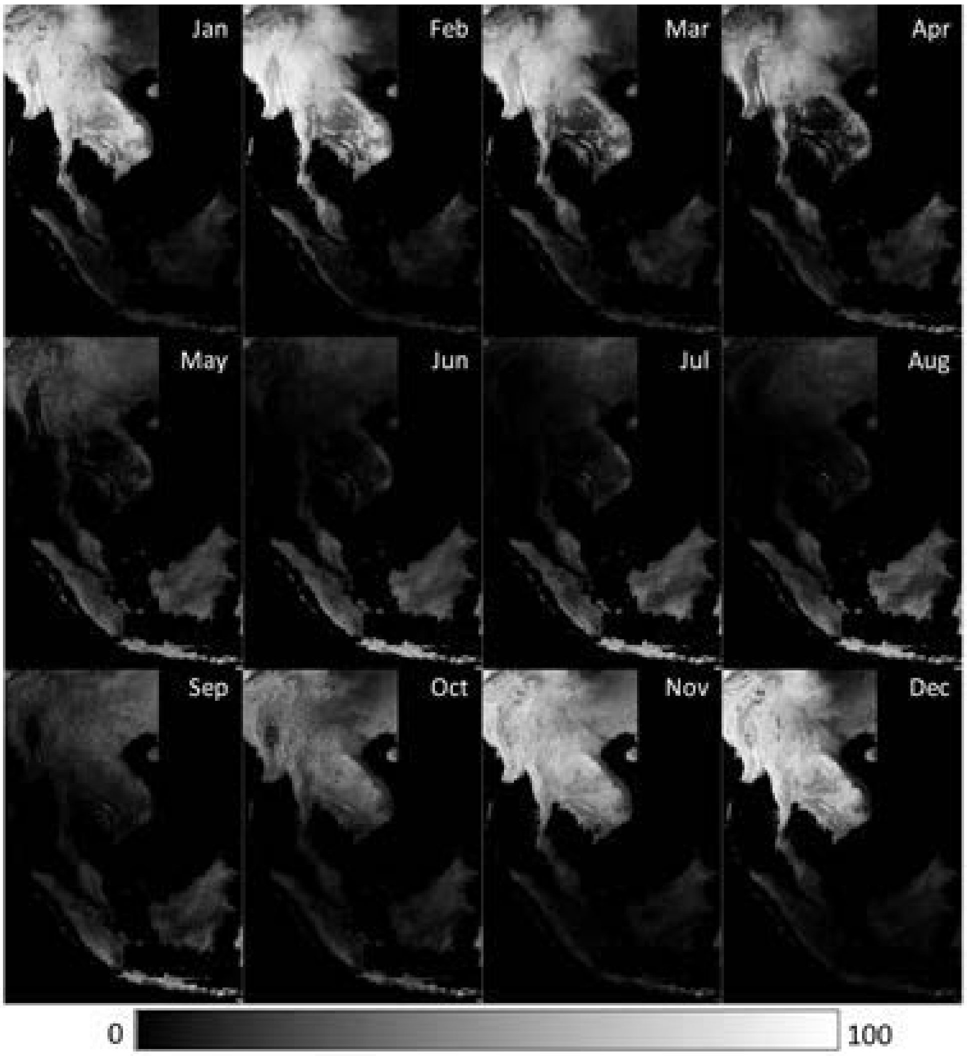

Fig. 2 Average monthly acquisition probabilities of cloud-free images in Continental and Insular Southeast Asia. The bright color shows high acquisition probabilities and the dark color shows low acquisition probabilities.

low all year round, such as the equatorial Indonesian islands, Malay Peninsula and coastal Vietnam (e.g. C3).

Annual Variations

Standard deviation was calculated using 9 years of data for each month (Fig. 5). Standard deviation was rather high in the dry season with high monthly acquisition probability, especially at the beginning and end of the dry season. This was caused by annual variations in the timing of seasonal changes. Fig. 4 also gives a visual description of the annual variations in the acquisition probability profile at some typical points belonging to each cluster. The difference between the 9-years average profile and the profile of each year in Fig. 4 shows the annual variations.

Summary of Annual Acquisition Probabilities in Forested Area at the National Level

Fig. 6 shows the frequency distribution of annual acquisition probabilities of cloud-free images in the forested areas of each country. Myanmar showed a peak in the high probability zone. Thailand and Lao PDR gave a similar frequency distribution. On the other hand, Indonesia and Malaysia had a peak in the low probability zone. Cambodia and Vietnam distributed in the middle range.

DISCUSSION

Spatiality, Seasonality and Annual Variation

This study quantitatively clarified the spatial and seasonal patterns of cloud-free image acquisition in Southeast Asia. The acquisition probability in the Indochina Peninsula, especially in inland Indochina, was rather high compared with other regions. On the other hand, the probability was rather low in coastal Vietnam, although it is also located in the Indochina Peninsula. The low acquisition probability in equatorial regions such as Kalimantan, Indonesia, supported the empirical facts quantitatively. As shown by our results, the achievable observation period should also be varied according to the difficulty of cloud-free image acquisition with optical sensors. Our clustering results can help to understand in

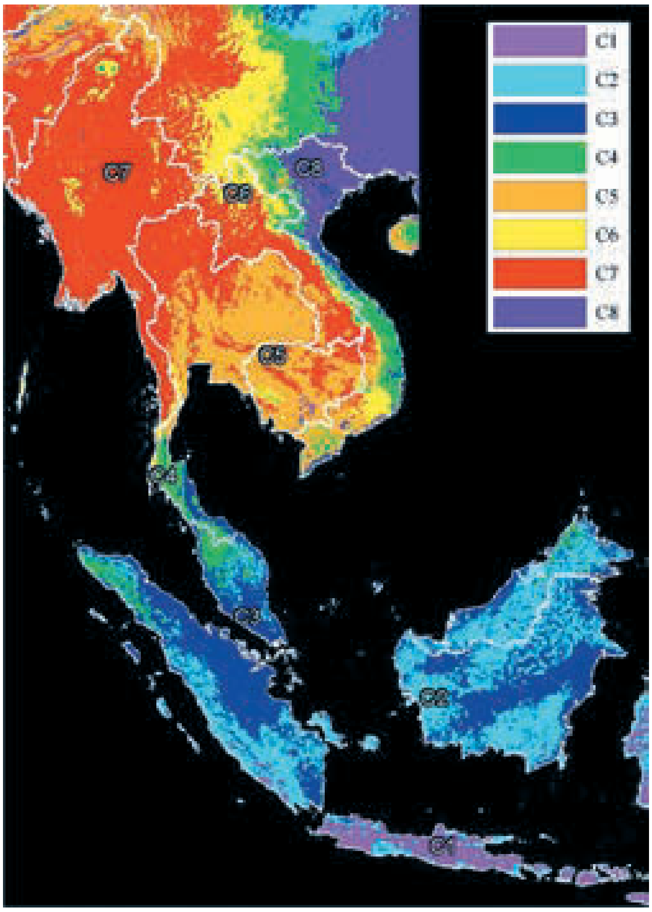

Fig. 3 Result of Clustering using averaged monthly acquisition probability profile. 8 classes (C1 to C8) are shown with different colors (C1: pink, C2: light blue, C3: blue, C4: light green, C5: orange, C6: yellow, C7: red and C8: purple).

detail the overall variety of difficulty in data accessibility. Long term observation of MODIS also helped to reveal the annual variations in each region.

Appropriate selection of the imagery acquisition date is crucial for change detection, and then the anniversary dates or anniversary windows are often used for analysis (Coppin and Bauer, 1996). Actual opportunities for monitoring are limited to the availability of data. In addition, although the probabilities are high in the dry season, for example, deciduous trees shed their leaves and it causes confusion due to the different types of land cover such as tropical dry forest, savanna, shrubland and grassland (Bautista et al., 2011). Especially, the influence becomes large at the end of the dry season. In such a case, more detailed setting of the time interval should be considered. On the other hand, in areas where there is no strong seasonality with evergreen vegetation types, the probabilities tend to be low all year round, for example, at the equator. However, the annual acquisition probability may directly show the probabilities of monitoring because monitoring can be done at any time period due to its stability in areas such as evergreen forests, although there may be minor seasonality factors such as leaf change. Therefore, in the application of optical sensors, the probabilities of cloud-free image acquisition during the targeted period when the acquired images can be suitably applied for the intended purpose of change detection or monitoring according to the applied method will be important. The monitoring period may have to be set longer in regions where the acquisition probabilities are low.

Now, there are many types of sensors and satellites observing land cover from space. Each sensor has advantages and disadvantages. For example, operational optical satellite sensors, such as onboard Spot, Landsat and IRS satellite series, have a moderately high spatial resolution, but a narrow observation width (Hirata et al., 2012). Frequent observation sensors such as MODIS and Spot Vegetation have a limited spatial resolution. The SAR sensor can conduct all-weather observation but has a disadvantage in terms of terrain area monitoring (GOFC-GOLD, 2012). Therefore, the selection of remote sensing data is an important issue. In the REDD-plus scheme, monitoring carbon levels is assumed to be conducted at the national or sub-national level to avoid leakage (Angelsen, 2008). It will be essential to consider the proper combination of methodology and remotely sensed imagery for large-area monitoring such as the REDD-plus scheme (Kiyono et al., 2011). Our results revealed the large difference in the acquisition probability of cloud-free images among countries and even within a country in some regions (e.g., Vietnam). Accessibility of the images can affect and limit the applicable remotely sensed data and methodology (GOFC-GOLD, 2012). It also influences the cost. Our clustering results can contribute to this discussion. More detailed clustering can be conducted by adding other sources such as terrain information that can be extracted using the Digital Elevation Model (DEM).

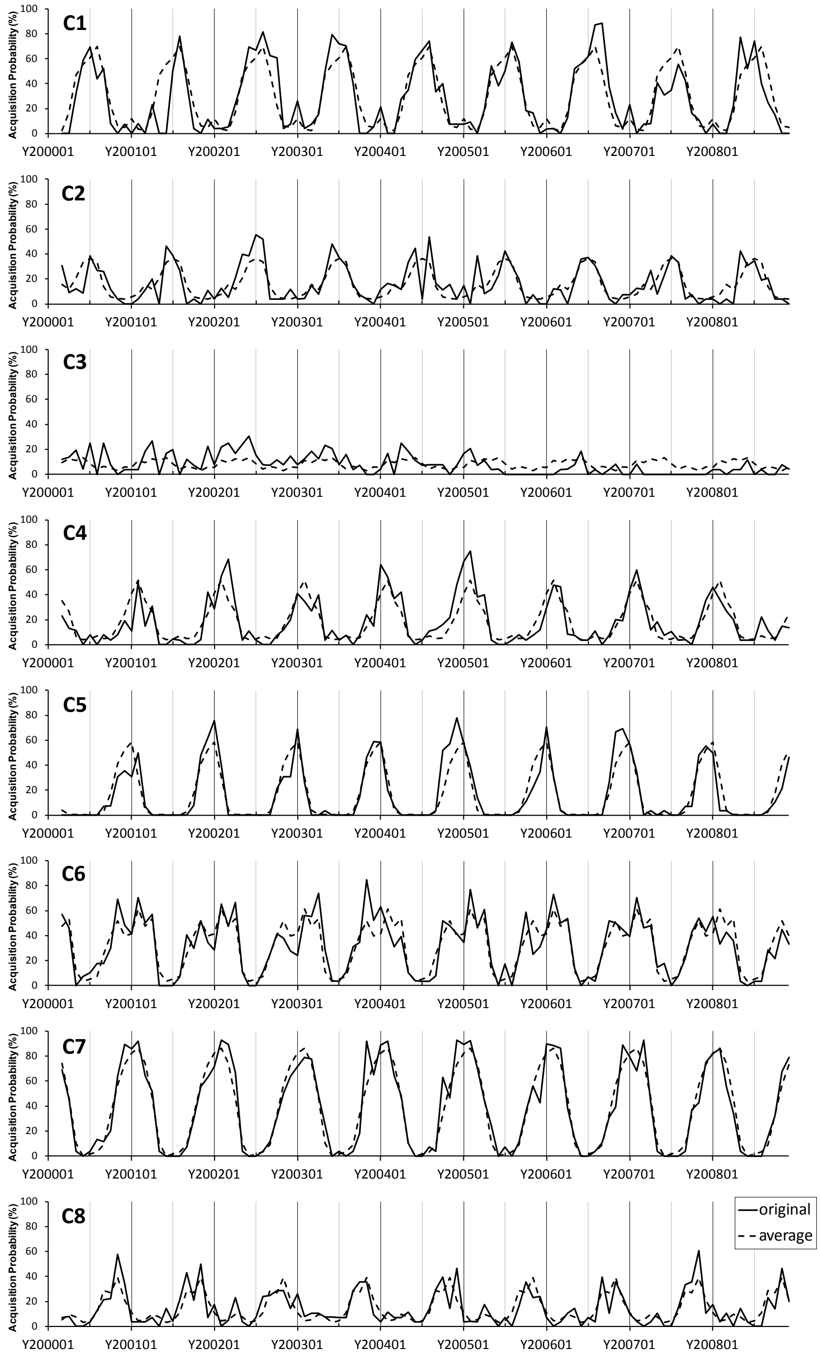

Fig. 4 Comparison of 9-years' average acquisition probability profile and original probability profile at a sample point for each cluster. The location of each point is shown in Fig. 3.

Other types of clustering or analysis that have been applied to the time-series Normalized Difference Vegetation Index (NDVI) can also be applied to utilize a seasonal pattern of amplitude and phase (e.g., Jakubauskas et al., 2001; Bradley et al., 2007).

Application of MOD35 MODIS Cloud Mask Products

In this study, MODIS cloud mask with a spatial resolution of 1km was utilized. Therefore, the spatial pattern could be analyzed in more detail than previous studies that were based on the Landsat scene level analysis (e.g., Kontoes and Stakenborg, 1990; Fuller et al., 1994; Asner, 2001; Akiyama and Kawamura, 2003; Sano et al., 2007; Ju and Roy, 2008). This study clearly revealed the spatial pattern of acquisition probabilities as explained above. In addition, using high frequency observation with long-term constant observation enables us to summarize acquisition probabilities of cloud-free images at monthly time intervals and to analyze any annual variations. These are the novel points of our analysis using MODIS cloud mask products. On the other hand, it should be taken into account that the concept of probability is slightly different between Landsat scene-based and MODIS pixel-based analysis. In this study, even small gaps in clouds

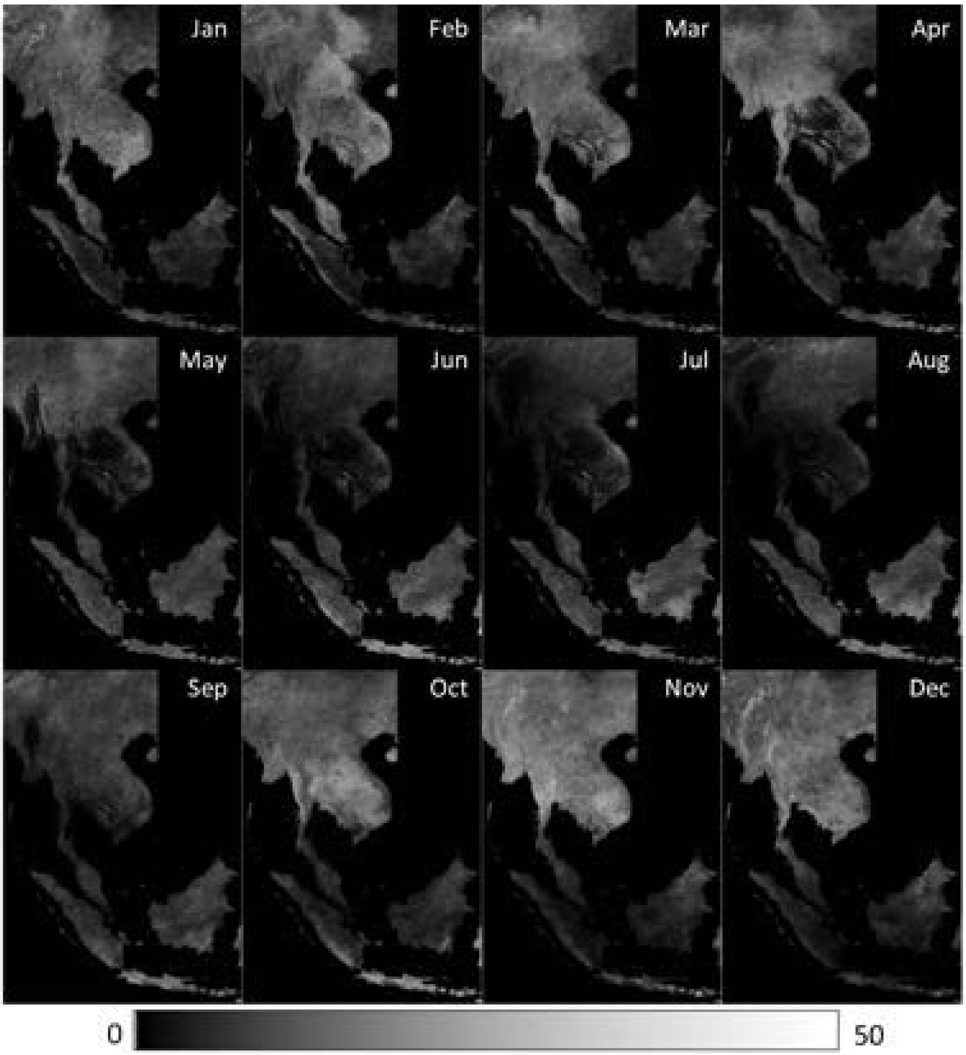

Fig. 5 Standard deviations of monthly acquisition probabilities at each pixel. The bright color shows high values of standard deviations and the dark color shows low values.

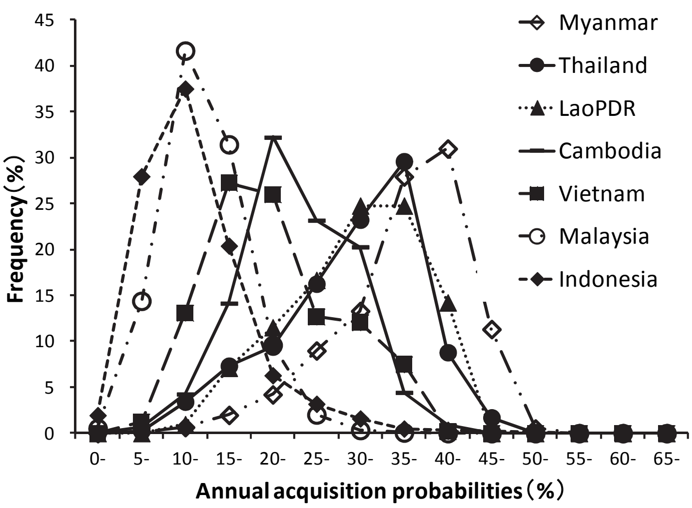

Fig. 6 Distributions of annual acquisition probability summarized in a 1-km Grid located in the forest type in each country.

could be counted as clear pixels, but when using Landsat images, especially for full or semi- automatic analysis, a wide extent of clear coverage is essential, for example, to collect Ground Control Points (GCPs) for geo-correction or to collect sufficient training data for supervised classification. In such cases, the probability based on the extent of a scene is more suitable.

MODIS cloud mask is one of the most reliable and efficient products at present because the algorithm is based on multiple tests using the advantages of multiple spectral observations of MODIS. However, there some errors remain (Ackerman et al., 1998). For example, while clouds are detected as a high reflectance in the visible band and low temperature in the Infrared wavelength, the results can be biased by the background land cover when setting a fuzzy threshold (Ackerman et al., 1998). In this study, the probability tended to be low in regions where the land was covered by dark cover objects. The accuracy of cloud detection could be improved through refinement of the algorithm and development of sensors and techniques in the future (Ackerman et al., 1998). Our procedure can be applied to other cloud mask products created using other sensors or methodologies. Climate changes and local land cover changes can cause changes in seasonal patterns and differences in timing. Such cases should be considered by changing or updating the averaging period and zoning.

CONCLUSION

MODIS cloud mask analysis clarified the spatial and seasonal patterns of acquisition probabilities of cloud-free images in Southeast Asia. Nine years of data analysis also clarified the annual variations. Some regions showed a high probability in the dry season influenced by the Asian monsoon, such as Inland Indochina. Some other regions showed a low probability all year round such as the equatorial Indonesian islands, Malay Peninsula and coastal Vietnam. These results should be considered when selecting suitable remotely sensed data and methods for periodic large-area monitoring.

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Article

Applicability of the Hemispherical Photography to Leaf Area Index Estimation in a Stand of Bamboo, *Phyllostachys pubescens*

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ABSTRACT

We evaluate an applicability of the hemispherical photography for estimating leaf area index (LAI) in a stand of bamboo, *Phyllostachys pubescens* Mazel ex Houz. In the *P. pubescens* stand, ten successive thinning regimes were conducted, and the repetitive hemispherical photography was performed before and after each thinning. LAI estimated from the photographs was then compared with that estimated by the allometric technique. There was a significant correlation between LAI estimated by these two methods, suggesting the applicability of the hemispherical photography. However, LAI estimated by the photographic method was significantly larger than that estimated by the allometric method. The discrepancy of the estimated LAI might be due to the bias caused by the culms and branches taken in photographs. The Monte Carlo simulation indicated that at least, but not more than, 12 hemispherical photographs per plot with 25 m^2 in area were necessary for stable estimation of LAI in a stand of *P. pubescens*. In conclusion, the hemispherical photography should be accepted as an effective alternative for estimating LAI in a stand of *P. pubescens*.

Keywords: allometric technique, hemispherical photography, leaf area index (LAI), Monte Carlo simulation

INTRODUCTION

Bamboo is the vernacular or common term for members of a particular taxonomic group of large woody grasses, which is widely distributed throughout the tropics, subtropics and temperate zones of the world (Scurlock et al., 2000). Lobovikov et al. (2007) estimated that there are roughly 37 million hectares of the bamboo forests in the world, which occupy 1% of the global forest area. Although the forest area has decreased in many countries, bamboo forests have progressively increased at a rate of 3% annually (Zhou et al., 2011). These facts indicate that the bamboo forests are one of the most typical types of forest in this area, and that they may strongly affect the global carbon cycling (Buckingham et al., 2011; Song et al., 2011; Lobovikov et al., 2012). Although many recent studies have focused on examining the capacity of fixing carbon in bamboo forests to assess their contributions to the global carbon cycle (e.g., Gratani et al., 2008; Yen et al., 2010; Liu et al., 2011; Wen et al., 2011; Yen and Lee, 2011; Zhou et al., 2011), there has been a debate whether the bamboo forest ecosystem is a carbon sink or source (Duking et al., 2011; Song et al., 2011; Zhou et al., 2011). The reason of this conflict will be that studies on the bamboo are remarkably scarce and little is known about the carbon cycling of the bamboo forests (Isagi, 1993; Isagi et al., 1997).

The leaf area index (LAI) is defined as the total one-sided area of photosynthetic tissue per unit ground area (Jonckheere et al., 2004). Since the leaf or canopy layer governs the carbon sequestration in a forest stand, LAI is a major determinant of the carbon cycle in forest ecosystem. Despite of its importance, the direct measurement of LAI is time-consuming and labor-intensive (Majasalmi et al., 2012), and hence it is an inapplicable method for the spatially and temporally intensive studies. A most widely used alternative measurement of LAI is the allometric technique, which relies on the allometric power relationship between leaf area and any dimension variables such as diameter at breast height (dbh) and tree height (see reviewed by Jonckheere et al., 2004). The allometric technique will be a powerful alternative for estimating the total leaf mass or LAI, if reliable and appropriate allometric equations can be obtained. As the most reliable approach, the allometric technique has often been applied to the estimation of the total foliage mass or LAI in the bamboo forests (Toyota and

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Mori, 1985; Kawahara et al., 1985, 1987; Isagi, 1993; Isagi et al., 1997; Murakami et al., 2006; Du et al., 2011). On the other hand, the remote sensing technique enables us to estimate LAI over a large area of bamboo forests (Zhang et al., 2011). This technique is however based on the empirical-statistical approach that relates ground-measured LAI to the spectral vegetation index. For this reason, it still requires the ground-truth of LAI estimated by the other direct or indirect method (Breda, 2003).

Another effective alternative for estimating LAI may be the hemispherical photography (e.g., Jonckheere et al., 2004; Zhang et al., 2005; Garrigues et al., 2008; Chianucci and Cutini, 2012). Once the photographs are taken, the tedious works for measuring the foliages in the field can be replaced by an easy estimation from the image analysis. Especially, an inexpensive digital camera that can be equipped the exclusive fish-eye lens is now available. The digital hemispherical photography should be useful in spatially and temporally intensive studies, since we can save on the cost, time and labor for film processing and image scanning (Inoue et al., 2004b). Furthermore, studies have shown the effectiveness of hemispherical photography for estimating LAI in both coniferous and broad-leaved forests (e.g., van Gardingen et al., 1999). These features make the hemispherical photography one of the most effective devices for estimating LAI. However, so far the studies on the measurement of LAI in a bamboo forest using hemispherical photography (including the other optical devices such as Plant Canopy Analyzer, LAI-2000) have been superficial (Onozawa et al., 2009; Shinohara et al., 2010; Komatsu et al., 2010; Kume et al., 2010; Zhang et al., 2011). In addition, accuracy of LAI in bamboo forests estimated by the hemispherical photographs has not validated with direct reference measurement of LAI, since LAI reported in these studies has been estimated as a supplemental information on the water cycling (Onozawa et al., 2009; Shinohara et al., 2010; Komatsu et al., 2010; Kume et al., 2010) or a ground-truth for the remote sensing (Zhang et al., 2011).

New shoots of *Phyllostachys pubescens* Mazel ex Houz., which is one of the largest bamboos in Japan, are produced in early spring at a density of 500-3000 shoots per ha, independent of the light environment within the stand (Li et al., 1998). After emergence, the shoots elongate rapidly and reach their mature heights (ca. 10-20 m: Li et al., 2000) in a matter of two or three months (Zhou et al., 2005). The branches and leaves of the new elongated culms are then expanded in the canopy layer of the old culms (Gratani et al., 2008). For these reasons, the bamboos compose the very dense stand with an extremely closed canopy (Li et al., 1999), suggesting that the canopy structure of bamboo forests would be markedly different from that of the forests composed of tree species. Therefore, it is necessary to examine whether the hemispherical photography can be applied to the estimation of LAI in bamboo forests as well as the coniferous and broad-leaved ones.

In addition, the hemispherical photographs should be taken under still and cloudy conditions (e.g., Inoue et al., 2004a, b, 2011a; Jonckheere et al., 2004; Yamamoto et al., 2010). The time and labor become intensive as the number of photographs increases. For these reasons, it is reasonable to taken the photographs as small number as possible with an appropriate precision. Sampling intensity is the key issue when performing ground measurement of LAI not only with LAI-2000 but also with hemispherical photography (Nackaerts et al., 2000; Weiss et al., 2004; Majiasalmi et al., 2012). However, it is unknown how many hemispherical photographs should be taken when estimating LAI in a bamboo stand. Answering these two questions will be useful not only for the spatially and temporally intensive studies on the carbon cycling in bamboo forests but also for the ground-truth of the remote sensing technique.

The objective of this study was thus to assess the applicability of hemispherical photography for estimating LAI in a stand of bamboo, *P. pubescens*. In this study, LAI estimated by hemispherical photographs was firstly compared to that by allometric technique, and then the applicability of the hemispherical photography to the *P. pubescens* forests was discussed. Secondly, the Monte Carlo simulation was applied to derive the number of photographs required for estimating LAI in a stand of *P. pubescens*.

MATERIALS AND METHODS

Study Site

This study was conducted in a stand of *P. pubescens* in a typical suburban forest, Mt. Toshima, located in the eastern part of Kumamoto City, Kumamoto Prefecture, western Japan (32°49'N, 130°48'E; Inoue et al., 2011b, 2012). The average annual temperature and annual rainfall in Kumamoto City were 16.8℃ and 2,060 mm, respectively. *P. pubescens* was distributed from the foot to the mountainside of Mt. Toshima, and the upper part of this mountain was dominated by the evergreen broad-leaved species such as *Quercus glauca* Thunb. ex Murray, *Castanopisis cuspidate* Schottky and *Symplocos lucida* Sieb. et Zucc. The study site was located on a south-facing gentle slope and the altitude ranged from 80 to 90 m. This stand was dominated by *P. pubescens*, and few seedlings of tree species (e.g., *Nageia nagi* Thunb. Kuntze, *Camellia japonica* L., *Cinnamomum camphora* L. Presl. and *Osmanthus* × *fortunei* Carr.) were scattered at the forest floor. According to the local residents, this site was originally used for upland farming until a few decades ago, and is now being turned into a *P. pubescens* stand because of the planting of bamboo and subsequent abandonment.

Field Inventory

A square plot of 15 m × 15 m was established in this stand, and the plot was then divided into nine 5 m × 5 m sub-plots. The diameter at 1.2 m height above ground level (dbh) of all culms was measured, and the culm position and age were also recorded. The culm age was determined by the following criteria: (1) 1-year-old bamboo had sheaths that still remained in the culm base and the culm surface was covered with a clear white powder; (2) In 2-year-old or greater bamboo, the sheaths disappeared from the culm base, the white powder began to disappear from the culm surface gradually, and the culm turned light green or yellowish green in color.

In this plot, ten successive thinning regimes were performed after the elongation of the new culms and the development of leaves of *P. pubescens* (from October 2010 till January 2011), so that the change in LAI with culm density could be evaluated and the effect of leaf fall of *P. pubescens* on the LAI estimation could be ignored. The thinning culms were preferentially selected from dead, older and smaller culms, so that the thinning ratio by the number of culm for each thinning was approximately 5% (based on the initial culm density) and the residual culms were distributed as random as possible. Only three dead smaller culms with no leaves were found among 129 culms in the plot before the thinning experiment, suggesting that the effect of these dead culms on the LAI estimation would be comparatively small. General description of the experimental stand is given in Table 1. For the detail of this thinning experiment, see Inoue et al. (2012).

Table 1 Changes in stand characteristics with thinning regimes in the *Phyllostachys pubescens* stand

Thinning	DBH (cm)*	Culm density (culms ha^{-1})	LAI (ha ha^{-1})**
Before	11.6 ± 2.4	5733	4.83
1st	11.7 ± 2.3	5467	4.70
2nd	11.7 ± 2.3	5156	4.46
3rd	11.8 ± 2.3	4889	4.34
4th	11.9 ± 2.2	4578	4.08
5th	11.9 ± 2.4	4311	3.86
6th	11.9 ± 2.4	4000	3.61
7th	11.9 ± 2.4	3733	3.31
8th	11.8 ± 2.4	3422	2.98
9th	11.9 ± 2.3	3156	2.79
10th	12.0 ± 2.3	2844	2.52

* Average ± SD

** Estimated from diameter at breast height by the allometric technique.

Estimation of Leaf Area Index

To estimate LAI in the *P. pubescens* stand, the repetitive hemispherical photography was performed before and after each thinning. For the photography, the center sub-plot was divided into twenty-five 1 m × 1 m quadrats. On the each corner of these quadrats, color hemispherical photographs were taken in still and overcast sky conditions using a digital cameras (Coolpix 4500, Nikon Corporation, Tokyo, Japan) with an exclusive fish-eye lens (Fish-eye converter FC-E8, Nikon Corporation, Tokyo, Japan). The camera was mounted at a height of 1.2 m above ground on a tripod and leveled with a bubble level (Inoue et al., 2004a, b, 2011a). The height of the seedlings found at the forest floor was lower than the camera height, indicating no effects of the seedlings on the estimation of LAI. The camera settings when taking photographs were as follows (Yamamoto et al., 2010): The reference exposure setting (shutter speed and lens aperture) for an open sky outside the forest was recorded using the Auto mode of the digital camera with an exclusive fisheye lens immediately before entering the forest. The photographs were then taken with the recorded reference exposure setting. The setting for the metering method of light for the digital camera was fixed using the center-weighted method. Inoue et al. (2004b) found no effects of different image quality and size of digital hemispherical photography on light environment estimates, and therefore the Normal image mode (2,272 × 1,704 pixels) was selected in this study. The resulting total number of hemispherical photographs taken in this study was 396.

The hemispherical photographs were downloaded directly from the digital camera to a personal computer (FM-V Deskpower, Fujitsu Corporation, Tokyo, Japan). An automatic thresholding algorithm based on the classification error (Kittler and Illingworth, 1986) was applied to the blue channel images (Inoue et al., 2011a). LAI was estimated from the binary images based on the algorithm proposed by Welles and Norman (1991) with the assumption of random spatial distribution of the leaves of *P. pubescens* (Zhang et al., 2011). The fish-eye lens used in this study was designed to produce a simple polar projection, but it did not conform exactly to this design specification (Inoue et al., 2004a). LAI was therefore estimated by calibrating the view angle and lens distortion of the fish-eye converter (Inoue et al., 2004a). These image analyses were performed using the LIA for Win32 (LIA32: Copyright K. Yamamoto) image processing program, developed by Delphi 5.0J (Inspire Corporation, Scot Valley, USA) and available freely on the Internet at http://www.agr.nagoya-u.ac.jp/~shinkan/LIA32/index-e.html.

For the comparison, LAI in the stand of *P. pubescens* was also estimated using the allometric power equations between leaf biomass and diameter at breast height (dbh). In this study, the following allometric equations determined in the two stands of *P. pubescens* in Satsuma and Aira Towns, Kagoshima Prefecture, southwestern Japan, were used to estimate leaf biomass (Murakami et al., 2006):

$$l = 0.0075\, d^{0.7578} \quad \text{(1-year-old culms for Satsuma)} \qquad (1)$$

$$l = 0.0198\, d^{0.6678} \quad \text{(1-year-old culms for Aira)} \qquad (2)$$

$$l = 0.0001\, d^{1.7238} \quad \text{(2-year-old or greater culms for Satsuma)} \qquad (3)$$

$$l = 0.0001\, d^{1.2998} \quad \text{(2-year-old or greater culms for Aira)} \qquad (4)$$

where l: leaf dry mass per culm, d: dbh. The leaf biomass for each culm was estimated by the two equations and then averaged. Total leaf biomass in the stand was computed by summing up the estimated leaf biomass for each culm. LAI was obtained by multiplying the computed total leaf biomass by the specific leaf area observed in our site (149.2 $cm^2\ g^{-1}$: Sakuta, unpublished data). The dead culms as mentioned above were excluded from the computation of LAI by the allometric technique, since they had no leaves. Hereafter, this method for estimating LAI is called “allometric method”, whereas the method using hemispherical photograph is called “photographic method”.

Data Analysis

LAI estimated by the photographic method, LAI(p), was compared with LAI based on the allometric method, LAI(a), using Wilcoxon sign rank test. Pearson’s correlation coefficient test and regression analysis were also performed to examine the relationship between LAI(a) and LAI(p).

To evaluate how many hemispherical photographs were required to estimate LAI appropriately, the change in LAI with the number of photographs was examined for each time (before and after each thinning) using the Monte Carlo simulation technique as follows: First, samples (n = 2–36) were randomly selected from the original data pool (n = 36) without replacement, and then average LAI was estimated for each number of photographs. After repeating the above procedure 10,000 times, the probability density function (PDF) of the average LAI was determined. Finally, the coefficient of variation (CV) was computed from the average and the standard deviation of the PDF, and then the change in CV with the number of photographs was analyzed. All statistical procedures were performed with the R software ver. 3.0.1 for Windows (R Development Core Team, 2013).

RESULTS

Fig. 1 compares LAI estimated by the allometric method, LAI(a), and by the photographic method, LAI(p), in the stand of *P. pubescens*. As the thinning progressed, LAI(a) monotonically decreased from 4.83 to 2.52 ha ha^{-1}, whereas LAI(p) decreased from 5.34 (before thinning) to 3.08 ha ha^{-1} (after 10th thinning). Although there was a significantly positive correlation between LAI(a) and LAI(p) (r = 0.927, P < 0.001), Wilcoxon sign rank test indicated that LAI(p) was significantly larger than LAI(a) (P < 0.01). The relationship between LAI(a) and LAI(p) could be expressed by the following linear equation:

$$\mathrm{LAI(p)} = 0.852\ \mathrm{LAI(a)} + 0.962 \quad (r^2 = 0.874, P < 0.001). \qquad (5)$$

The intercept of Eq. (5) was significantly different from zero (P < 0.05), indicating that the ratio of LAI(p) to LAI(a) was not a constant.

Fig. 2 depicts the relationship between the number of hemispherical photographs and the coefficient of variation (CV) of LAI computed with the Monte Carlo simulation technique. Since the variation in LAI was the largest after 6-th thinning regime, only the result at the time just after 6-th thinning is given in this figure. The CV rapidly decreased with increasing number of photographs when the number of photographs was <12, whereas it was almost stable and <2% when the number of photographs was >12.

DISCUSSION

Comparison of LAI Estimated by Allometric and Photographic Methods

Comparison of LAI estimated by the two different methods indicates that LAI(p) was significantly larger than that by LAI(a) (see Fig. 1). Several studies have compared LAI estimated by hemispherical photography with the direct

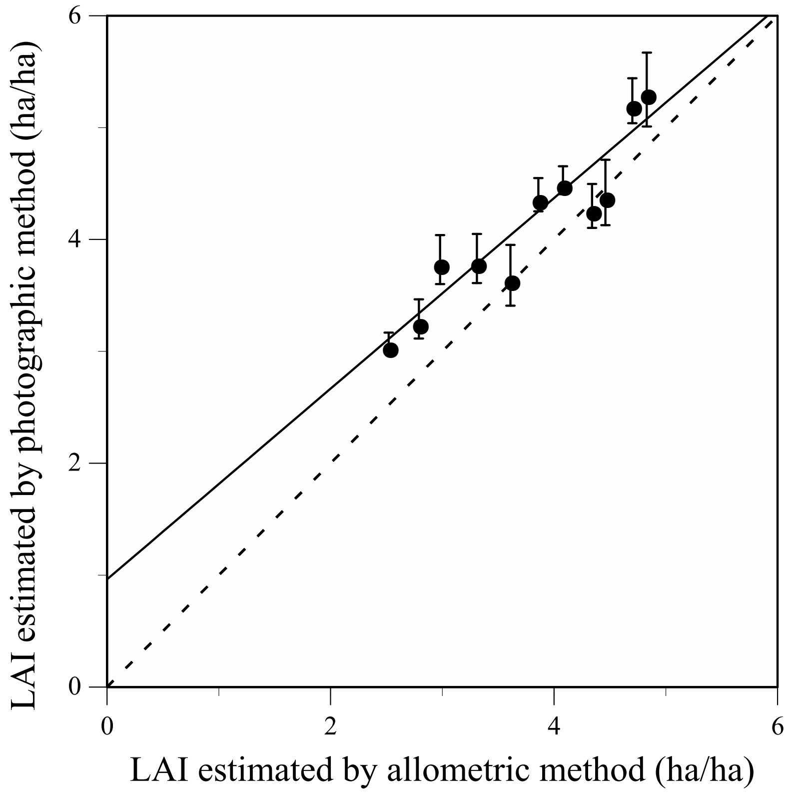

Fig. 1 Comparison of LAI estimated by allometric method with that by photographic method. The solid, broken lines and error bars indicate the regression line, 1:1 and the standard error of LAI, respectively.

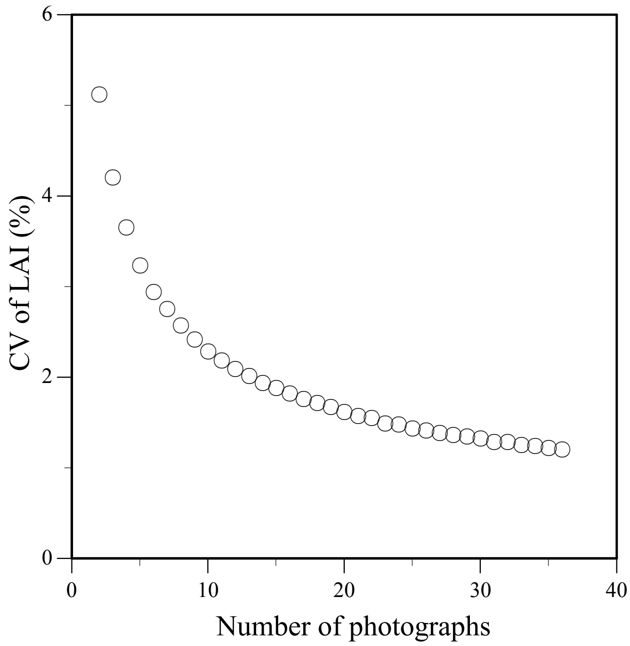

Fig. 2 Relationship between the number of photographs and the coefficient of variation (CV) of LAI in a stand of *Phyllostachys pubescens* computed by the Monte Carlo simulation.

measured LAI (e.g., Comeau et al., 1998; van Gardingen et al., 1999; Breda, 2003). Most of them conclude that the hemispherical photography underestimates LAI compared with the direct measurement. Jonckheere et al. (2004) summarize that the sources of error when estimating LAI using hemispherical photography are divided into the image acquisition, image analysis and violation of model assumptions. Among the sources of error, Jonckheere et al. (2004) said that the clumping of leaves seems to be the main factor causing the underestimation of LAI. By contrast, Zhang et al. (2011) argued that the assumption of random spatial distribution of the leaves is generally true for bamboo forests. For this reason, we assume the random spatial distribution of the leaves when estimating LAI from hemispherical photography, which results in the overestimation of LAI compared with the allometric method. These facts imply that the influence of the other factors on LAI estimation which produces an overestimation may be greater than the influence due to the clumping bias (Breda, 2003; Jonckheere et al., 2004).

The possible another reason of the discrepancy between LAI(a) and LAI(p) might be due to the bias caused by the culms and branches taken in photographs. As Weiss et al. (2004) indicated, the estimate from hemispherical photography is an effective leaf area index (LAIe) or plant area index (PAI) rather than LAI. To obtain not LAIe but LAI, the bias due to the contribution of culms and branches should be corrected. Chen (1996) found the relationship between LAIe and LAI as follows:

$$\mathrm{LAI} = (1-\alpha)\ \mathrm{LAIe}\ (\gamma_e/\Omega_e) \tag{6}$$

where α is the ratio of woody surface area to total surface area; γ_e is the shoot clumping factor; Ω_e is the clumping index quantifying the effect of foliage clumping at larger scales than the shoot, and γ_e/Ω_e is the total stand clumping index. Assuming that the foliage distribution is spatially random (Zhang et al., 2011), the term, γ_e/Ω_e, in Eq. (6) becomes unity (Barcley et al., 2000) and Eq. (6) can be rewritten as

$$\mathrm{LAIe} = \mathrm{LAI}/(1-\alpha). \tag{7}$$

Now suppose that LAIe and LAI in Eq. (7) are, respectively, equal to LAI(p) and LAI(a), we have

$$\mathrm{LAI(p)} = \mathrm{LAI(a)}/(1-\alpha). \tag{8}$$

By eliminating LAI(a) from Eqs. (5) and (8), the ratio of woody surface area to total surface area, α, can be written as

$$\alpha = (0.962/\mathrm{LAI(p)} - 0.148)/0.852 \tag{9}$$

In this study, the observed LAI(p) ranged from 3.08 to 5.34 ha ha^{-1}. Substituting these values of LAI(p) into Eq. (9) yields the estimate of the ratio α in our site, which varies from 0.038 to 0.193 with LAI(p). As shown in Eq. (5), the ratio of LAI(a) to LAI(p) in the stand of *P. pubescens* was not a constant. The reason of this inconstancy would be that the ratio of woody surface area to total surface area varies with culm density as suggested by Eq. (9). Gower et al. (1999) reported that the contribution of woody surface area to total surface area ranges from 5 to 35%. Breda (2003) also reviewed the ratio reported in previous studies and found that the value of α ranges from 3 to 41%. The estimated ratio for the studied stand of *P. pubescens* (3.8 to 19.3%) falls within a reported range for the tree species (Gower et al., 1999; Breda, 2003) and into the category of lower value of α. Since the stand of *P. pubescens* bears more leaves compared to that of tree species (e.g., Isagi et al., 1997), the lower value of α showed the reasonability of the result of the present study. These facts demonstrated that the hemispherical photography should be accepted as an effective alternative for estimating LAI in a stand of *P. pubescens*.

How Many Hemispherical Photographs are Necessary When Estimating LAI?

In the present study, 36 hemispherical photographs were taken before and after each thinning regime. However, it is preferable that LAI can be estimated from the hemispherical photographs as small number as possible. Therefore, the Monte Carlo simulation was applied to examine how many photographs are necessary when evaluating LAI in the *P. pubescens* stand. To determine the optimal number of photographs for estimating LAI, we use -0.1% as the threshold of the change in the CV (dCV/dn), i.e., a decrease in CV of less than 0.1% when increasing the number of photograph by one. As shown in Fig. 2, CV rapidly decreased with increasing the number of photographs when dCV/dn < -0.1%, whereas the CV slightly decreased with increasing the number of photographs and almost stable when dCV/dn > -0.1%. The minimum number of photographs with continuous dCV/dn > -0.1% is defined as the optimal number of photographs in the present study. With this criterion, the optimal number of photographs is estimated to be 12, and CV of LAI is less than 2%. For the photographs taken after 4-th thinning with the smallest variation in LAI, it is necessary to take only six photographs based on the same criterion. Therefore, to estimate LAI in the *P. pubescens* stand, it would be necessary to take at least 12 hemispherical photographs per plot with 25 m^2 in area but not necessary more than 12 photographs.

CONCLUSIONS

This study evaluates an applicability of hemispherical photography for estimating LAI in the stand of *P. pubescens*. The result showed that LAI estimated by photographic method, LAI(p), is highly correlated with LAI estimated by the allometric technique, LAI(a), suggesting the applicability of the hemispherical photography. We also propose an effective sampling strategy; only 12 hemispherical photographs per plot with 25 m^2 in area are enough for estimating LAI in *P. pubescens* stands. These findings will be effective in the future studies for evaluating the carbon cycling in stands of *P. pubescens*. In conclusion, the hemispherical photography should be accepted as an effective device for estimating LAI in a stand of *P. pubescens*.

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