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Article

Examination of Maximum Sustainable Timber Yield Based on a Profitability Simulation

Yusuke Yamada [*1] and Satoshi Tatsuhara [*1]

ABSTRACT

Sustainable timber production that improves timber self-sufficiency is needed in Japan. We focused on predicting the maximum yield that can be supplied sustainably, considering the financial index, and examined the corresponding amounts of timber produced in relation to timber prices and logging costs. The study area consisted of privately owned forests in the area of former Sanpoku Town, Murakami City, Niigata Prefecture, Japan (38°21 − 33'N, 139°27 − 34'E). Maximum sustainable yield, which satisfied some assumed requirements, was acquired by developing a forest management model for the simulation. We also assessed the effects of timber market prices and logging costs. The results suggest that even slight changes in log prices have a large influence on maximum sustainable yield, implying that forest owners are operating on a slim profit margin. However, the results also suggest that efforts to reduce costs should be effective for enhancing profits, leading to a larger timber supply. Our results indicate that future timber yields could be dramatically increased by practicing restrained clear-cutting for several decades.

Keywords: financial evaluation, simulation, sustainability, timber production

INTRODUCTION

The growing stock of plantation forests has been increasing considerably in Japan. According to a white paper on forestry (Japanese Forestry Agency, 2010), total growth in plantation forests reached 82 million m^3, which is sufficient to supply the annual timber demand in Japan (78 million m^3 in 2008). Moreover, considering the age distribution of plantation forests, Japan has sufficient growing stock. The age distribution forms a peak at approximately 40-50 years, which is due to the large-scale conversion of natural hardwood forests to coniferous plantations after 1950.

In contrast, timber self-sufficiency has progressed little. Imported timber exceeded domestic timber supply in 1969, and the self-sufficiency ratio has been declining since then. Although the self-sufficiency ratio increased from 18.2% in 2000 to 24.0% in 2008, the increase was not due to rising domestic supply but to a decrease in imports. The amount of imported timber decreased recently because of the recession in Japan and a higher export tax in Russia. Foreign wood was thus diverted to more attractive markets such as China.

Efforts should be made to improve Japan's self-sufficiency. Timber logging operations must be linked with efforts to maintain domestic forest ecosystems. Japan can also contribute to the global sustainability of forest resources by consuming its own timber, as timber production in developing countries for export to developed countries such as Japan is the main reason for deforestation in tropical areas (Houhuku, 1994).

Constructing large timber manufacturing complexes could help increase the domestic timber supply. A large sawmill can produce a large amount of relatively inexpensive lumber. In Kyushu, a southern island of Japan, a new timber production system has been established in recent years, and a comparatively large sawmill is the most important part of this system. Efforts to make the timber supply system more efficient are underway. Sustainable timber production can make this system work more efficiently and can also provide incentives to forest owners (Repetto, 1987).

Some studies have used simulations to predict maximum sustainable yields, which are the maximum amount of timber that an area can sustainably supply. Matsumoto *et al.* (2007) predicted sustainable timber production if private plantation forests in Kuma-cho, Ehime Prefecture, were induced to meet typical "normal forest" levels. Adams *et al.* (1982) simulated how intensified management would magnify the long-term timber supply. Methods for sustainably producing timber in tropical forests have been estimated by some researchers (Vanclay, 1996; Boot and Gullison, 1995). However, few studies have financially evaluated sustainable timber

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production and accounted for individual forest stands. Actually, timber cannot be supplied from unprofitable stands. Therefore financial evaluation is vital for estimating sustainable timber production.

The objectives of this study were to predict maximum sustainable yields, considering the financial index, and to examine the relationships between maximum sustainable yields and timber prices and between maximum sustainable yields and logging costs. In other words, how much stable timber production can be expected under different scenarios, such as variations in timber prices or logging costs? Annual timber production and the number and locations of harvested stands were predicted in a simulation targeting only the profitable stands. First, we developed a forest management model for the simulation. The maximum sustainable yields that satisfied certain assumed requirements were acquired by repeated simulations. In addition, the effects of market timber prices and logging costs were assessed.

MATERIALS AND METHODS

Study Area and Data

The study area consisted of privately owned forests in the area of the former Sanpoku Town (now merged into Murakami City), Murakami City, Niigata Prefecture, Japan. The Sanpoku area (38°21–33'N, 139°27–34'E), located in northernmost Niigata Prefecture (Fig. 1), is one of the most active forestry areas in Niigata Prefecture. In total, 23,175 ha of forest are individually owned, which occupy 82% of the total area.

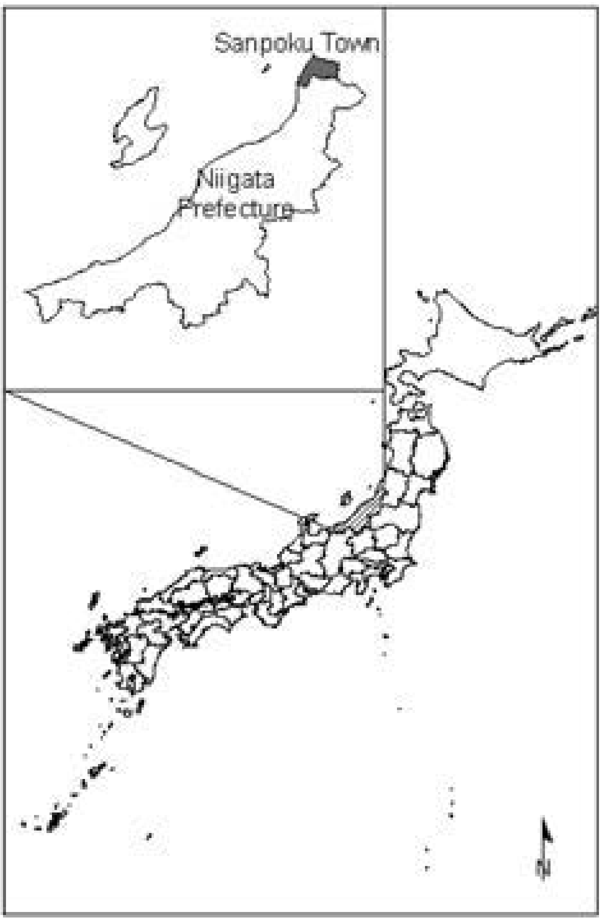

Fig. 1 Study area location

The studied stands were composed of sugi (*Cryptomeria japonica* D. DON) and represented single-story plantations larger than 0.1 ha. Stands <0.1 ha were eliminated from the study using the 2008 forest inventory because such stands do not generate profits. In total, we studied 14,881 stands covering a total area of 8,656 ha. The current age distribution of the studied stands formed a peak that is typical of Japanese forests. Both forest inventory and map data for 2008 were provided by the Niigata prefectural government. Some stand data were registered as forest inventory data and not found in the forest map, and vice versa. These data were also eliminated from the study.

Interviews with officials of the forest owners' cooperative in Murakami City, a timber-processing company, and a timber-producing company in the study area were conducted on 21–22 September 2010 to collect information on current conditions of regeneration and logging. Current annual timber production was about 20,000 m^3, based on the interviews.

Model Structure

The model consisted of stand sectors and a decision sector. Stand sectors contained the stand condition and some submodels, including a growing stock and a gross income submodel, a logging cost submodel, a regeneration submodel, a profit submodel, and a thinning submodel. Using the stand sectors' results, the decision sector identified which stands were to be clear-cut. These simulations were repeated for 150 years. Microsoft Excel VBA was used to construct the model.

Stand condition

The submodels used the conditions of each stand for computing. Site quality, stand area, current age, forest zone, and average slope were obtained from the 2008 forest inventory. The forest zone is defined in the city forest plan by the city government and categorizes each forest stand by expected function. Distance from a road, maximum yarding distances, and average yarding distances were calculated from digitized 1:5,000-scale forest maps with a 10 × 10-m spatial resolution using Spatial Analyst in ArcGIS 9.3 (ESRI, Tokyo, Japan). These calculated values were then added to the inventory data listed in Table 1.

Growing stock and gross income submodel

Growing stock was predicted using a method developed by the Niigata Prefectural Government. The average height of dominant and co-dominant trees was calculated with the following height/age curves, depending on site quality (NIIGATA PREFECTURAL GOVERNMENT, 1980):

$$HT = 34.7894\{1\text{-exp}(-0.0428\text{-}0.0259\,t)\} \text{ for site quality 1,}$$
$$HT = 31.9528\{1\text{-exp}(-0.0471\text{-}0.0254\,t)\} \text{ for site quality 2,}$$
$$HT = 28.8730\{1\text{-exp}(-0.0451\text{-}0.0254\,t)\} \text{ for site quality 3,}$$
$$HT = 25.7535\{1\text{-exp}(-0.0462\text{-}0.0254\,t)\} \text{ for site quality 4,}$$

where t is age in years, and HT is average height in meters.

Table 1 Values and equations used for stand conditions

	Abbreviation	Unit	Value or equation	Note
Site quality	*SQ*			*1
Area	*A*	ha		*1
Initial age	*age*			*1
Forest zone	*Z*			*1, 4
Average slope	*s*			*1
Distance from road	*Smin*	m		*2
Maximum yarding distance	*Smax*	m		*2
Average yarding distance	*Save*	m		*2
Average lateral yarding distance	*ly*	m	*A*/(*Smax*–*Smin*)	
Lateral yardable distance		m	60	*3
Cable re-stretching frequency	*n*		*ly*/60 (round down)	

*1 Values cited from forest inventory data 2008
*2 Values calculated by ArcGIS9.3 (ESRI)
*3 Value obtained from interviews
*4 Forest zone is defined in the city forest plan by the city government and categorizes each forest stand by its expected function.

Then, stand volume was calculated using stand condition values and the equations in Table 2 from the stand density control diagram for sugi plantations in Niigata Prefecture (Niigata Prefectural Government, 1980). The number of trees was assumed to decrease as a result of self-thinning and artificial thinning.

A silvicultural system was assumed as below. Density at planting was set at 2,500 trees/ha for each site. Reinforcement planting was omitted from consideration based on the interviews. The thinning system was assumed to be low thinning. The thinning ratio was 30% in terms of density, and thinning was performed at 25, 35, and 46 years. Forest owners in the study area usually conducted thinning in forests older than 46 years, because subsidies for thinning in these forests, when conducted 10 years or more after a previous thinning, are higher than in other forests.

Gross income from each stand was calculated by multiplying stand volume, average merchantable volume ratio, and average log price in October 2010 on the Niigata timber market, which was 10,903.19 yen/m^3. The average log price was computed by averaging log prices using log volume as the weight of logs less than 4 m in length as follows:

$$\text{Average log price} = \sum(\text{Log price} \times \text{Log volume}) / \sum \text{Log volume}$$

Logging cost submodel

The following logging operation system was assumed for calculating logging cost

Table 2 Values and equations used to calculate growing stock

	Abbreviation	Unit	Value or equation	Note
Density at planting	*d*	/ha	2,500	*1
Timber price	*P*	yen/m^3		
Density	N	/ha	[*age*]	
Average height of dominant and co-dominant trees	*HT*	m	[*SQ*, *age*]	
Stand log volume per ha	*V*	m^3/ha	{0.06004657*HT*^(−1.35233688) + 3743.3*HT*^(−2.82482815)/*N*}^(−1)	*2
Stand-form height	*Hf*		0.667196 + 0.387485*HT* + 0.189979*HT* (*N*^0.5)/100	*2
Basal area	*G*	m^2/ha	*V* / *Hf*	*2
Quadratic mean diameter	*dg_ave*	cm	200 × (*G* / *N*))^0.5	*2
Mean diameter	*dave*	cm	−0.382224 + 0.986197*dg_ave*	*2
Average tree volume	*v*	m^3	*V* / *N*	
Log volume	*Vt*	m^3	*V* × *A*	
Average merchantable volume ratio	*r*			
Gross income	*R*	yen	*Vt* × *r* × *P*	
Gross income per ha	*Rt*	yen/ha	*V* × *r* × *P*	

*1 Value obtained from interviews
*2 Equations cited from the stand density control diagram for a sugi plantation stand in Niigata Prefecture (Niigata Prefectural Government, 1980)

Felling with a chain saw → cable yarding
→ bucking with a chain saw

This system was assumed because about 90% of logging used cable yarding, according to the interviews.

Logging cost was the sum of operation costs for felling, yarding, and bucking, as well as transportation costs. UMEDA *et al.* (1982) described the calculation of costs for logging operations and common logging costs, which include the costs for installing and removing the yarder and log deck and transporting workers. SAWAGUCHI (1996) described the calculation of yarding costs. The submodel applied the values and equations for productivity from these studies to calculate logging cost, incorporating current conditions such as wages, prices, and amount of necessary labor into the method to make the analysis more practical (Table 3).

Table 3 Values and equations used to calculate logging cost

	Abbreviation	Unit	Value or equation	Note
Wage	w'	yen/day	11,000	*1
Ratio of insurance	I		0.25	*1
Ratio of extra wage	Ex		0.1	*1
Total wage	w	yen/day	$w' \times (1 + I + ex)$	
Price of chainsaw	chP	yen	291900	
Rate of depreciation of chainsaw	chR	/h	0.1147	*2
Uptime of chainsaw	chH	h/day	4	*2
Depreciation of chainsaw	$chLh$	yen/h	$chP \times chR$	
Depreciation of chainsaw	$chLd$	yen/day	$\mathrm{c}H \times cLh$	
Mixed oil consumption	mA	ℓ/day	3.8	*2
Mixed oil price	mP	yen/ℓ	180	*1
Mixed oil expenses	mC	yen/day	$mA \times mP$	
Chain oil consumption	coA	ℓ/day	1.2	*2
Chain oil price	coP	yen/ℓ	272	*1
Chain oil expenses	coC	yen/day	$coA \times coP$	
Saw chain price	sP	yen	8,500	*1
Bearable volume of saw chain	sA	m^3	350	*2
Depreciation of saw chain	sC	yen/ m^3	sP / sA	
Light oil consumption	lA	ℓ/day	17	*2
Light oil price	lP	yen/ℓ	115	*1
Light oil expenses	lC	yen/day	$lA \times lP$	
Mobil oil consumption	mA	ℓ/day	0.65	*2
Mobil oil price	mP	yen/ℓ	400	*2
Mobil oil expenses	mC	yen/day	$mA \times mP$	
Rate of depreciation of yarding machine	lmR	/h	0.0417	*2
Yarding machine price	lmP	yen	4200000	*2
Uptime of yarding machine	lmH	h/day	6	*2
Depreciation of yarding machine	$lmCh$	yen/h	$lR \times lP$	
Depreciation of yarding machine	lmC	yen/day	$lH \times lCh$	
Number of people in a yarding group	lPe		3	*1
Depreciation of yarding machine equipment	aC	yen/ m^3	171	*2
Transportation fee for yarding	wF	yen	14,290	*2
Amount of labor for log deck	bP	person · day	2	*1
Productivity of loading on a track	f	m^3/day	48	*2
Amount of loading labor	fPe		2	*2
Loading cost	fW	yen/ m^3	$W \times fPe / f$	
Capacity of track	tA	m^3	6.6	*2
Log transportation fee	tF	yen/car	20,000	*1
Log transportation cost	tC	yen/ m^3	tF / tA	

Table 3 Values and equations used to calculate logging cost (continued)

	Abbreviation	Unit	Value or equation	Note
Productivity for felling	*cP*	m^3/day	12.295 × *v*^0.5 – 0.564	*2
Felling wage	*cW*	yen/ m^3	*w* / *cP*	
Depreciation of chainsaw	*chL*	yen/ m^3	*chLd* / *cP*	
Fuel expenses of chainsaw	*chF*	yen/m^3	(*mC* + *coC*) / *cP*	
Depreciation and expenses for felling	*cLF*	yen/ m^3	(*chL* + *cLF* + *sC*) × (1 + *ex*)	
Productivity for yarding	*lP*	m^3/day	(*Save*^(–0.2896)) × (*v*^0.5337) × (*ly*^(–0.04891)) × 10^2.611	*3
Yarding wage	*lW*	yen/m^3	*w* × *lPe* / *lP*	
Yarding fuel expenses	*lmF*	yen/m^3	(*lC* + *mC*) / *lP*	
Depreciation of yarding machine	*lmL*	yen/m^3	*lmC* / *lP*	
Yarding cost	*lC*	yen/m^3	(*lW* + *lmF* + *lmL* + *aC*) × (1 + *ex*)	
Cost for installing and removing log deck	*bC*	yen	*w* × *bP* (when *V* >700)	*1
Amount of labor for installing and removing yarder	*wPe*	person · day	(0.0763 × *Smax*+2.4) × (1 + 0.35 + 0.7×*n*)	*4
Cost for installing and removing yarder	*wC*	yen	*w* × *wPe*	
Total cost at a logging site	*oC*	yen	(*cW*/(1 + *ex* + *i*) + (*cLF* + *lC*)/(1 + *ex*) + *fW*) × *V* + (*wC* + *bC*)/(1+ *ex* + *i*)	
Cost of transporting workers	*pT*	yen	*oC* × (8.1–3.4 × log10(*oC* / 1000000))/100	*2
Common logging cost	*Ct*	yen	*wC* + *wF* + *bC* + *pT*	
Common logging cost	*C*	yen/m^3	*Ct* / *V*	
Total logging cost per m^3	*Tv*	yen/m^3	*C* + *fW* + *tC* + *lC* + *cW* + *cLF*	
Total logging cost	*T*	yen	*Tv* × *V*	
Total logging cost per ha	*Ta*	yen/ha	*T* / *A*	

*1 Values obtained from interviews
*2 Values or equation cited from UMEDA *et al.* (1982)
*3 Equation cited from TOYAMA and TATSUHARA (2007)
*4 Equation cited from SAWAGUCHI (1996)

Regeneration cost submodel

As mentioned above, planting density was 2,500 trees/ha without reinforcement planting. The interviews revealed that neither stem straightening nor pruning was conducted. Stem straightening involves straightening stems deformed by heavy snowfall. Planting in a stand was conducted in the year following clear cutting. The standard amount of labor (person days/ha) required for each regeneration operation in each site quality was based on data reported by TATSUHARA and DOBASHI (2006) (Table 4). The actual amount of labor for each stand was estimated from the standard amount of labor multiplied by a distance coefficient calculated from the slope and the distance to the nearest road (TAKAHASHI *et al.*, 1996). Gross regeneration cost was calculated from the actual amount of labor, workers' wages, and other values (Table 5). Workers' wages were assumed to be the same as those used to calculate logging cost.

Table 4 Standard labor amount and unit cost for regeneration operations according to site quality

	Standard amount of labor (person days/ha)				Standard unit cost (yen/ha)
Site quality	1	2	3	4	
Site preparation	28.5	28.5	28.5	28.5	
Planting	35.1	42	42	42	1,018,730
Reinforcement planting	0	0	0	0	
Releasing	54.7	54.7	66.2	66.2	132,300×n [*1]
Stem straightening	0	0	0	0	
Veining	10	10	10	10	
Cleaning	14	14	14	14	155,620
Pruning	0	0	0	0	
Sum	142.3	149.2	160.7	160.7	

[*1] *n* was set at 5 for site quality 1, and 2 and 6 for site qualities 3 and 4, respectively.

Table 5 Values and equations used to calculate regeneration cost

	Abbreviation	Unit	Value or equation	Note
Seedling price	sa	yen	150	*1
Seedling cost per ha	saC	yen/ha	$sa \times d$	
Slope index	sI		$[s]$	
Slope coefficient	sC		$1 + 0.1 \times (sI - 1)$	*2
Amount of regeneration labor	l	person˙day	Table 4	
Actual amount of regeneration labor	l'	person˙day	$L \times (0.95858 + 0.01523 \times sI + 0.00008 \times Smin + sC - 1)$	*2
Wage for regeneration	aW	yen/ha	$w \times l'$	
Planting and management cost	aC	yen/ha	$(aW + saC + ssC) \times (1 + ex)$	
Standard unit cost for regeneration	aS	yen/ha	Table 4	
Subsidies for regeneration	$aSub$	yen/ha	$[aS]$	
Regeneration cost per ha	pC	yen/ha	$aC - aSub$	
Regeneration cost	pCt	yen	$A \times pC$	

*1 Value obtained from interviews
*2 Equations cited from Tatsuhara and Doi (2006)

Government-subsidized regeneration operations (Japanese Afforestation Institute, 2008) and subsidies for regeneration operations were calculated as follows:

Subsidy per hectare = Standard unit cost × Assessment coefficient × Subsidy rate.

The standard unit cost was the cost per hectare for each regeneration operation determined by prefectural governments (Table 4). Table 6 shows the assessment coefficient and subsidy rates. The assessment coefficient was a weight decided by prefectural government policy. The subsidy rate was the ratio at which both central and prefectural governments subsidize the standard unit cost multiplied by the assessment coefficient, and was also decided by both government bodies. Standard unit costs depend on the kinds of operations, whereas the assessment coefficient and subsidy rate are contingent on forest zones. Finally, the regeneration cost was determined by subtracting the subsidies from the gross regeneration cost.

Profit submodel

Profits from clear-cutting each stand were calculated by subtracting logging and regeneration costs from gross income as follows:

Profits = Gross income − (Logging cost + Regeneration cost).

Decision sector

This sector identified which stands were to be clear-cut each year. Until the total volume of the stands identified to be clear-cut reached an amount fixed in advance by simulation, stands were chosen to be clear-cut based on the order of profits per area. In this simulation, stands that did not make a profit were not chosen. To avoid overcutting, timber production 10% more than the fixed amount was prohibited each year. The methods used to fix the amount beforehand are described in the next section.

Furthermore, clear-cutting was prohibited for 15 years after subsidized thinning according to a regulation regarding subsidies for thinning operations; thus, clear-cutting was allowed only in stands 61 years old or older, because the last thinning was assumed to have been performed at 46 years.

Thinning submodel

This submodel identified whether to carry logs out of each stand after each thinning. The same timber price was used as in clear-cutting to determine the gross income from thinning. Thinning costs were calculated for cases in which timber was logged or not logged. The government subsidizes thinning operations (Table 7). Profits for thinning with logging were finally determined by subtracting the thinning cost from the sum of gross income and subsidies. When positive profits were calculated for thinning with logging, timber was carried

Table 6 Assessment coefficient and subsidy rate for Niigata Prefecture subsidies

Operation	Regeneration	Thinning under 46 years	Thinning at 46 years	
Forest zone			*1	*2
Assessment coefficient	170	170	180	150

Forest zone	*1	*2
Subsidy rate	0.5	0.4

*1 Soil and water conservation zone
*2 Sustainable resource utilization zone

Table 7 Standard unit costs for thinning (yen/ha)

Without logging	Under 46 years	118,730									
	At 46 years	230,540									
With logging		Volume of thinning logs (m^3)									
		0–20					>20				
	Under 46 years	267,430					343,510				
		Volume of thinning logs (m^3)									
		0–50	50–75	75–100	100–125	125–150	150–175	175–200	200–225	225–250	>250
	At 46 years	427,030	641,690	852,400	1,022,840	1,194,560	1,408,050	1,557,480	1,762,430	1,967,370	2,172,320

out of stands. Otherwise, thinned trees were left on the forest floor.

Simulations were also conducted with thinning logs either supplied or not supplied. Table 8 shows the values and equations used to calculate thinning cost. Some were the same as for clear-cutting, but others were not.

Simulations to Obtain Maximum Sustainable Yield

We repeatedly conducted simulations using the model described in the previous section to obtain maximum sustainable yields corresponding to the three scenarios mentioned below. Maximum sustainable yields were obtained using the binary method. The binary method is a process that attempts to find a solution to a problem by making progressively better guesses at the optimal value of the objective function. First, the maximum and minimum of the possible range of target annual timber production were fixed, and then an amount of annual timber production was fixed in the possible range for the first simulation. If the simulation met the scenario's conditions, the amount was changed to the middle of the maximum and the previous amount, and the minimum was changed to the previous amount. Otherwise the amount was changed to the middle of the minimum and the previous amount, and the maximum was changed to the previous amount. The simulation was then repeated with the new amount. When the change in amounts became <100 m^3, the process was stopped and the amount of the last simulation was taken as the maximum sustainable yield.

Scenario 1: Annual timber production never decreased below fixed amounts.

Scenario 2: Annual timber production exceeded fixed amounts persistently after the first 25 years of the simulation.

Table 8 Values and equations used to calculate thinning cost and profit

	Abbreviation	Unit	Value or equation	Note
Thinning volume	tV	m^3	$0.3 \times Vt$	
Thinning revenue	tr	yen	$tV \times \mathrm{P}$	
Thinning productivity for felling	tcP	m^3/day	$9.1071 \times v$^0.5 + 0.482	*1
Thinning wage for felling	tcW	yen/ m^3	$w \times tcP$	
Thinning productivity for yarding	tlP	m^3/day	$7.4874 \times \exp(-0.002 \times Save)$	*2
Thinning wage for yarding	tlW	yen/ m^3	$w \times lPe / tlP$	
Thinning cost for yarding	tlC	yen/ m^3	$(lmF + lmL + aC + tlW) \times (1 + ex)$	
Total cost at thinning site	toC	yen	$(tcW / (1 + (ex + i)) + (cLF + tlC)/(1 + ex) + fW) \times tV + wC / (1 + ex)$	
Cost for transporting workers for thinning	tpT	yen	$toC \times (8.1–3.4 \times \log10(toC / 1000000)) / 100$	*3
Thinning common cost	tCt	yen	$wC + wF + tpT$	
Thinning common cost	tC	yen/ m^3	tCt / tV	
Thinning cost for logging	tTv	yen/ m^3	$tC + tlC + cLF + tcW + fW + tC$	
Thinning cost for logging	tT	yen	$tV \times tTv$	
Amount of labor for thinning	tP	person day	1/(22.817 × v^0.2903)	*4
Thinning cost without logging	t	yen	$tP \times w \times tV$	
Thinning profit when logged	tR	yen	$tr - tT$	

*1 Equation calculated from a figure by UMEDA *et al.* (1982)
*2 Equation calculated from a figure by GOTO (1988)
*3 Equation cited from UMEDA *et al.* (1982)
*4 Equation cited from MIZUTA and MITOBE (2008)

Table 9 Maximum sustainable yields in each scenario (m^3/year)

	Scenario 1	Scenario 2
Current log price	24,200	25,400
Log price 5% below the current price	11,100	19,600
Log price 5% above the current price	32,200	※
Logging cost reduced by 5% from the current cost	30,900	※

Table 10 Maximum sustainable yields for each scenario including thinned logs (m^3/year)

	Scenario 1	Scenario 2
Current log price	24,600	25,600
Log price 5% below the current price	11,500	19,900
Log price 5% above the current price	32,700	※
Logging cost reduced by 5% from the current cost	31,400	※

Annual timber production may decrease below the fixed amount for the first 25 years. This period was chosen because the yield shortage occurred mainly during the first 25 years due to the age distribution of the stands.

Scenario 3: Annual timber production is conducted to exceed a fixed amount, increasing from the current timber production of 20,000 m^3 until the fixed amount reaches the maximum sustainable yield defined by scenario 2. This scenario is based on the assumption that a new large timber-processing factory will be constructed.

We also observed changes in sustainable production according to different situations; log prices rose or fell 5% from current prices, and logging costs fell 5% in scenarios 1 and 2.

RESULTS

Timber Supply

Table 9 shows the maximum sustainable yields in each scenario. At current log prices, the maximum sustainable yield in scenario 1 was 24,200 m^3, which was about 1,000m^3 less than that in scenario 2 (scenario 1 < scenario 2). Changes in log prices had a large influence on maximum sustainable yields in both scenarios 1 and 2. The higher the log price, the larger the sustainable timber production (5% below < current < 5% above). A reduction in logging costs also had a strong effect. Maximum sustainable yields in scenario 2 could not be calculated at a 5% higher log price or a lower logging cost because falling of production below the fixed amount did not concentrate on the first 25 years (Fig. 2).

Sustainable production including thinned logs was a few hundred cubic meters larger than that excluding thinned logs (Table 10). Other simulation results including thinned logs, such as profits and growing stock, were almost the same as the simulations excluding thinned logs. Therefore, the results presented below refer to simulations excluding thinned logs.

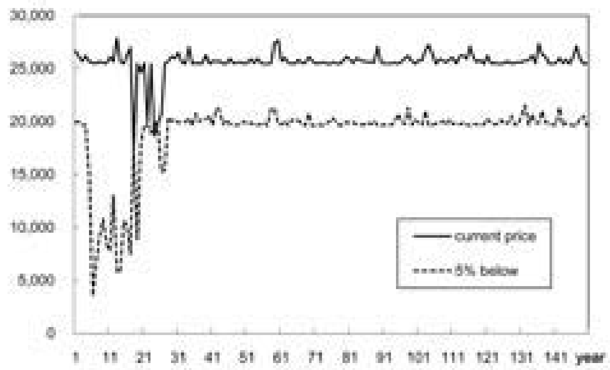

Fig. 2 Changes in clear-cut production for scenario 2

Clear-cutting Profits

Figure 3a shows the clear-cutting profits for different log prices and logging costs in scenario 1. They all had similar tendencies. Profits dropped during the first 10 years, then increased gradually. Finally, profits became steady at particular amounts. Profits computed with a higher log price or cheaper logging costs exhibited higher amounts initially; however, their reduction rates were relatively high and their recovery rates were low.

The profit curves for clear-cutting in scenario 2 were similar to those in scenario 1 during the first 10 years but subsequently leveled off (Fig. 3b).

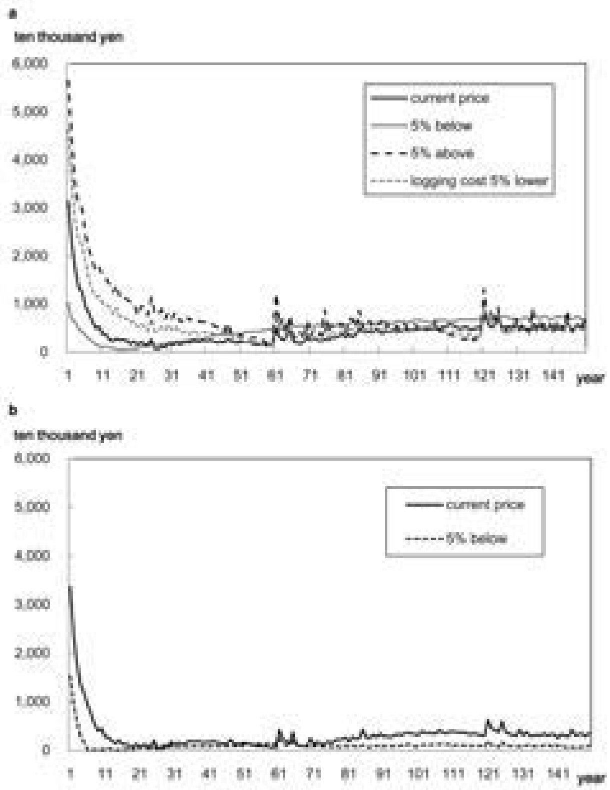

Fig. 3 Change in clear-cut profits for each scenario
a, Scenario 1; b, Scenario 2.

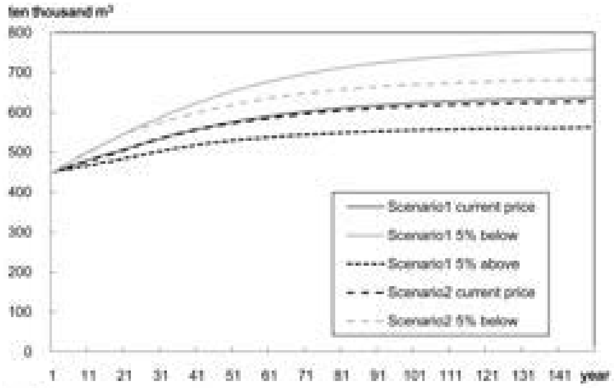

Fig. 4 Changes in growing stock for each scenario

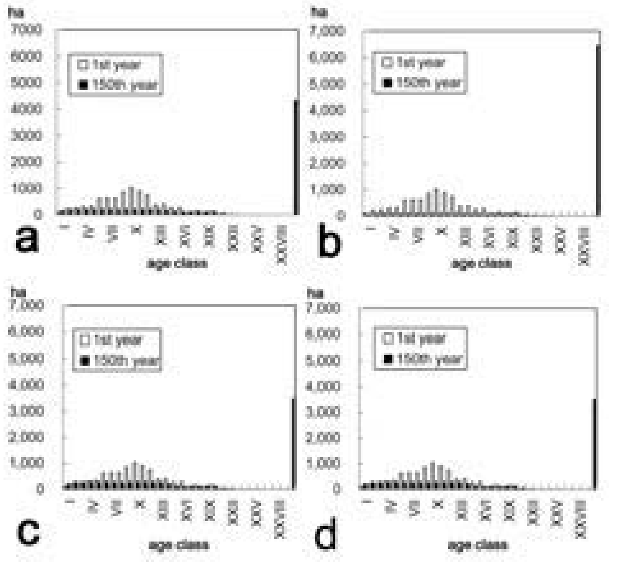

Fig. 5 Age distribution for each scenario
a, Scenario 1 with the current log price; b, Scenario 1 with a 5% lower log price; c, Scenario 1 with a 5% higher log price; d, Scenario 1 with a 5% lower logging cost.

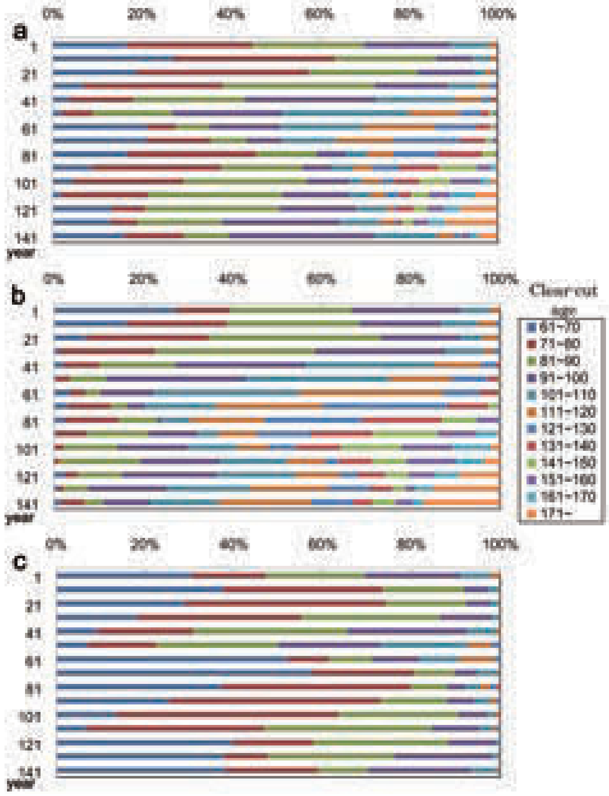

Fig. 6 Clear-cutting age distribution ratio
a, Scenario 1 by the current log price; b, Scenario 1 by a 5% lower log price; c, Scenario 1 by a 5% higher log price.

Volume of Growing Stock

Growing stock in the study area tapered off over time in each scenario (Fig. 4). The larger the annual timber production, the less growing stock accumulated.

Age-class Distribution

Figure 5 shows the age-class distributions at the beginning and end of the scenario 1 simulation. As mentioned above, the age-class distribution formed a peak at the beginning of the simulation. In contrast, a broad distribution formed at the end of the simulation, resembling a normal forest, except for stands aged over 150 years, which were never clear-cut. Every scenario, including scenario 2, showed the same tendencies.

Age-class Distribution of Clear-cut Stand

Figure 6 shows the age-class distribution at which the stands were clear-cut for each 10 year period in scenario 1 with each log price. Relatively young stands less than 100 years old were clear-cut mainly in the first few decades. After that, aged stands (>100 years old) were clear-cut rather than young stands (<100 years old). However, in the simulation with a 5% higher log price, the ratio of young stands continued to exceed that of aged stands.

Scenario 3

In scenario 3, timber production was assumed to gradually increase over 25 years from the current volume of 20,000 m^3 to 25,400 m^3, which was the maximum sustainable yield for scenario 2. Timber production in this scenario never fell below the fixed amount (Fig. 7). Profits did not increase but remained steady after 10 years.

DISCUSSION

Maximum sustainable yields in the former Sanpoku Town area were predicted by assuming three scenarios and simulating forest growth and profits. The simulations suggested that this area can supply more timber than at present, even though timber was produced only from profitable stands at the current log price. Timber production in scenario 2 was much larger than that in scenario 1, suggesting that much more timber can be supplied if stands are not clear-

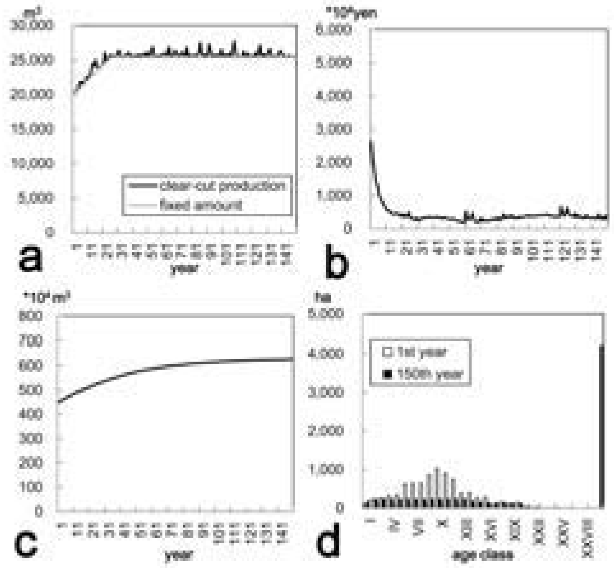

Fig. 7 Scenario 3 results
a, Clear-cut production; b, Clear-cut profit; c, Growing stock; d, Age distribution.

cut until several decades from now. The same conclusion was reached for scenario 3.

Changes in log prices and costs strongly influenced timber production, suggesting that forest owners are operating on a slim margin. Considering the unstable log prices, as frequently observed in Japan, it might be reasonable for owners to abstain from clear cutting. However, this result also suggests that efforts to reduce costs should be effective for enhancing profits, which would lead to a higher timber supply.

Profits decreased considerably during the first 10 years (Fig. 3) because of the rule for selecting stands to be clear-cut. Clear-cut stands were chosen based on the order of profits per area, so that most stands remaining after 10 years would produce relatively poor profit margins. Particularly in the simulation with a 5% higher log price, the timber amounts supplied were so high that most rich stands were clear-cut during the first decade. Profits decreased because timber was supplied from poor stands, which produce very little profit. This study focused only on sustaining timber production. However, studies on sustaining profits by supplying timber will also be needed.

After 50 years, the scenario 1 profits with current log prices were predicted to exceed those of a 5% higher log price (Fig. 3), which was due to the clear-cut age distribution. With a 5% higher log price, the clear-cut stands tended to be younger than those with current log prices because too many stands were cut before maturation (Fig. 6). This led to lower profits in a simulation with a 5% higher log price.

Growing stocks in the study area increased in each scenario because the area of stands that were never clear-cut was much larger than that of the clear-cut stands. Stands not expected to gain from clear-cutting in the future should be converted from merchantable forests to environmental forests. Applying a proper management principle to each stand is one of the most efficient zoning methods (Mitsuda *et al.*, 2009). Classification into merchantable forests and environmental forests could provide a possible zoning method.

Although profits and sustainable production are closely related, it is difficult to predict log prices and technical progress. Buongiorno (1996) conducted forest sector modeling and price forecasting of waste newspapers that were sold to produce newsprint in the conventional method and a new method that was not yet in use. Our study did not include price or technological progress predictions. Further studies will be needed for more precise timber production forecasts.

This model did not include profit stability simulations and ignored the possibility of reducing costs by simultaneously managing some neighboring stands or by making improvements in the logging system. These points were considered limitations of the model structure (Toyama, 2011). The model should be improved if it is to be used to simulate a practical case involving a large lumber factory.

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Article

Development of Two-way Volume Equation for Bamboo, *Phyllostachys nigra*

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ABSTRACT

A two-way volume equation for one of the three major useful bamboos in Japan, *Phyllostachys nigra* var. *henonis*, is developed and the goodness of fit is evaluated using the data collected from two different districts. The model used here was the generalized theoretical volume equation. The normal form-factors at 0.7 and 0.8 for *P. nigra* were steady at 0.622 and 0.558, respectively. Inserting these values into the generalized theoretical volume equation enabled us to determine the coefficients of the volume equation. Although the estimated apparent culm volume was significantly smaller than actual one, the relative mean error of the estimated volume was comparatively small. The volume equation for *Phyllostachys bambusoides* Sieb. et Zucc. could be directly applied to *P. nigra*, whereas that for *Phyllostachys pubescens* Mazel et Houz. could not. This fact indicated that the inter-species characteristics of culm form should be carefully considered when evaluating the bamboo resources by the volume equation. In conclusion, the generalized theoretical volume equation would be effective when evaluating the resources and comparing the stand productivity for *P. nigra*.

Keywords: apparent culm volume; bamboo, culm form, generalized theoretical volume equation, normal form-factor

INTRODUCTION

Bamboo is highly versatile and rapidly renewable, long been used as a timber alternative for flooring, construction, furniture, charcoal, crafts and food (Buckingham *et al.*, 2011). In addition, recent technological developments cleared way for bamboo to be used extensively in manufacturing the reconstituted panel and board products, fuel, pulp and paper (Drust *et al.*, 2004). Zhou *et al.* (2005) also reviewed the environmental functions of bamboo forests such as soil conservation and carbon fixation. Because of these economic and environmental values, bamboo has received increasing attention over the last two decade in Asia, Africa and Latin America (Ruiz-Perez *et al.*, 2001) and is expected to contribute to development in bamboo growing rural areas as “poor man’s timber” (Lou *et al.*, 2010).

In Japan, there are more than 150,000 hectares of bamboo forests (Lovovikov *et al.*, 2007). New shoots occur naturally and annually without planting or seeding in bamboo forests, and they reach the mature size in a matter of two or three months (Zhou *et al.*, 2005). Therefore, bamboo has a potential as plentiful biomass resources in Japan, but not used effectively (Minami and Saka, 2005). In order to establish the effective utilization of bamboo resources and sustainable management of bamboo forests, reliable data and information with regards to their resources are required (Kleinn and Morales, 2006). Culms are major component among aboveground parts of bamboo (e.g., Suzuki and Uchimura, 1980; Yen *et al.*, 2010; Yen and Lee, 2011), and are more useful compared to branches and leaves. Culm volume is therefore one of the most important information when evaluating bamboo resources (Inoue *et al.*, 2011; Suga *et al.*, 2011) and comparing stand productivities (Aoki, 1955; Camargo and Kleinn, 2010). However, there is still a lack of availability of basic models for estimating apparent culm volume, i.e., the total culm volume including the hollow part, or wood volume, i.e., the volume of the woody walls of the culms (Kleinn and Morales, 2006; Camargo and Kleinn, 2010).

Phyllostachys nigra var. *henonis*, which is native to China (Li *et al.*, 2005), is one of the three major useful bamboos in Japan along with *Phyllostachys pubescens* Mazel et Houz. and *Phyllostachys bambusoides* Sieb. et Zucc. (Uchimura, 2009). *P. nigra* was probably introduced from China about 800 years ago, and have been traditionally used for edible shoots and industrial arts (Suzuki and Nakagoshi, 2011). Although *P. nigra* occupies only about 0.4% of the total bamboo growing

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area in Japan (UCHIMURA, 1980), its area exceed more than 20% of bamboo growing area in a certain district (e.g., FORESTRY and FISHERIES DEPARTMENT of KUMAMOTO PREFECTURE, 2005). This implies that *P. nigra* might be useful biomass resources in its much growing area. However, studies on *P. nigra* are extremely scarce, which involve the culm form (OTA, 1950), productivity (SUZUKI and UCHIMURA, 1980), amounts of litter fall and sheaths (WATANABE, 1983), fuel properties (SCURLOCK *et al.*, 2000), growth behavior (LI *et al.*, 2005), stand dynamics (SAROINSONG *et al.*, 2006) and spatial pattern (SAROINSONG *et al.*, 2007).

In previous studies (INOUE *et al.*, 2011; SUGA *et al.*, 2011), the two-way volume equations for *P. pubescens* and *P. bambusoides* were derived so that the apparent culm volume can be estimated from diameter at breast height (dbh) and culm height. INOUE *et al.* (2011) found that there was a need for distinguishing the volume equation among these bamboo species, suggesting that the volume equation for *P. nigra* may also be different from those for the two species. However, to our knowledge, there have been no models for evaluating the culm volume of *P. nigra*. It is also unknown whether the volume equation for the two species can be directly applied to *P. nigra*. For the effective utilization and sustainable management of *P. nigra*, it is necessary to develop a model for evaluating its culm volume.

The objective of the present study was thus to develop the two-way volume equation for estimating apparent culm volume for *P. nigra*. First, the two-way volume equation was determined using the generalized theoretical volume equation (INOUE *et al.*, 2011; SUGA *et al.*, 2011). Second, the goodness of fit and applicability of the determined volume equation were evaluated based on the data collected from two different districts. Third, the volume equation for *P. nigra* was compared with those for other bamboo species, i.e., *P. pubescens* and *P. bambusoides*, determined in previous studies (INOUE *et al.*, 2011; SUGA *et al.*, 2011).

MATERIALS AND METHODS

Data

The data used in this study was collected from two stands of *P. nigra* in Ito campus of Kyushu University (ITO: 33°36' N, 130°13' E, 60 m a.s.l.) in Fukuoka City and in the campus of Fukuoka University of Education (FUE: 33°48' N, 130°36' E, 50 m a.s.l.) in Munakata City, Fukuoka Prefecture, western Japan. These stands were about 40 km away from each other. The average annual temperature and annual rainfall for the last decade at the nearest observatory were, respectively, 16.1 ℃ and 1,677 mm for ITO and 15.6 ℃ and 1,640 mm for FUE, indicating that these areas will be a favorable condition for the growth of bamboo (SCURLOCK *et al.*, 2000). Both stands were very dense and their canopies were closed, and hence no other vegetation was found on the forest floors.

In each stand, healthy and living sample culms with various sizes were felled at ground level for direct measurement of height and diameter in October 2011. The number of samples was 100 for ITO and 50 for FUE. The culm height was measured directly with a tape measure to the nearest tenth of a meter. The external culm diameter at 1.2 m height above ground level (dbh) and ten successive points were measured with a digital caliper to the nearest tenth of a centimeter. The measurement points were located along the culm at equal intervals of one tenth of the direct measured culm height (relative height: 0.1, 0.2, ..., 1.0). General description of the samples is given in Table 1.

Analysis Methods

The apparent culm volume for each sample was computed by the sectional measurement method (WEST, 2004). The sample culms collected from ITO were randomly bisected into two sets of data, i.e., modeling and test data (n = 50 for each set). The samples from FUE were also pooled for the test data (n = 50), so that an applicability of the determined volume equation can be evaluated. For the modeling data, the normal form-factors for the ten relative heights, i.e., $\lambda_{0.1}$, $\lambda_{0.2}$,..., $\lambda_{1.0}$, were computed, and then their averages and coefficients of variation (CV) were calculated. The dependence of each normal form-factor on the culm sizes, i.e., dbh and culm height, was analyzed with Spearman's correlation coefficient by rank test. From the viewpoints of the smallness of CV and

Table 1 General description of *Phyllostachys nigra* sample culms

	Diameter at breast height (cm)	Culm height (m)	Apparent culm volume (dm^3)
ITO (n = 100)			
Average	2.7	6.3	2.4
Standard derivation	0.7	1.4	1.7
Maximum	4.3	9.3	7.5
Minimum	1.1	3.1	0.2
Median	2.6	6.1	1.8
FUE (n = 50)			
Average	2.9	7.3	3.6
Standard derivation	1.1	2.0	3.1
Maximum	4.9	11.3	12.2
Minimum	0.9	2.7	0.1
Median	2.9	7.5	2.6

independence on the culm sizes, the steady normal form-factors at two different relative heights were selected. The coefficients of the volume equation for *P. nigra* were then determined by substituting the averages of the steady normal form-factors and their relative heights into the following generalized theoretical volume equation:

$$v = \frac{\lambda_j \pi d_b^2 h}{4[(1 - h_b/h)/j]^{\log(\lambda_i/\lambda_j)/\log(j/i)}} \quad (1)$$

where v: apparent culm volume; d_b: diameter at breast height; h: culm height; h_b: breast height (= 1.2 m in this study); λ_i and λ_j: averages of the steady normal form-factors at relative height i and j, respectively. For the detail of the derivation of Eq. 1, see INOUE *et al.* (2011) or SUGA *et al.* (2011).

For the test data from ITO and FUE, the apparent culm volume for each sample culm was estimated by inserting the measured dbh and culm height into the determined volume equation. For each district, the goodness of fit of the volume equation was evaluated by the mean error (ME), relative mean error (%ME), root mean square error (RMSE) and relative root mean square error (%RMSE). The estimated apparent culm volume was compared with the actual one with Wilcoxon signed-rank test. All statistical procedures were performed with the R software (R DEVELOPMENT CORE TEAM, 2006).

RESULTS

Normal Form-factors for *P. nigra*

Fig. 1 depicts the average and coefficient of variation (CV) of the normal form-factors for *P. nigra*. The average of the normal form-factor decreased from culm tip to base. CV of the normal form-factor was the smallest at 0.8 in relative height, and gradually increased from there toward both ends of culm. CVs of the normal form-factors from 0.5 to 0.9 in relative height were less than 10%, indicating that the variations in these normal form-factors were smaller than those in other form-factors.

The correlation coefficients between normal form-factors and culm sizes are given in Fig. 2. Spearman's correlation coefficient by rank test indicated that $\lambda_{0.2}$, $\lambda_{0.7}$ and $\lambda_{0.8}$ were not significantly correlated with diameter at breast height (r = -0.106, P = 0.463 for $\lambda_{0.2}$; r = -0.224, P = 0.119 for $\lambda_{0.7}$ and r = 0.001, P = 0.993 for $\lambda_{0.8}$), whereas $\lambda_{0.1}$, $\lambda_{0.2}$, $\lambda_{0.7}$ and $\lambda_{0.8}$ were not significantly correlated with the culm height (r = 0.207, P = 0.149 for $\lambda_{0.1}$; r = -0.027, P = 0.850 for $\lambda_{0.2}$; r = -0.184, P = 0.201 for $\lambda_{0.7}$ and r = 0.081, P = 0.578 for $\lambda_{0.8}$). On the other hand, other normal form-factors were significantly correlated with either diameter at breast height and culm height ($P < 0.05$).

Determination and Goodness of Fit of the Volume Equation

Because of the smaller variation and independency on culm sizes, $\lambda_{0.7}$ and $\lambda_{0.8}$ were selected to determine the coefficients of the volume equation. Relationships of $\lambda_{0.7}$ and $\lambda_{0.8}$ to culm sizes are shown in Fig. 3, indicating that these normal form-factors were independent of the culm sizes. Substituting their averages, i.e., $\lambda_{0.7}$ = 0.622 and $\lambda_{0.8}$ = 0.558, and the relative heights into Eq. 1, we obtained the following two-way volume equation for *P. nigra*:

$$v = \frac{0.622\pi d_b^2 h}{4[(1 - h_b/h)/0.7]^{0.813}} \quad (2)$$

Fig. 4 compares the estimated and actual apparent culm volume for *P. nigra* collected from ITO and FUE. The mean error (ME), relative mean error (%ME), root mean square error (RMSE) and relative root mean square error (%RMSE) are summarized in Table 2. For ITO, there was a slightly significant difference between estimated and actual apparent culm volume ($P < 0.01$), with ME and RMSE being -0.092 dm^3 and 0.013 dm^3, respectively. The estimated culm volume for FUE was also significantly smaller than the actual one (P <

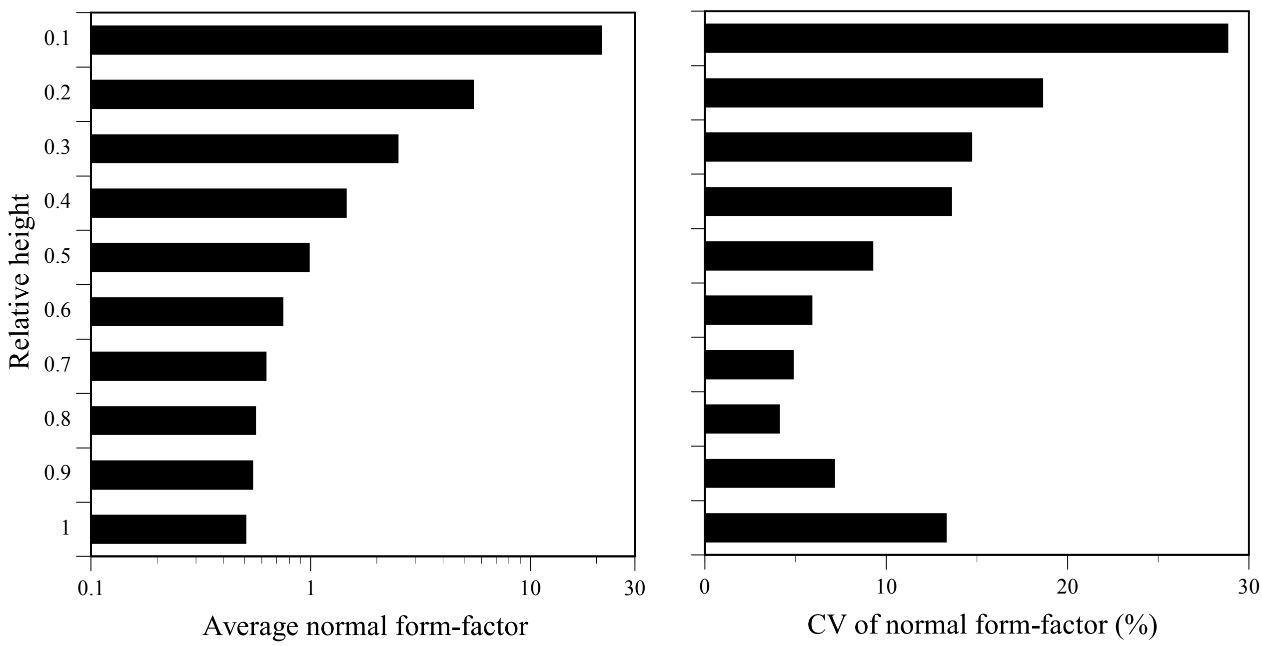

Fig. 1 Average and coefficient of variation (CV) of normal form-factors for *Phyllostachys nigra*

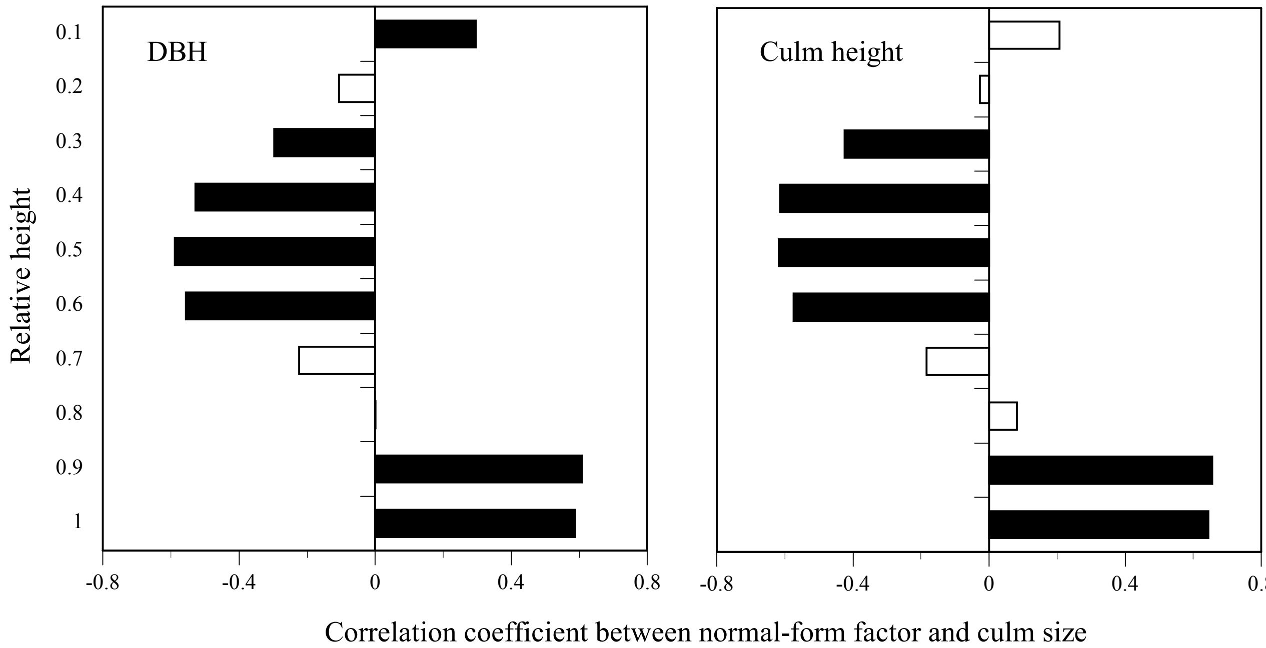

Fig. 2 Correlation coefficients between normal form-factors and culm sizes for *Phyllostachys nigra*. The black and white bars indicate significant and insignificant correlation coefficients at 5% level, respectively.

0.001), with ME and RMSE being -0.232 dm^3 and 0.460 dm^3, respectively. %ME and %RMSE were, respectively, -3.936% and 0.557% for ITO and -6.422% and 12.703% for FUE.

DISCUSSION

Culm Form of *P. nigra*

In this study, the generalized theoretical volume equation was applied to the development of the two-way volume equation for *P. nigra*. The coefficients of this volume equation are determined based on the analysis of the normal form-factors. As shown in Fig. 1, the coefficients of variation (CV) of the normal form-factors from 0.5 to 0.9 in relative height were less than 10%. Similar findings were reported for *P. pubescens* (Suga *et al.*, 2011) and *P. bambusoides* (Inoue *et al.*, 2011). This supports that these normal form-factors will be effective in determining the coefficients of the generalized theoretical volume equation for bamboo species (Inoue *et al.*, 2011).

The normal form-factors at 0.6 and 0.9 in relative height, $\lambda_{0.6}$ and $\lambda_{0.9}$, for *P. pubescens* and *P. bambusoides* were not correlated with culm sizes (Inoue *et al.*, 2011; Suga *et al.*, 2011). By contrast, these normal form-factors for *P. nigra* were significantly correlated with culm sizes, and $\lambda_{0.7}$ and $\lambda_{0.8}$ were not alternatively correlated (see Fig. 2). The result suggests that the steady normal form-factors would vary with bamboo species. Our data also demonstrated that $\lambda_{0.6}$ was negatively correlated with culm sizes, whereas $\lambda_{0.9}$ was positively correlated. Since $\lambda_{0.6}$ was larger than $\lambda_{0.9}$ (see Fig. 1), the difference between $\lambda_{0.6}$ and $\lambda_{0.9}$ becomes smaller with an increasing in culm sizes. This fact means that the culm form for *P. nigra* becomes non-tapering with the culm sizes, whereas $\lambda_{0.7}$ and $\lambda_{0.8}$ are steady at constant levels.

Goodness of Fit of the Determined Volume Equation

Table 2 Mean error (ME), relative mean error (%ME), root mean square error (RMSE) and relative root mean square error (%RMSE) between estimated and actual apparent culm volume for *Phyllostachys nigra*

	ME (dm^3)	%ME (%)	RMSE (dm^3)	%RMSE (%)
Estimation from the volume equation for *Phyllostachys nigra* (Eq. 2 in the text)				
ITO (n = 50)	− 0.092	− 3.936	0.013	0.557
FUE (n = 50)	− 0.232	− 6.422	0.460	12.703
Estimation from the volume equation for *Phyllostachys pubescens* (Eq. 3 in the text)				
ITO (n = 50)	− 0.185	− 7.881	0.386	16.493
FUE (n = 50)	− 0.484	− 13.380	0.815	22.509
Estimation from the volume equation for *Phyllostachys bambusoides* (Eq. 4 in the text)				
ITO (n = 50)	0.049	2.097	0.229	9.791
FUE (n = 50)	− 0.013	− 0.349	0.297	8.212

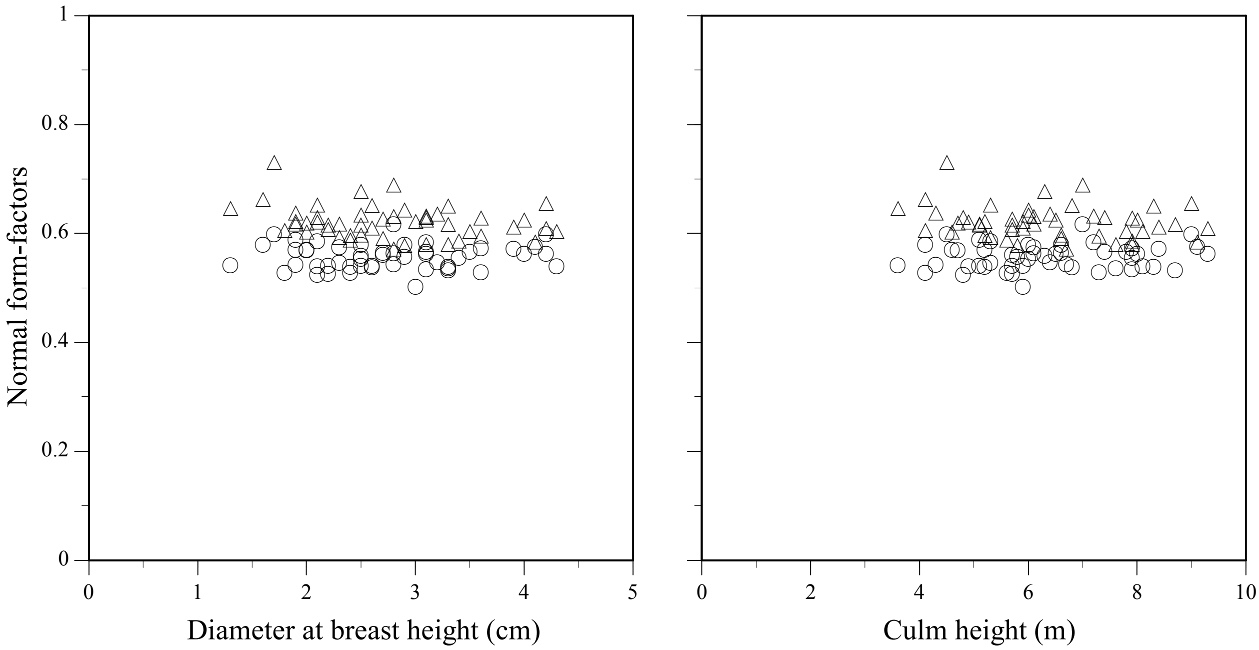

Fig. 3 Relationships of normal form-factors to diameter at breast height and culm height for *Phyllostachys nigra.* The triangle and circle indicate the normal form-factors at 0.7 and 0.8 in relative height, respectively.

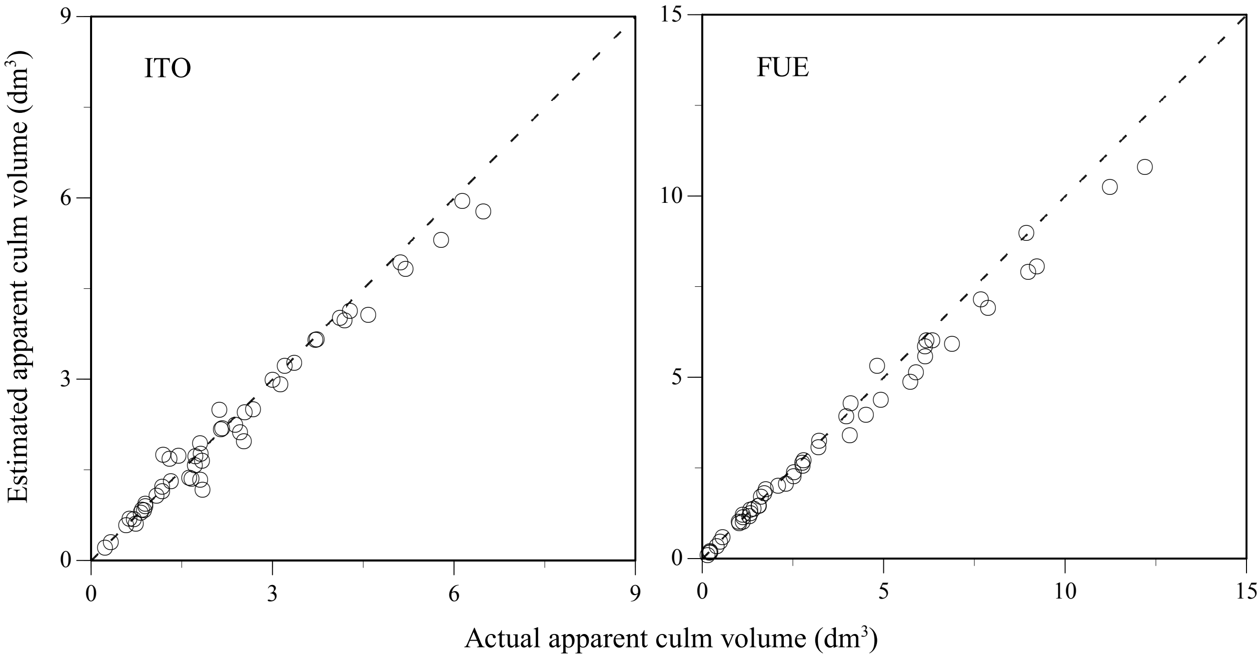

Fig. 4 Comparison of the estimated and actual apparent culm volumes for *Phyllostachys nigra.* The broken line indicates 1:1.

The generalized theoretical volume equation used in this study was originally proposed as the theoretical volume equation for estimating the stem volume of coniferous tree species (Inoue and Kurokawa, 2001). Inoue *et al.* (2011) and Suga *et al.* (2011) generalized this volume equation to apply to the bamboo species as well as the coniferous tree species. Inoue and Kurokawa (2001) reported that the relative mean error of the theoretical volume equation was 1.543% for *Cryptomeria japonica* D. Don and 8.402% for *Chamaecyparis obtusa* Endl. Inoue *et al.* (2002) also found that the relative mean error of the volume equation ranged from-1.091% to 11.400% for *Larix kaempferi* grown in four different districts. In addition, Inoue (2006) applied the volume equation to *C. japonica* grown in three districts with different management regimes, and reported that relative mean error ranged from 0.923% to 15.908%. Furthermore, the empirical volume equations used widely produced a comparable goodness of fit of the theoretical volume equation (Inoue, 2006; Inoue and Kurokawa, 2001; Inoue *et al.*, 2002). Inoue (2006) applied the generalized theoretical volume equation to *P. pubescens*, with the relative mean error being 0.172%. For *P. bambusoides*, SUGA *et al.* (2011) also reported that the relative mean error of the generalized theoretical volume equation ranged from -5.558 to 1.122%.

The result of this study showed that the estimated apparent culm volume was significantly smaller than actual one for both districts, with the relative mean error being -3.936% for ITO and -6.422% for FUE (see Fig. 4 and Table 2). There are no clear difference in relative mean error of the estimated volume between the previous studies and this study. Therefore, the significant difference between the estimated and actual apparent culm volume for *P. nigra* does not always deny the effectiveness of the determined generalized theoretical volume equation, Eq. 2. When estimating the volume for bamboo and coniferous tree species, it should be noted that the generalized theoretical volume equation would produce a comparable relative mean error found in this study and previous ones, i.e., about ±10% (INOUE, 2006; INOUE and KUROKAWA, 2001; INOUE *et al.*, 2002, 2011; SUGA *et al.*, 2011).

Comparison of the Volume Equations

The generalized theoretical volume equation has been applied to other bamboo species as follows:

$$v = \frac{0.908\pi\, d_b^2\, h}{4[(1 - h_b/h)/0.6]^{1.742}} \tag{3}$$

for *P. pubescens* (SUGA *et al.*, 2011) and

$$v = \frac{0.737\pi\, d_b^2\, h}{4[(1 - h_b/h)/0.6]^{0.761}} \tag{4}$$

for *P. bambusoides* (INOUE *et al.*, 2011). For the test data of *P. nigra*, the apparent culm volume was estimated with these volume equations. The statistics of the goodness of fit are summarized in Table 2. For both districts, the estimated apparent culm volume was significantly smaller than actual one when applying Eq. 3 for *P. pubescens* (P < 0.01 for ITO and P < 0.001 for FUE). By contrast, there was no significant difference between estimated and actual apparent culm volume when applying Eq. 4 for *P. bambusoides* to *P. nigra* from FUE (P = 0.717). Although there was a significant difference between estimated and actual apparent culm volume for *P. nigra* from ITO (P < 0.05), the relative mean error was comparatively small (2.097%). This result suggests that the common volume equation, Eq. 2 or 4, could be applied to *P. nigra* and *P. bambusoides*, whereas the different volume equation, Eq. 3, should be applied to *P. pubescens*.

This failure of diversion of Eq. 3 will be caused by the difference in the culm form between the bamboo species: The averages of $\lambda_{0.6}$ and $\lambda_{0.9}$ for *P. nigra* were, respectively, 0.743 and 0.541, whereas these normal form-factors varied with culm sizes (see Fig. 2). By contrast, the averages of $\lambda_{0.6}$ and $\lambda_{0.9}$ were, respectively, steady at 0.908 and 0.448 for *P. pubescens* (SUGA *et al.*, 2011) and at 0.736 and 0.543 for *P. bambusoides* (INOUE *et al.*, 2011). The difference between $\lambda_{0.6}$ and $\lambda_{0.9}$ is smaller for *P. nigra* than *P. pubescens*, indicating that *P. nigra* holds a non-tapering culm form compared to *P. pubescens*. For this reason, the apparent culm volume for *P. nigra* having more non-tapering culm form will be underestimated when applying the volume equation for *P. pubescens* having more tapering form. Similar result was reported between *P. pubescens* and *P. bambusoides* (INOUE *et al.*, 2011). By contrast, no clear differences in the normal form-factors were found between *P. nigra* and *P. bambusoides*, suggesting that the culm form of *P. nigra* would be similar to that of *P. bambusoides*. Because of the similarity of the culm form, the apparent culm volume of *P. nigra* could be successfully estimated by applying Eq. 4 for *P. bambusoides*. These facts indicate that the species characteristics of culm form should be carefully considered when evaluating the bamboo resources by the volume equations.

Recommendation for Future Studies

In the world, there are 1250 bamboo species within 75 genera, and most of them would be overlooked biomass resources (SCURLOCK *et al.*, 2000). Although the utilization and management of bamboo require information on the amount of the resources (KLEINN and MORALES, 2006), it is impractical to separate the volume equation by each bamboo species. In reality, various bamboo species are classified into several groups based on the patterns of their culm forms, and then the volume equations should be prepared for each group. For instance, *P. nigra* and *P. bambusoides* are ascribed as the same group of bamboo and the common volume equation, i.e., Eq. 2 or 4, is applied to these species. By contrast, *P. pubescens* should be distinguished from *P. nigra* and *P. bambusoides*, and it is necessary to apply the different volume equation, i.e., Eq. 3.

Various measures have been proposed and used for quantifying the stem form of a tree (e.g., INOUE, 2005). Among them, the normal form-factors used in this study might be one of the most effective measures for classifying various bamboo species into several groups, since their steady values can be directly used for determining the coefficients of the generalized theoretical volume equation. From this viewpoint, there is a need for further studies on the inter-specific variation in normal form-factors of culms across a wide range of bamboo species.

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Article

An Analysis of Harvest and Assessing Maturity for Sustainability in Myanmar Teak Forests

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ABSTRACT

This study aims to analyze the human disturbance tendency of Myanmar teak forests, and to propose an index for sustainable forest management in the study site. Enumeration data providing information on growth of teak forests in Pyu Kun Reserve Forest before and after harvest were used to demonstrate the potential use of maturity as a yield regulation index for the sustainable management of natural teak forests in Myanmar. Data from 64 compartments were classified into seven girth at breast height (gbh) classes, and subjected into four time series corresponding to periods before and after the first and second harvests to investigate the general disturbance tendency of the teak forests. Results of the study revealed that previous harvesting activities were unsustainable as almost all of the large trees were cut. Significant disturbance was also noted on trees in the smaller girth classes between the time period after the first harvest and before the second harvest. Under the condition of no legal harvest at this time period, the disturbance was attributed to illegal logging by relatively poor people. Maturity index, which was simply derived from the number of trees and required year for growing up to lower limit gbh at gbh classes, could assess the impacts of harvesting and disturbances to the sustainability of teak forests in Myanmar.

Keywords: disturbance tendency, maturity index, teak forests

INTRODUCTION

Teak (*Tectona grandis*) is one of the most commercially important species in the world. It owes its reputation as good timber from the incomparable combination of its qualities: termite, fungus and weather resistances, lightness with strength, attractiveness, workability, and seasoning capacity without splitting, cracking, warping or materially altering shapes (Hoe, 1969). Teak is also renowned in the ship building industry and a major raw material for buildings, bridge and wharf construction, piles, furniture, cabinet work, railway carriages, heel spokes and felloes and general carpentry. Teak grows naturally in moist and dry deciduous forests below 1,000 meter elevation (Pandey and Brown, 2000).

Teak is indigenous in Myanmar where mixed deciduous forests occur about 39% of the total land area. Therefore, Myanmar is well known for having a wide expanse of good quality teak forest reserves (Bryant, 1997). Accordingly, the forest management system in Myanmar, which is the Myanma Selection System (MSS) formerly known as Brandis Selection System (BSS), was primarily based upon the management of the country's natural teak forests. Forest management under MSS features annual harvest on a sustained basis and calculation of the future yield. Brasnett (1985) stated that the future yield can be controlled by area, volume and number of trees. Generally, irregular tropical forests, which are often composed of several species only with a few of which are marketable, are regulated using number of trees as basis (Osmaston, 1984).

In the previous BSS, a minimum girth limit for harvestable teak trees was set and only the annual increment of the harvestable trees were supposed to be harvested as annual yield (Brandis, 1896). To achieve this, the BSS methodology required a presentation of the number of harvestable trees in a cutting plan. Under the BSS, the forests are organized into felling series for the convenient of working according to drainage and geographical situation. The felling series are subdivided into 30 blocks by defining 30-year of felling cycle. One block per year is harvested and the whole felling series is worked in the course of a 30-year felling cycle. The extracted number of harvestable trees must be within the bounds of the annual allowable cut, which is determined for each felling series based on the principle of sustained yield management (Dah, 2004). However, this methodology did not assure long term sustainability by considering any indices throughout the harvesting period (Brandis, 1896). In

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addition, it is also important to estimate the multi-temporal sustainability for managing teak forests on a long-term basis.

Recently, growth prediction (Tint and Schneider, 1980) and age-independent individual tree models for teak to predict tree diameter growth (Zin, 2005) were used to manage teak stands in Myanmar. The development of these models tried to improve the management of teak forests on a sustained yield basis but until now there is no study on developing indices to estimate multi-temporal sustainability for teak forests.

The objective of this study was to propose a yield regulation index for the sustainable forest management of natural teak forests in Myanmar. This concept is based on the previous study of Shiraishi *et al.* (2006), which proposed the use of maturity index on yield regulation of forests. Maturity indices assess the effects of harvesting on maintaining sustainability of forest stands.

METHODS

Study Site

The study was conducted at one of the Reserved Forests in Bago Yoma region, which is situated in the central part of lower Myanmar. According to Kermode (1964), teak trees of superior quality can be found in Bago Yoma area. Bago Yoma, which literally means Bago mountain range, covers about 5.07 million ha of total land area, with 1.8 million ha of natural teak forests nestled inside it. It had been known as a home of teak and was also the birth place of the scientific forest management, the Myanmar Selection System (MSS). The region includes thirty-one townships, eight administrative forest districts and four divisions. The study was conducted in Pyu Kun Reserve Forest (RF) which is under the Taungoo Extraction Agency, one of the administrative forest districts in Bago (East) Division of Bago Yoma. Pyu Kun RF is the largest reserved forests in Bago (East) Division. It has a total of 174 compartments and has the most number of available enumeration data for teak (Fig. 1).

Data Source

Data on forest conditions of Bago Yoma region were collected from the Planning and Statistics Division, Forest Department in Naypyitaw (capital) and Myanma Timber Enterprise. According to Zin (2005), permanent sample plots were first installed in Bago Yoma region in 1982 and were measured in 1987 and 1992. In this study, the forest enumeration data of Pyu Kun RF were used to analyze the growth of teak. Forest enumeration is one of the silvicultural operations in MSS (Kyaw, 2004). It is conducted one or three years before timber extraction in selected compartments to tally the total number of teak trees in each compartment. A 100% enumeration of each compartment entails counting all teak trees with a girth at breast height of 4 feet and above. Through this operation, it can be checked how many trees from those selected compartments will be cut and how many will be left for the future.

In Pyu Kun RF, there are a total of 174 compartments but only 110 of which have history of enumeration data at the time of data collection. Out of 110, 64 compartments were selected as those compartments having two harvesting records. These data were collected from the District Forest Office (DFO) of Taungoo, Forest Department, Extraction Agency Offices of South Taungoo and South Bago, and the Division Office of Deputy General Manager, Taungoo, Myanma Timber Enterprise. The status of harvest in the study site and the statistics of the 64 compartments are shown in Tables 1 and 2, respectively. The collected data were composed of numbers of compartments, numbers of felled/girdled trees, numbers of trees left at the time of felling, total production amount (by trees), and time intervals of harvest. The records of girdling or marking trees and trees left were traced back from 1976 up to 2009.

Data Analysis

Sixty-four compartments which would provide information about the growth of teak trees before and after harvest were selected to investigate the general human disturbance tendency of teak forests in this area. Data of cut or left trees were classified into seven girth at breast height (gbh) classes (Table 3). Enumeration data was reclassified into the following series of time measurements: before 1st harvest (t_1), just after 1st harvest (t_2), before 2nd harvest (t_3), and just after 2nd harvest (t_4). For the analysis of disturbance occurrence through the growth rate of teak in each girth class, only the trees measured at t_2 and t_3 were considered. By applying the time interval between t_2 and t_3, the increment number of trees per year was calculated to estimate growth rate for each girth class. The growth rate was assumed as the increment of trees within the same girth class.

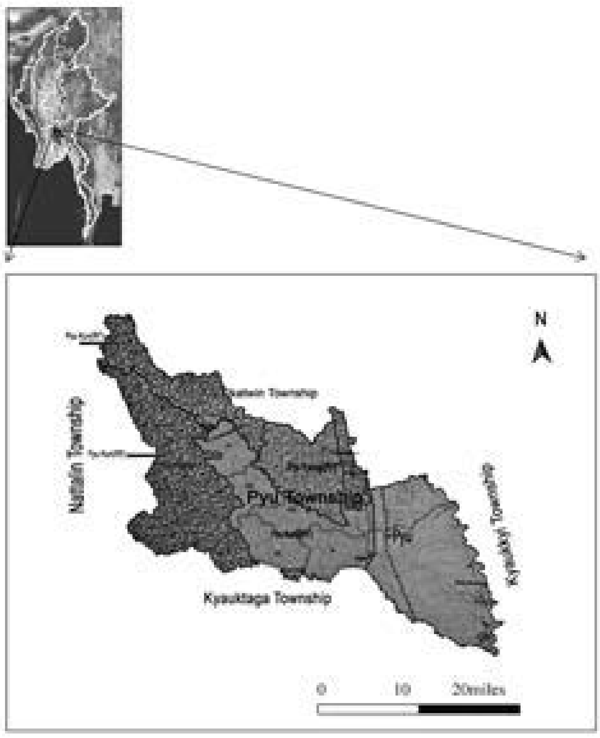

Fig. 1 Location of study area of Pyu Kun RF of Pyu Township
Source: Planning and Statistics Division, Forest Department and Bago Yoma Greening Project

Table 1 Status of harvest in Pyu Kun RF

Forest Areas in Pyu Kun RF				
No.of Compartments	Status of Harvest	Area before 1st Harvest (ha)	Area at 1st Harvest (ha)	Area at 2nd Harvest (ha)
64	Two Times	33,007	32,730	31,019
46	One Time	23,916	23,098	-
13	No Harvest	7,474	-	-

Table 2 Statistics of the 64 compartments in Pyu Kun RF

Items	Unit	Average	Min	Max	Standard Deviation
Area	ha	517	105	752	143
Teak density					
Before 1st harvesting (t_1)	Stems/ha	4.23	2.90	13.42	0.15
After 1st harvesting (t_2)		2.76	2.17	10.03	0.15
Before 2nd harvessting (t_3)		1.36	1.04	5.13	0.20
After 2nd harvesting (t_4)		0.48	0.53	3.01	0.05

Table 3 Girth (gbh) class of teak and the required year for growing up for each gbh class

gbh class (i)	Unit: ft.& in, Lower Limit $\leqq g_i <$	Unit: ft.& in, Upper Limit	Unit: cm, Lower Limit $\leqq g_i <$	Unit: cm, Upper Limit	The required year for each gbh class (yrs.)
g_1	4’00”	5’00”	122	152	31
g_2	5’00”	5’06”	152	168	45
g_3	5’06”	6’00”	168	183	53
g_4	6’00”	6’06”	183	198	64
g_5	6’06”	7’00”	198	213	77
g_6	7’00”	7’06”	213	229	95
g_7	7’06”	+	229	+	125

The growth rate (I) within the same class and average growth rate (G) for 64 compartments were defined as:

$$I = (C_{i,y'} - C_{i,y}) / (y' - y) \qquad (1)$$

$$G = \sum_{i=1}^{7} (C_{i,y'} - C_{i,y}) / N \qquad (2)$$

where

y' is the year at t_3

y is the year at t_2

$C_{i,y'}$ is the number of trees per hectare in gbh class i at t_3

$C_{i,y}$ is the number of trees per hectare in gbh class i at t_2

N is the total compartment

i is girth class (g_1 to g_7)

g is girth at breast height.

Average growth rates were accumulated through girth at breast height classes (g_7 to g_1, g_7 to g_2, g_7 to g_3, g_7 to g_4, g_7 to g_5, and g_7 to g_6) to find out where the disturbance occurs significantly. In addition, the total gbh distributions before and after first-second harvesting were calculated using the enumeration data.

The maturity of forest resources found in natural teak bearing stands was calculated based on the study of Shiraishi *et al.* (2006). In this study, the maturity based on the gbh classes (i) was defined as follows:

$$M = \sum_{i=1}^{7} N_i Y_i \qquad (3)$$

where

M is the maturity of the target stand

N_i is the number of trees in gbh class i per ha.

Y_i is the required year for growing up to gbh class i.

The required years (Y_i), for growing up to gbh class i, were calculated by the following Mitscherlich equation:

$$Y_i = -\frac{1}{k} \ 1\text{n} \ \frac{G_i M^{-1} - 1}{-L} \qquad (4)$$

where

M, L and k are parameters

G_i is the lower limit gbh at gbh class i.

After estimating parameters by applying Mitscherlich equation, the required years (Y_i) for growing up to gbh class i were calculated by the formula (4) derived from the original Mitscherlich equation. The parameters were estimated from the yield table showing the gbh of teak (Japan International Forestry Promotion and Cooperation Center, 1996). The parameters M, L and k are 96.861, 0.977 and 0.021, respectively. By using the formula, maturities of stands before and after first-second harvesting were calculated.

The maturities were calculated in total gbh distribution.

In addition, the maturities in specific gbh distributions were also calculated and considered the utility of maturities as index for considering sustainable management at stands level.

RESULTS AND DISCUSSION

The average gbh distribution of teak trees over time series is shown in Fig. 2. Here, trees enumerated before and after first-second harvests were allotted to four time series; t_1, t_2, t_3, and t_4. First and second harvestings were conducted at t_2 and t_4. Therefore, the trees enumerated before first and second harvests (i.e., t_1 and t_3) were composed of all teak trees that were supposed to be either cut or left. On the other hand, the trees measured at t_2 and t_4 were considered as the trees left after harvesting as exploitable teak trees had already been harvested at these times. Results revealed that at t_2 and t_4 (after first and second harvests), all of the largest trees were harvested without leaving any seed trees for the next regeneration. However, it was also noted that the girth distribution of teak stands after the first harvest (t_2) were comparatively better than those after the second harvest (t_4). At t_4, there were no more mature trees left to be harvested with significant loss of trees observed in gbh class g_5 and g_6. This was probably due to decreasing girth limit at the time of second harvest. Under the condition of no disturbance and no legal harvest at t_3, the number of trees at time series t_3 must be more than those at t_2. However, according to the results of enumeration data, disturbance occurred in the small-stemmed trees between t_2 and t_3. Apparently, about 80% of younger trees between gbh class g_1 and g_4 were lost at this time series.

The results of average number of trees increment per hectare per year within the same girth class are shown in Fig. 3a. Also, the average growth rates accumulated through girth class g_7 to g_1, g_7 to g_2, g_7 to g_3, g_7 to g_4, g_7 to g_5, and g_7 to g_6 were shown to find out where the disturbance occurred significantly (Fig. 3b). A significant decrease in tree increment was observed in the lower girth classes, between g_1 and g_3. In Myanmar, transporting legally harvested trees is carried out by elephants which are expensive animals and could not be owned by local people (MAR, 2007; ZAW, 1997). At this time, no legal harvesting was conducted in the area. Therefore, it can be deduced that the main reason of the decreasing stand density under the small gbh class was attributed to illegal logging by relatively poor people.

From these observations, it can be concluded that

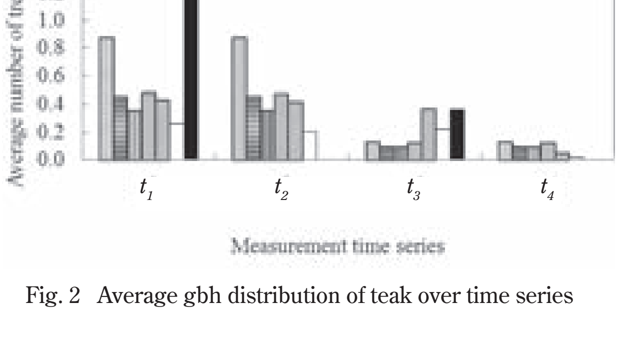

Fig. 2 Average gbh distribution of teak over time series

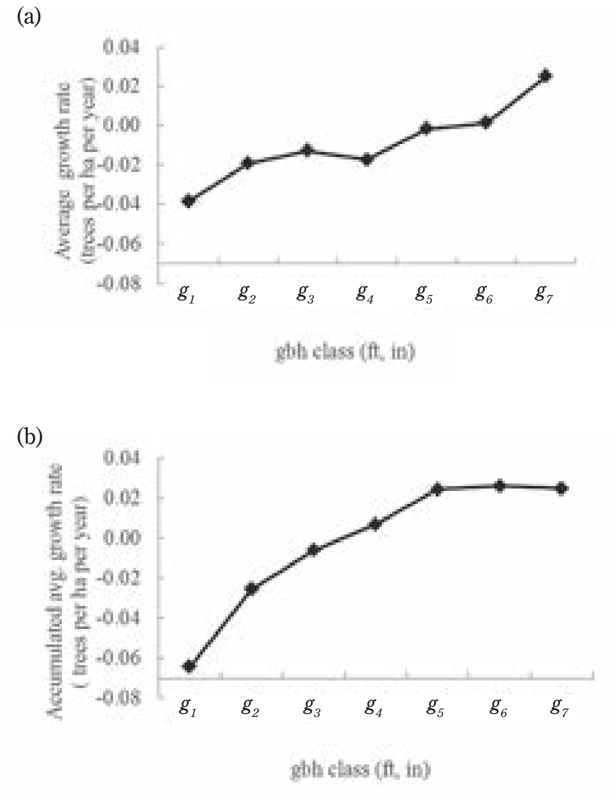

Fig. 3 Disturbance tendency through (a) average and (b) accumulated average growth rate of teak

the implementation of silvicultural operations, such as gap planting and maintenance against disturbances, for younger teak stands is seriously necessary.

A periodic check must also be done at least twice before harvesting time, as many trees might get lost because of the long period before the next harvest. Otherwise, the existing mature trees might also disappear due to illegal logging and/or natural disturbance such as forests fire. Sufficient resources such as labor, budget and time should be invested for the sake of managing Myanmar's invaluable natural teak forests. Moreover, as most of the mature trees are harvested and no seed trees are left, assisted natural regeneration is encouraged through improvement felling, enrichment and gap planting.

The calculated teak gbh distributions of first and second harvesting in Pyu Kun RF are shown in Fig. 4. The first and second harvested trees were distributed in higher gbh classes of g_5 and above. The total number of trees left after the first harvesting was observed to have decreased by approximately 50%. According to data sources, no legal harvesting was conducted between measurement time t_2 and t_3. Therefore, the difference of number of trees between measurement time t_2 and t_3 was attributed to illegal logging.

The maturity of the teak forests in the study area, which was based on the gbh distribution (Fig. 4) and parameters substituted into formula (4) is shown in Fig. 5. Maturity indices were found to be decreasing throughout all measurement times. The maturity significantly decreased at t_2 and t_4, because first and second harvestings were conducted just before these measurement times. This also suggests that maturity decreased not only due to harvesting but also because of illegal logging. Further, the use of maturity indices

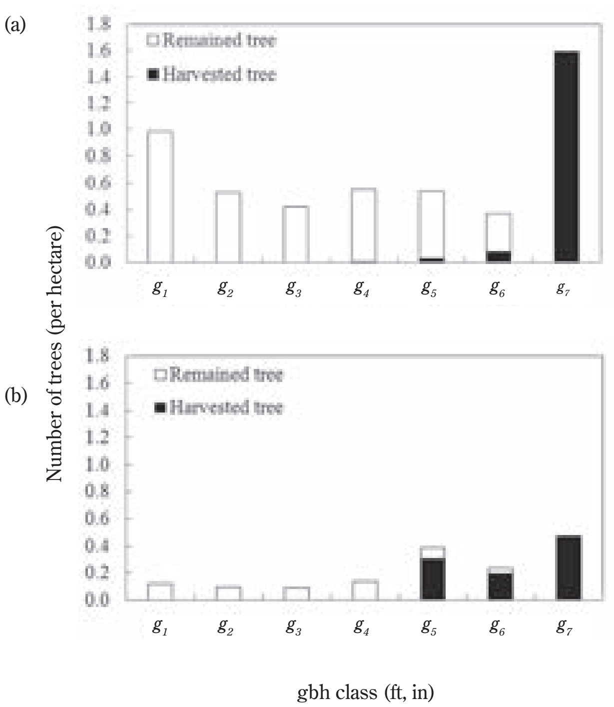

Fig. 4 Total teak gbh distribution of (a) first and (b) second harvesting derived from enumeration data of Pyu Kun RF

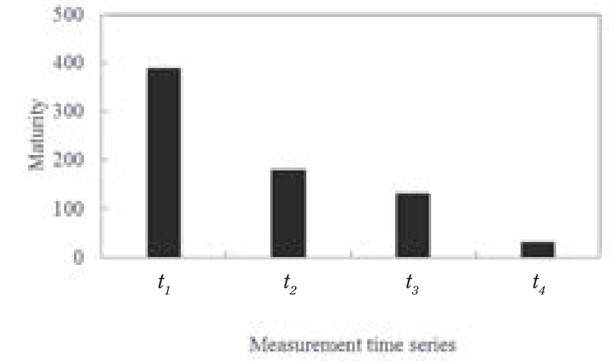

Fig. 5 Maturity of teak stands in Pyu Kun RF

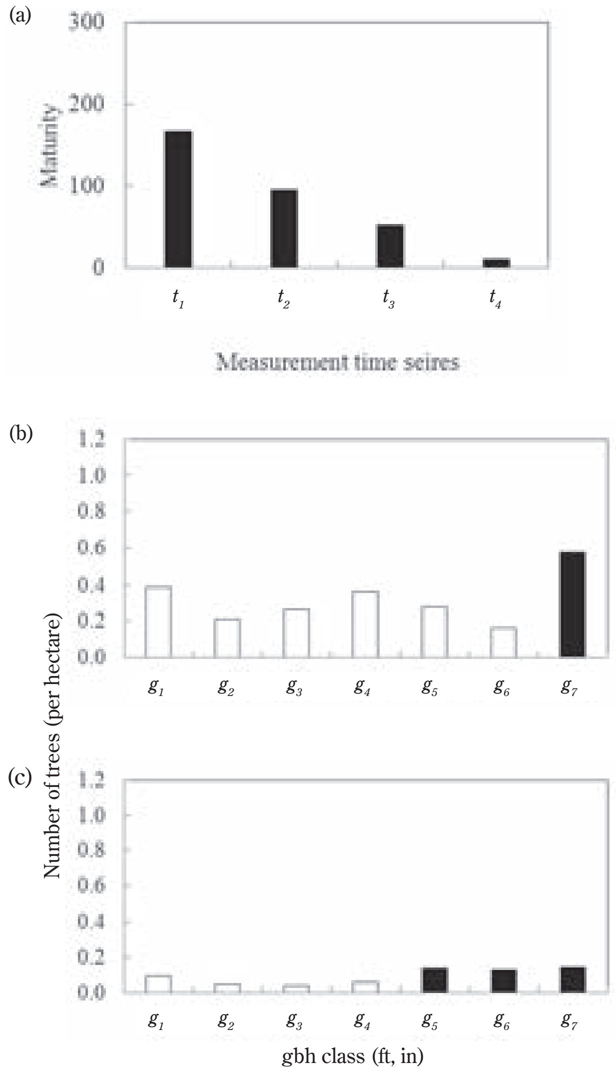

Fig. 6 First example of the (a) maturities and gbh distributions of (b) first and (c) second harvesting in specific teak stands

clearly showed the unsustainability of the target teak forests.

Although these results were calculated from all compartments, Figs. 6, 7 and 8 show three examples of maturities and gbh distributions estimated in specific teak stands. In Fig. 6a, maturity was simply decreased. As mentioned above, the illegal logging activities on the small gbh classes have a strong negative effect on the maturity of the stand (Figs. 6b and 6c).

As compared with Fig. 6, the difference of maturity between measurement time t_2 and t_3 in Fig. 7 was found to be relatively small. However, after second harvesting, the maturity dramatically decreased (Fig. 7a), implying that the second harvesting is not sustainable in terms of maintaining the maturity of the stands.

In Fig. 8a, the maturity in measurement time t_3 recovered before the second harvesting. At the same time, the maturities of measurement time t_3 and t_4 are higher than that of measurement time t_1 and t_2, respectively. Therefore, it can be concluded that the sustainability of these teak stands would be relatively higher compared to the previous examples (Figs. 6 and 7).

According to the current enumeration data of the study site, approximately five teak trees are observed in one hectare. In this case, the sustained yield of teak could not rely on only the number of large trees. In the new concept of maturity, the required years for growing up to a girth class were taken into account. In introducing the presented indices, the simple growth curve was used. As long as the number of trees by years is increasing in each girth class, the maturity of that forest could be considered stable and that stand could be chosen for harvesting operation.

The study was able to show how maturity indices can be used to analyze the impacts of harvesting and disturbances to the sustainability of teak forests in Myanmar. An advantage of

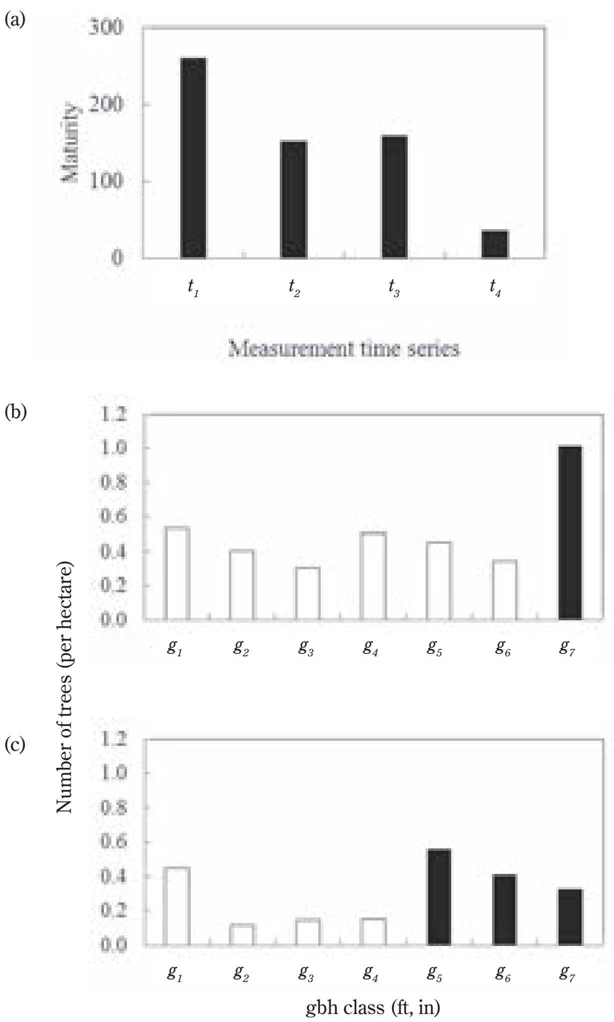

Fig. 7 Second example of the (a) maturities and gbh distributions of (b) first and (c) second harvesting in specific teak stands

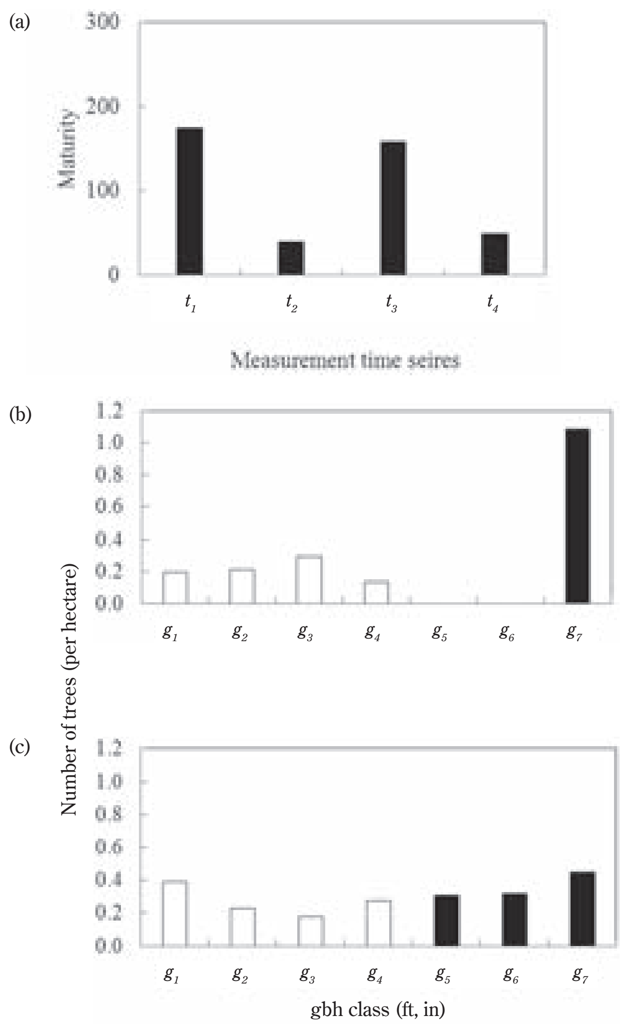

Fig. 8 Third example of the (a) maturities and gbh distributions of (b) first and (c) second harvesting in specific teak stands

the maturity index is that the index allows us to compare the states among stands or forests numerically. The maturity is calculated by the required year and number of stems (formula (3)). As mentioned above, the required year is the age for growing up for each gbh class. By adding arbitrary prediction period as felling cycle (year) to the required year, it would be possible to predict the future maturity. The diameter transition matrix (TANAKA, 1993), which is also used for predicting future forest resource, can be applied by using fixed prediction period, for example 5 or 10 years. But, this maturity index can be used for the arbitrary prediction period (year). This flexibility is also an advantage of this maturity. Traditionally, the teak forests in this site were managed by considering the number of trees (BRYANT, 1997). The maturity index is also calculated by the number of trees. Therefore, this maturity is adaptive for the traditional management system of the teak forest in this study site. Because the number of trees is readily measured in many harvested stands of the teak forests under the current management system, this maturity index could be practically applied to existing forest management system of study sites.

CONCLUSION

In conclusion following three points can be made. First, the study revealed that existing harvestings were unsustainable as the many large trees were removed. Second, disturbances were also quantified on trees in the lower girth classes between the time period after the first harvesting and before the second harvesting. Under the condition of no legal harvest at this time period, the disturbance was attributed to illegal logging. Third, Maturity index enabled us to assess the impacts of harvesting and illegal logging to the sustainability of teak forests in the study site.

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Article

The Possibility of A/R CDM as the Adaptation Measure: Case Study in Fiji and Kenya

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ABSTRACT

The Afforestation and Reforestation project activity under the Clean Development Mechanism (A/R CDM) is one of the policies set under the Kyoto Protocol. A/R CDM is to remove greenhouse gases by the afforestation or reforestation project in developing countries. There are restrictions and barriers to promote A/R CDM under the present rules because of complex rules, low profitability, and low priority for many countries. On the other side, A/R CDM has the specific advantages. One of these is the potential as adaptation and the object of this paper is to disclose this possibility of A/R CDM. This paper focused on 2 A/R CDM projects as case studies, in Fiji (to plant mangrove trees) and in Kenya (to plant indigenous fruit trees IFTs). Adaptation is to take social, economic and ecological adjustments to decrease the damage of climate change, and had been drawn attention especially among developing countries which were vulnerable to bad effects of climate change. The results of field surveys showed that both forestation projects have functions not only as mitigation but also as adaptation as follows; 1) In the mangrove planting in Fiji, local people understood the function of biodiversity conservation as conservation for marine species and the function of bank protection as a breakwater against high waves. 2) The IFT planting in Kenya has some functions to keep and conserve biodiversity in the local ecosystem threatened by loggings and to work as the role of food security. The adaptation measure has regionality (as adaptation measure and policy should be implemented according to site specific circumstances and characteristics for its best effects) and it is important point to have high adaptability to the locals as these projects. A/R CDM, with various second effects such as adaptation, can be evaluated as the cobenefits-typed climate policy. Facing the limitations of A/R CDM under present rules, it is expected to reevaluate its specific advantages for the promotion of A/R CDM from the viewpoint of equity and human security. At present, conceivable means are proposed as follows; conversion of credit prices through the introduction of a new basis of variation from the viewpoint of adaptation and project support through the Adaptation Fund. Recently, REDD (Reducing Emissions from Deforestation and Forest Degradation) in developing countries has been the focus of attention. REDD has many characteristics similar to environmental forestry, because it is a policy to prevent the deforestation and forest degradation and vegetation on site. REDD is highly expected to become a useful scheme with possibility doing a good job as the adaptation in a forest sector in the future.

Keywords: adaptation, A/R CDM, climate change, cobenefit, indigenous tree

INTRODUCTION

Climate Change is one of the global environmental problems, and causes many disasters such as the rise of sea level, the increase of abnormal climate, the destruction of biodiversity, and so on. Intergovernmental Panel on Climate Change (IPCC) (2007) published some research results in its Fourth Assessment Report, as below;

- CO_2 atmospheric concentration: from 280 ppm (before industrial revolution) to 379 ppm (2005)
- sea level rise: 3.1 mm per year on average from 1993 to 2003
- rainfall: increased in East part of North / South America, North part of Europe, North and Central parts of Asia; decreased in Sahel, Mediterranean Area, South part of Africa, South part of Asia in recent 15 years
- temperature rise: will increase 1.8 – 4.0 degrees till 2100

The United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (KP) were

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adopted in 1992 and 1997, respectively, to prevent climate change. Developed countries (the Organization for Economic Co-operation and Development countries and the countries in transition) aimed to achieve the goals mentioned in KP to reduce greenhouse gases (GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6)) for the first commitment period (2008–2012) through domestic actions and the Kyoto Mechanism. The Kyoto Mechanism includes the Clean Development Mechanism (CDM), the Joint Implementation, and the Emission Trading, which follows a market mechanism that developed countries can implement for cost-effective actions. In CDM, developed countries implement emission reduction projects in developing countries (host countries), and in turn receive credit called Certified Emission Reduction (CER), which can be used to achieve the Kyoto goals. CDM has two main categories: the afforestation and reforestation project activities under CDM (A/R CDM) and emission CDM. The scope of emission CDM includes all but the sink sector (Any process, activity or mechanism which removes GHGs from the atmosphere. Forests and other vegetation are considered sinks). A/R CDM targets on the afforestation (forestation on lands that have not been forested for at least 50 years) and the reforestation (forestation on lands that have not been forested since 1990) and is different from emission CDM in several points. The carbon sequestration function draws more attention for mitigating climate change (FAO, 2007). A/R CDM policy is expected to address both climate change and forest decrease.

We have two approaches against climate change. One is the "Mitigation" to prevent climate change through the GHG reduction and another is the "Adaptation" to take social, economic and ecological adjustments to decrease the damage of climate change. Mitigation can reduce the exposure to climate change and adaptation can reduce sensitivity to climate change (IPCC, 2007). Kyoto Protocol's goal of the 5.2% GHG reduction for all developed countries is the mitigation and Kyoto Mechanism including CDM is considered the mitigation policy, with a limited role for adaptation (SETTLE *et al.*, 2007). IPCC (2007) pointed out Africa, Alliance of Small Island States (AOSIS) and North and South Pole as vulnerable areas to climate change, specifically small islands, low-lying coast and delta area, (semi-) arid area, polar area, precipitous mountainous area and tundra. These areas are endangered by critical damages such as the land (settlement or plantation) submersion under water, decrease of the productivity by decrease of rainfall, and the destruction of culture / tradition / ecosystem by the melting of frozen land. From the viewpoints of "Equity" and "Human Security," various measures especially adaptation must be implemented as soon as possible in these areas. The precautional implementation of adaptation measure and policy was cost effective and useful (SETTLE *et al.*, 2007; IPCC, 2007; MIMURA, 2006). KAMEYAMA (2005) defined "Equity" as the criteria for benefit and/or cost distribution and its procedure which most of stakeholders can agree. "Human Security" is "to protect the vital core of all human lives in ways that enhance human freedoms and human fulfilment" (COMMISSION ON HUMAN SECURITY, 2003).

MATERIALS AND METHODS

Developing countries expect CDM not only as the climate policy (to reduce GHG emissions) but also as the (sustainable) development policy and the adaptation policy for them. However, there are many problems of CDM like regional unbalance or sectoral unbalance. The regional unbalance is more true about A/R CDM as the registered project is only 32 (as of October 2011). This is due to A/R CDM's specific features, such as high uncertainty and low profitability (FUKUSHIMA, 2006; 2010). On the other hand, A/R CDM has the specific advantages such as local development or ecological conservation. One of these advantages is the potential as the adaptation measure and the object of this paper is to disclose this possibility of A/R CDM. For this purpose, firstly, I arranged the discussions about the adaptation and A/R CDM so far. Then, this paper focused on two A/R CDM projects as case studies, in Fiji (to plant Mangrove trees) and in Kenya (to plant Indigenous Fruit Trees (IFTs)), and verified their possibility as the adaptation measures through field researches. Finally, based on these researches, I suggested the direction how to promote A/R CDM. This paper chose two projects because Fiji and Kenya belong to AOSIS and Africa which were one of the most vulnerable areas and essential to take measures against climate change.

This research is significant as two points bellow;

- to verify the secondary effects of the A/R CDM projects as the adaptation measure through case study, under the situation that adaptation and A/R CDM adopt the bottom-up approach,
- to suggest the feasible A/R CDM projects in AOSIS and Africa as feasible areas, under the situation of regional unbalance of CDM

The research methods were mainly literature research and interviews to stakeholders in Japan and host countries (Fiji and Kenya). Interviews to stakeholders have been implemented from October 2003 to September 2010. Researches in Fiji were implemented for 94 days in July, September and November, 2005, April 2007, February 2008, February 2009, and September 2010. At the research in September 2005 and February 2008, I used the questionnaire and researched about the expectation for mangrove planting project in September 2005, and the usefulness of mangrove trees in February 2008 for the local people in Lomawai (project site). The number of informants was 45 and 30 for each. The informants were chosen 1 adult (at least over 15 years old) from each household of project site in principle, considering age and gender balance (see Table 1). Research in Kenya was implemented for 51 days in September to November 2007. In Kenya, I researched the local people's utilization status of IFT at the village area including their market in Kilifi (project site). I researched about how to consume and conserve, the local preference at the village area, and about species to be sold, quantity and price, style and place to trade at the market (For the detail of research results about the local preference and utilization of IFT at the project site, see FUKUSHIMA *et al.* (2010)).

The outlines of Fiji project and Kenya project are as

Table 1 Sample number of informants

Age		-20	21-30	31-40	41-50	51-60	61-70	71-	Total
Sep. 2005	Male	1	3	5	7	1	5	3	25
	Female	3	2	6	4	3	2		20
	Total	4	5	11	11	4	7	3	45
Feb. 2008	Male	1	5	5	3	1			15
	Female	2	5	3	5				15
	Total	3	10	8	8	1	0	0	30

below (see Table 2). The Fiji project has been conducted by Taishi Design Office named "Participatory forestation program in Fiji with Low-income Community." The project site is in Lomawai village, Nadroga State in Fiji (177°18'0"E, 18°2'0"S). The village is located in south west area of Fiji's main island, Viti Levu, where is a vulnerable to sea level rise. Fiji project is small-scale typed environmental forestry using three types of mangrove: *Bruguiera gymnorrhiza*, *Rhizophora samoensis*, *Rhizophora stylosa*. The project scale is 250 ha and the estimated amount of CO_2 removal for 30 years of the project period will be 112,608 CO_2-t (TAISHI DESIGN OFFICE, 2006). This project was officially adopted as "CDM/JI Feasibility Study Programme" by Global Environment Center Foundation in 2005 and 2006. Taishi Design Office has been conducting a feasibility study for getting A/R CDM in operation and they forested 100 thousand trees in August 2004 as test-planting. In the Kenya project, a forestation of IFT is planned as a part of the project called "Use and conservation of indigenous fruit tree diversity for improved livelihoods in Eastern Africa" started from 2003 (CHIKAMAI *et al.*, 2004). An application of its forestation into A/R CDM has been under consideration. In this project, Bioversity International has conducted analysis and examination for use, consumption, conservation, management and promotion of IFT. The possible site is around Kilifi village in Coast State, which is located in a coastal southeast area of Kenya (39°50'5"E, 3°38'8"S). It has also vulnerability for the effect of sea level rise, and it is semi-arid area by going inland a little. Bioversity International has identified 125 kinds of IFT through the surveys in Coast State and disclosed the important 5 kinds of local IFT (*Adansonia digitata*, *Tamarindus indica*, *Dialium orientale*, *Ziziphus mauritiana*, *Landolphia kirkii*) for the local people on site. Both projects are aimed for biodiversity conservation (environmental conservation) and local empowerment, but remain in examination stage of making the projects in operation as A/R CDM projects. They have a financial barrier and it is difficult to make it BaU (Business as Usual). Therefore, they are going through the feasibility by raising profitability with the GHG credit income issued according to GHG removal.

THE PROGRESS OF DISCUSSION ABOUT ADAPTATION

The adaptation had been drawn attention especially among developing countries which were vulnerable to bad effects of climate change. At COP10 (2004, in Buenos Airies, Argentina), the adaptation became one of the main themes especially followed by the increase of interests of not only developing but also developed countries. The discussion about the adaptation made remarkable progress since then[1].

In COP10 (2004), "the Buenos Aires programme of work on adaptation and response measures" was adopted, and from COP12 and COP/MOP2 (2006, in Nairobi, Kenya), "Nairobi Work Programme on Impacts, Vulnerability and Adaptation to Climate Change" started. These programmes examined the adaptation measure, especially about methodology, data, modeling, vulnerability analysis, adaptation plan, measure and action, and set in Sustainable Development. At COP13 and COP/MOP3 (2007, in Bali, Indonesia), countries agreed the operation way of "the Adaptation Fund." The Adaptation Fund aims to finance activities such as the project for adaptation and work programme, and elaborated in COP7 (2001, in Marrakesh, Morocco). The Adaptation Fund is financed from the share of proceeds on the CDM and other source of funding.

For vulnerable countries to climate change, main focus of the climate policy is considered as the adaptation. For these developing countries, the adaptation policy is not only as a parecautional measure but also ways to level up for social basic own facilities for disaster precaution, water resources and agriculture (MIMURA, 2006). Then, they expect the investments from developed countries. In this context, many researchers argued the the need to mainstream adaptation into climate and development policy (KLEIN *et al.*, 2007; PRABHAKAR and SHAW, 2008; KIRSHEN *et al.*, 2008; THE RESEARCH COMMISSION ON THE EFFECT OF GLOBAL WARMING AND ADAPTATION, 2008).

The definition of vulnerability is "the degree to which systems are susceptible to, and unable to cope with, adverse impacts" (IPCC, 2007) and "the degree to which a socio-economic and environmental system is likely to experience harm due to exposure to a risk, hazard, or changing conditions, such as climate change" (KESKITALO, 2008). MIMURA (2006) defined the vulnerability as the sensitivity

Table 2 The outlines of Fiji and Kenya projects

Project Site	Nadroga State, Fiji	Coast State, Kenya
Participant	Taishi Design Office	Bioversity International
Project Style	Small-Scale / Environmental forestry typed	Small-Scale / Environmental forestry typed
Tree Species	Mangrove Tree	Indigenous Fruit Tree (IFT)
Main Object	Local Development and Environmental Conservation	Community-led Biodiversity Conservation

Source: Created by author referring to TAISHI DESIGN OFFICE (2006) and CHIKAMAI *et al.* (2004).

[1] The information about daily negotiation at COP was collected mainly from "Earth Negotiation Bulletin" (http://www.iisd.ca/ (accessed on October 8, 2011)) by International Institute for Sustainable Development.

to the external force of some systems and the capacity to translate, adjust to or utilize its effects, and represented as "The scale of external force / (the registance− the sensitivity)." As the scale of external force increase according to climate change, it is the adaptation policy to decrease vulnerability through enhancing registance (Carina and Keskitalo, 2008; Prabhakar and Shaw, 2008).

As above, the adaptation is paid more and more attention especially by developing countries with rapid progress of discussion. At the Third Assessment Report, IPCC (2001) stated the adaptation as complement to the mitigation, but at the Fourth Assessment Report, IPCC (2007) stated as "Adaptation and mitigation can complement each other and together can significantly reduce the risks of climate change." The adaptation is thought to be two wheels with the mitigation as more early and serious effects of climate change are to be expected than before (Wilbanks *et al*., 2003).

On the other hand, the discussion about the adaptation just started. There is no international agreed definition what is the adaptation to effects of climate change and what activities can be the adaptation measure and policy. The cost of adaptation could amount to at least 5 to 10% of GDP, but the knowledge and information about ability and cost is insufficient for each region and sector (IPCC, 2007; Prabhakar and Shaw, 2008). Any index or criteria to evaluate the adaptation measure and policy is not yet established. Harasawa *et al*. (2003) analyzed the characteristics of the adaptation measure and suggested that it depends on the progress of technology, institutional management, fund availability, information and social capacity whether the adaptation measure functions well or not.

The mitigation measure is effective all over the globe and it is independent of the project area. However, the effect of the adaptation measure and policy is just limited to the project area (JICA, 2007). This means the adaptation measure and policy should be implemented according to site specific circumstances and characteristics for its best effects (Adger *et al*., 2003; Klein *et al*., 2007). The adaptation measure and policy should be examined for each area and sector with latest knowledge and information. The approach of adaptation is such as technical action, improvement of legal systems and information, economic approach including insurance, and human resource development (The Research Commission on the Effect of Global Warming and Adaptation, 2008).

So far, researches of the adaptation of forest sector are still insufficient (Harasawa *et al*., 2003) and just limited to the transition of forest ecosystem (especially for natural forest) to high latitude according to temperature rise (The Research Commission on the Effect of Global Warming and Adaptation, 2008). However, response of forest to climate change is very uncertain (Carina and Keskitalo, 2008).

Some issues about the adaptation are: the unequal responsibility of bad effect of climate change and cost distribution for adaptation between developed and developing countries (Matsumoto, 2005). As one of these issues, many developing countries are concerned about the Adaptation Fund. At COP14 (2008), Tuvalu referred to the Adaptation Fund as the "survival fund" for AOSIS. Many countries agreed to the Adaptation Fund needed to become operational as soon as possible. The financial foundation of the Adaptation Fund depends on the share of proceeds from CDM, but it is not enough as the registered number and scale of CDM is shorter and smaller than expected (Muller, 2007). At COP13 and COP/MOP3, countries discussed to include the target of the share of proceeds from not only CDM but also from Joint Implementation and Emission Trading. Switzerland proposed to introduce the world common tax for the financial resources of the Adaptation Fund at COP12. This would be hot issue at international discussions hereafter.

THE LIMITATION OF A/R CDM AS THE MITIGATION POLICY UNDER THE PRESENT RULES

To show the limitation of A/R CDM under the present rule, firstly I focus on the regional balance of CDM. Total amount of registered CDM project is 3508 as of 8th Oct 2011 (see Fig. 1). More than 80% of registered projects are occupied by only 6 countries (China 1,613 projects, India 732, Brazil 196, Mexico 132, Malaysia 101, Viet Nam 78). On the contrary, AOSIS and Africa countries which are with high vulnerability and need urgent measures against climate change have very small CDM projects. For AOSIS, only 17 projects (0.48%) by 7 countries (Cyprus 8, Cuba 2, Fiji 2, Dominican Republic 2, Jamaica 1, Papua New Guinea 1, Guyana 1) are registered so far. For Africa, 76 projects (2.17%) by 18 countries (South Africa 20, Egypt 10, Morocco 6, Uruguay 6, Kenya 5, Nigeria 5, Uganda 5, Rwanda 3, Cote d'Ivoire 3, Cameroon 2, Democratic Republic of the Congo 2, Senegal 2, Tunisia 2, Tanzania 1, Ethiopia 1, Madagascar 1, Mauritania 1, Zambia 1) are registered. The regional unbalance as one of the problems of CDM is apparent from these data. Even in AOSIS (43 countries) and Africa (53 countries), the registered CDM projects concentrate on only a few countries such as South Africa. This is partly due to the insufficient institution for host countries (Pedersen, 2008; Ekoko, 2000).

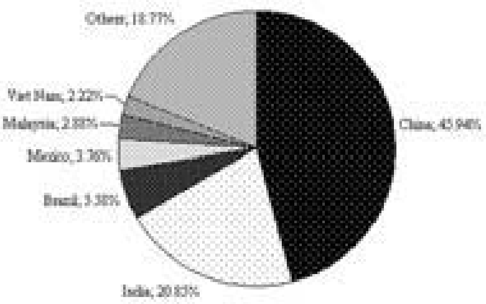

Fig. 1 The registered CDM projects by host countries
Source: Created by author referring to http://cdm.unfccc.int/Statistics (accessed on October 8, 2011)

Based on forest features such as non-permanency (forest will be distinguished and cannot keep CO_2 permanently), uncertainty (forests would not always grow as expected), and long-term (forest needs a long time to grow), the rules for A/R CDM, such as credits with term (tCER and lCER) and longer crediting period (UNFCCC, 2001; 2003; 2004; 2009), were determined at COP9 (2003) for normal scale and COP10 (2004) for small scale. The limit of small scale was set 16,000 t-CO_2 per year. As the A/R CDM projects are usually implemented at rural areas, small-scale projects need to be developed or implemented by low-income communities and individuals (UNFCCC, 2004).

Through interviews to stakeholders (especially to project participants) and reviews of BROWN *et al.* (2000), VAN VLIET *et al.* (2003), OLSCHEWSKI *et al.* (2005), GROEN *et al.* (2006), KIRBY and POTVIN (2007), MINANG *et al.* (2007), SKUTSCH *et al.* (2007), and FUKUSHIMA and NAKAJIMA (2008), FUKUSHIMA (2006; 2010) revealed advantages and disadvantages of A/R CDM as below;

<The advantages>

(A) A/R CDM is one of a few ways that host countries, especially local areas, can take part in Kyoto Protocol and aims to achieve both environmental conservation and local development.

(B) The requirements of A/R CDM can be useful indicators to improve forestation projects for two main project participants, private companies and Non Governmental Organizations (NGOs), as A/R CDM is environmentally, economically and socially conscious.

(C) A/R CDM can give market incentive to the carbon sequestration function of forest (so far, only timber (including non-timber forest products) production function has been given) and it can be a new forestry business.

<The disadvantages>

(1) complex rules
(2) unsellable credit
(3) low profitability
(4) insufficient support by the government
(5) difficulty participating in the local project
(6) long-term corporate risk
(7) unfavorable attitude to A/R CDM by many countries
(8) delay of international discussion compared with the emission CDM

While A/R CDM can be evaluated as an innovative mechanism in various points such as local development, A/R CDM has its limitation under the present rule with so many disadvantages as above.

FUKUSHIMA (2009) also analyzed the network of stakeholders, and revealed that the each stakeholder, especially project participant was isolated and the network among stakeholders was weak.

These limitations are also clear from the fact that registered project is still only 32 (0.91% of total registered CDM projects) even in 2011. This is also the limitation as a mitigation policy. In A/R CDM, the amount of GHG removal, that is the acquisition of GHG credit, is less and uncertain than that of the emission CDM, so that A/R CDM does not have so much incentive for project participants who regard the A/R CDM as a business tool.

Judging from the submitted projects and the result of interview survey for the stakeholders, there are two types of A/R CDM project styles: (A) industrial forestry typed and (B) environmental forestry typed, which are based on project scale and check for logging (see Table 3). In most cases, industrial forestry is accompanied by logging and it uses fast-growing trees like *Eucalyptus* and *Acacia* and exotic species as monoculture forestry to get materials (COSSALTER and PYE-SMITH, 2003). On the other hand, environmental forestry is not basically assumed to do logging and it uses indigenous species for the purpose of vegetation restoration and biodiversity conservation. Considering the cost of management or transportation, industrial forestry needs some large scale of the project because advantage of scale should be taken into account. And environmental forestry is small-scale from the standpoint of profitability in general.

In common, indigenous trees, which is often used for environmental forestry, are slow-growing than fast-growing trees used for industrial forestry. Indigenous trees have less amount of GHG removal, that is, less merit of GHG credit. Therefore, the feasibility of environmental forestry as A/R CDM is getting much lower. From the viewpoint of business, A/R CDM will be limited for industrial forestry typed and as far as it goes, it can be assumed that it is quite difficult to make the environmental forestry typed to be conducted as A/R CDM projects.

Table 3 A/R CDM project styles

		Project Scale	
		Large	Small
Logging	Yes	(A) Industrial forestry typed	-
	No	-	(B) Environmental forestry typed

POSSIBILITY OF ADAPTATION FOR A/R CDM PROJECTS

As stated above, A/R CDM projects by using environmental forestry have difficulty from business perspective. It has, however, various secondary effects aside from GHG reduction. This paper examines a variety of its functions as the adaptation measure by some case studies.

First, I show the multiple functions of forest. In FAO (2006; 2007) and KANNINEN *et al.* (2007), functions of forest are described as follows (see Table 4). And SCIENCE COUNCIL OF JAPAN (2001) measured its monetary value for each function (They evaluated the Japanese forest, not the world forest). On the assumption of A/R CDM, in the present market, the functions to be measured by monetary value are only (2) Global Environmental Conservation (Carbon Fix) and (8) Material Production (Timber Production). As stated before about the merits of A/R CDM, A/R CDM is an epoch-making mechanism in a particular point that the Carbon Fix function as well as Material Production function can be evaluated by monetary value as the GHG credit. On the other hand, it should be pointed out that many important functions like Biodiversity Conservation and Disaster Prevention have been underappreciated. The "underappreciated" functions will be examined here as an adaptation measure.

About the Fiji project, mangrove trees used to be logged to refine ore, especially limestone, and now have been destroyed to produce traditional dye stuff called TAPA. Ore smelting companies did not plant trees after logging and there was no custom to replant mangrove trees for the

Table 4 Multiple functions of forest and its monetary value

Functions of forest	Quantitative evaluation	Details of function	Monetary value (Billion Yen)
(1) Biodiversity conservation	Impossible	—	—
(2) Global environment conservation	Possible	Carbon fix	1,239
(3) Prevention of landslide disaster	Possible	Prevention of soil erosion	8,442
Soil conservation		Prevention of soil disruption	28,257
(4) Water increment	Possible	Flood alleviation	6,469
		Storage of water resource	8,741
		Clarification of water quality	14,636
(5) Creation of comfortable environment	Partly possible	—	—
(6) Health and recreation	Partly possible	—	—
(7) Culture	Impossible	—	—
(8) Material production	Possible	—	(Dependent on market)

Source: Created by author referring to FAO (2006; 2007), KANNINEN *et al.* (2007), and SCIENCE COUNCIL OF JAPAN (2001).

local people. As a result, the deforestation of mangrove has been deteriorating at the project site. WWF Fiji conducted a field survey in 2000 to recommend a prevention of overuse for the village, and the village set a logging prohibited area (THAMAN and NAIKATINI, 2003). Though Japanese NGO, OISCA implemented just one-time small-scale forestry project in 1996 for the purpose of environmental education mainly for primary school students (OISCA, 2008), there was no progress on OISCA's project. The test planting project by Taishi Design Office in 2004 was the first experience for most of the local people. The local people participated in collecting seeds and tree planting and Taishi Design Office donated money to the village as their wages.

According to and FAO (1994) and THAMAN and NAIKATINI (2003), mangrove is a generic name of halophyte in marine and brackish water, which is a kind of forests growing in tidal zone in the tropic and subtropics. Mangrove, in various senses, is a valuable ecosystem. On the other hand, it is very vulnerable to environmental changes and is said to be first to be damaged by climate change. It is very difficult to recover the ecosystem of mangrove once destroyed, so that there is high uncertainty on measuring success and failure of mangrove planting compared with a regular planting.

Mangrove tree is utilized in various ways as building materials, fuel, and medical use (WATLING, 1987; 1988). The ecosystem of mangrove becomes a habitat for many animals and plants to maintain and conserve biodiversity. It grows in a coastal environment and is highly evaluated in a specific function of bank protection as a breakwater. The Asahi News Paper (of 22nd December 2007) reported that mangrove worked quite well as a natural breakwater to relieve damages from Tsunami caused by Sumatra Earthquake in Indonesia in late 2004.

The results of field surveys about the expectation for mangrove planting project in September 2005 about the usefulness of mangrove trees in February 2008 for the local people in Lomawai village are as follows (see Tables 5 and 6): Though any incentives like direct income and local development are important for the locals, the survey results in 2005 showed that the locals well recognized the function of biodiversity conservation as "conservation for marine species (fish, crabs, shrimps, etc.)" and the function of bank protection as "a breakwater against high waves." The survey results in 2008 also showed that local people understood the various usefulness of mangrove trees. As explained above, it is significant to conserve and regrow mangrove trees, having these functions in the site, to be worried about destruction of marine ecosystem like corals and increase of high waves as a bad effect of climate change. Therefore, mangrove planting can be evaluated as a way of the adaptation measure judging from a bibliographical survey and a field survey.

Next about the Kenya project, most of the local people of the project site earn their living from agriculture and fishery. Though any other resource of income is limited to sales of charcoal, it is found that IFT is logged to make charcoal. IFT has been threatened to decrease the number. Any other its reasons are population increase, urbanization, expansion of farm land, changes of food consumption trend (increase of foreign fruits trees' consumption, decrease of IFT consumption), and decrease of local knowledge (for sustainable use of IFT) (MAUNDU, 1996; HABTE, 2004).

Based on the preceding studies by LEAKY and SIMON (1998), CHIKAMAI *et al.* (2004), SIMITU *et al.* (2005), JAMA *et al.* (2007), and AKINNIFESI *et al.* (2008), the significance of

Table 5 The expectation for mangrove plantation

Detail	Number
Conservation for marine species (fish, crabs, shrimps, etc.)	24 (53%)
Financial income	8 (18%)
Improvement of soil	7 (16%)
Environmental conservation, Prevention of climate change	4 (9%)
Village development	4 (9%)
GHG removal	3 (7%)
Breakwater against high waves	3 (7%)
Others	5 (11%)

Source: Created by author referring to Fukushima and Nakajima (2008) based on the survey result in September 2005.
Note: n = 45, free and multiple answers

Table 6 The usefulness of mangrove tree

Detail	Number
Conservation for marine species (fish, crabs, shrimps, etc.)	22 (73%)
Utilization as timber (fire wood, building material, etc.)	21 (70%)
Improvement of soil	7 (23%)
Breakwater against high waves	6 (20%)
Conservation for coastal area	3 (10%)
Collection of good salt	3 (10%)
Utilization as medicine	2 (7%)
GHG removal	1 (3%)

Note: n = 30, free and multiple answers

IFT is as follows; new income opportunities, diversity in production, market differentiation, extended season of fruit availability, reduced labour, satisfaction of rural household consumption needs, high nutritional benefit, reduced homogenisation of landscape, and conservation of tree genetic resources. Besides, they said that consumption, promotion and conservation of IFT can contribute for achievement of Millenium Development Goals such as "poverty reduction," "reduction of a lower infant mortality," and "protection of the spread of HIV/AIDS, malaria, and any other diseases." Bioversity International recognized the importance of IFT as above and started "Use and conservation of indigenous fruit tree diversity for improved livelihoods in Eastern Africa" project.

Bioversity International has identified 125 kinds of IFT in the research site in Coast State (Fond *et al*., 2006). It is clarified the fact as follows: about domestication, 71 kinds of IFT (56%) are completely wild, 34 kinds (28%) are completely domesticated, and 11 kinds (9%) are both wild and domesticated. About marketability, only 17kinds (14%) are sold in markets in city areas, and 40 kinds (32%) in local area. On the other hand, more than half, 69 kinds (55%) are only for local consumption. Most of the kinds, 115 kinds (92%) are used for any other ways of consumption for fuels, medical use, pesticides, ceremonies or cultus and spiritual usage.

As a result of a market survey in 2007, people have a difficulty in earning their lives only by sales of IFT, because IFT has a low productivity and a low marketability according to seasonality. This result shows that there is low incentive for the locals to regrow IFT with a low marketability, therefore, IFT has been logged and used for any other use like making charcoal and has not been regrown by planting (Fukushima *et al*., 2010).

From the field survey, two interesting customs about IFT consumption in Kilifi were revealed. One was that "children were the main consumers of IFT." This point can be regarded as a good custom to save overuse and achieve sustainable use of IFT. The other one was that "IFT was used in time of food-shortage by low-yielding of grains and fish catches regardless of ages," which means IFT has a function of nutritional source in time of food-shortage on the spot. That is a kind of "food security." There has been a worry of destruction of biodiversity and destabilization of food production as a bad effect of climate change in Africa, it can be said that the IFT with such a function has high importance.

Therefore, IFT planting has some functions to keep and conserve biodiversity in the local ecosystem threatened by loggings and to work as the adaptation measure of climate change because of the role of food security.

As stated above, it was examined that both forestation projects has functions not only as mitigation but also as adaptation. As these projects use indigenous trees, feasibility and suitability is very high because the local people have any relationship with indigenous trees in their ordinary life. And because there has been no custom of planting in both Fiji and Kenya, there is great significance to conserve and revive the ecosystem through introduction of the projects. Both projects has a great significance with secondary effects, but at present, the promotion of the projects as A/R CDM has difficulty in realization from the viewpoints of profitability and cost of applying as they both are small-scale forestry's project.

Of course, focused its function of protecting bank, it is undeniable that a mangrove planting has less functions than maintenance of seawall. And focused of its function of food supply, IFT planting has not worked better than crop plant and (foreign) fruit trees for food. The project evaluation of these projects must be lower only by focusing attention on the function of adaptation. However, as stated above, mangrove or IFT plantation should be evaluated in multiple ways. They should be regarded as something with not only the functions of mitigation and adaptation but also cultural and traditional values as IFT, the promotion of the projects as A/R CDM is desired strongly.

Takahashi (2006) said that adaptability is a potential ability of adjustment in order to cope well with climate change and variability by a certain system's changing characters and actions. Thus, it means an ability to plan and conduct an effective adaptation and respond to increasing risks and stresses to decrease the frequency and degree of harmful results from climate change. Mimura (2006) write up the predominant factor as follows (see Table 7).

On evaluating these two projects based on adaptability, planting increases the amount of local "resources" and the local people acquire "technique" necessary to planting. Through conducting projects, the locals develop "knowledge/recognition" that they understand the significance of forestry. As a result, the personal ability and the ability of the "community" are improved through making "social system" in

Table 7 Predominant factors of adaptability

Predominant factors	Contents
Resources	Amount of available resources such as funds and facilities
Knowledge / Recognition	Human ability including technique, experiences, education level etc.
Information management	Basic knowledge to notice the appearance of environmental changes /effects and understand the meanings
Technology	Accessibility to the information of effects and adaptation, personal or group ability to cope and interpret it
Social system	Availability of an adapted technique and accessibility to necessary technique information
Community	Community network to overcome bad effects jointly in a belonged social group
Risk management	System and ability to share and diversify risks among stakeholders

Source: Created by author referring to Mimura (2006)

good condition and the ability of "risk management" improves on site. From this aspect, it can be insisted that conducting projects can make the local adaptability improved. Enhancing local adaptability thorough appropriate adaptation is one of the keys to reduce vulnerability (Carina and Keskitalo, 2008; Prabhakar and Shaw, 2008).

DISCUSSION

As stated above, it was examined that environmental forestry typed A/R CDM has validity not only as mitigation but also as adaptation. Especially both projects selected as case studies use indigenous trees, and then they are expected as the projects to reflect the real local situation from the viewpoints of adaptability and feasibility. They have highly significance from the some viewpoint of theory, local needs, and the area balance of CDM which is focused on the specific part of the world. Especially, the adaptation measure has regionality and it is important point to have high adaptability to the locals. It can be considered that forestry project (A/R CDM projects) having a function of adaptation targets such trees with salt or drying resistance, or windbreak.

Though A/R CDM has limitations as mitigation, it can be expected to have various second effects of GHG reduction and a function as adaptation because it can be implemented in rural areas in developing countries and targets at a forest with multiple functions. It is "equity" and "human security" that should be noted here. As discussed previously, however significant the project might be, it is difficult to implement a project only from the viewpoint of CDM as the mitigation measure to be evaluated by CO_2 removal. To promote the project, it is necessary to revise the rules and any incentive for the project promotion in any way is expected to be introduced. At present, conceivable means are proposed as follows: conversion of credit prices through the introduction of a new basis of variation from the viewpoint of adaptation and project support through the Adaptation Fund. There is no consensus about the use of the Adaptation Fund so far and the specialists said there is possibility to support through the Adaptation Fund. In either case, as IPCC (2007), Takahashi (2006) and Mimura (2006) stated, the implementation of adaptation measure is proactive and more effective than reactive way on the aspect of costs. It is desirable to promote the projects like the mangrove planting in Fiji and the IFT planting in Kenya by taking action earlier like a proposal of giving any incentive.

In recent years, the Japanese Ministry of Environment has insisted the importance of cobenefits-typed combating global warming/CDM. Overseas Environmental Cooperation Center (2007) defines that cobenefits means "to educe two different profits simultaneously from one activity by being aware of both the needs to prevent a global warming and to develop the developing countries" and cobenefits-typed combating global warming means "an action to meet the needs of development as well as combating global warming." For the developing countries, there is a worry that development might be hindered by handling mitigation-centered climate policies. From the standpoint that more subjective and effective countermeasures can be promoted by implementing conducting climate policies with the viewpoint of satisfaction of the needs for development, cobenefits-typed climate policy was proposed. Likewise, JICA (2007) stated that developing countries, making economical development a matter of top priority, have difficulties in implementing measures of climate policies. Therefore, any ways with "second effects" are desirable like improvement of atmosphere and water quality, waste and recycling policy, and energy conservation. As proved above, AR/CDM focused on mangrove or IFT is just a cobenefits-typed. From this point of view, promotion of the projects agrees with these policies.

Recently, REDD (Reducing Emissions from Deforestation and Forest Degradation) in developing countries has been the focus of attention. This has the stance to prevent deforestation and forest degradation in developing countries by the introduction of any projects, programs, or measures. Through this action, host countries or stakeholders are provided incentives to GHG emissions reduction which is estimated by the historical background. REDD has its roots in COP11 and COP/MOP1 (2005), proposed by Papua New Guinea and Costa Rica (UNFCCC, 2005). In COP13 and COP/MOP3 (2007), it was addressed as one of major subjects.

STERN (2006) and IPCC (2007) noted that there are 5.8 billion tones of GHG emissions annually by deforestation in the world and preventing deforestation and forest degradation is urgent as climate policy. REDD has many characteristics similar to environmental forestry which is focused on this paper, because it is a policy to prevent the deforestation and forest degradation and vegetation on site (FUKUSHIMA, 2010). It is necessary to keep an ear to the ground about the proceedings with future negotiation on the types of projects. REDD, however, can be promoted on a large scale even though it is environmental forestry typed. REDD is highly expected to become a useful scheme with possibility doing a good job as the adaptation in a forest sector in the future.

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Article

Comparison of Regression Methods for Fitting Allometric Equations to Biomass of Mizunara Oak (*Quercus crispula*)

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ABSTRACT

This study examined the use of linear and non-linear regression techniques for estimating parameters of allometric equations for the biomass of mizunara oak (*Quercus crispula* Blume) trees growing in deciduous secondary forests that are dominated by the species. Four plots were sampled in secondary forests and 31 mizunara oak trees were sampled outside the experimental plots to measure biomass. Three typical allometric equations used for biomass estimation were fitted to the mass of each component and the sum of some components using three least-squares regression methods: non-linear regression without weighting observations, generalized non-linear regression assuming that the variance of each observation was expressed as a power function of the corresponding mean value, and linear regression after fitting a logarithmically transformed function to logarithms of the data. Errors in the predictions were compared among the three regression models. The fitted allometric equations were applied to tree census data from the experimental plots to examine variation in stand biomass estimates among the three regression methods. In terms of errors, generalized non-linear regression was slightly preferable to logarithmic linear regression and unweighted non-linear regression. Branch mass and foliage mass had different values of variance parameter (half of the exponent of the power function), even though both showed large variation around their regression lines. When the variance parameter was greater than 1.0, as occurred with branch mass, logarithmic linear regression was slightly better than generalized non-linear regression. When applying fitted allometric equations to other data, the three regression methods may produce only slightly different estimates of stem mass; however, estimates for branch mass and foliage mass may differ largely according to the regression method used.

Keywords: biomass, error variance, hardwood, regression model

INTRODUCTION

Estimation of allometric equation parameters is important for accurately estimating tree biomass and carbon stocks in forests. In many studies, power functions were not fitted directly to biomass data; instead, logarithmically transformed functions were fitted to logarithms of the data using linear regression (e.g. SAH *et al*., 2004; CHAVE *et al*., 2005; BASUKI *et al*., 2009). SPRUGEL (1983) mentioned two reasons for using this method: the logarithmic transformation simplifies the calculations required to fit power functions by using linear least-squares regression techniques, and in most cases the statistical validity of the analysis increases because the variance is equalized over the entire prediction range of the variables.

Statistical software facilitates the use of non-linear least-squares regression techniques. However, non-linear regression requires initial parameter values and does not guarantee that a solution to an equation will be found. As noted by SCHABENBERGER and PIERCE (2002), researchers tend to avoid non-linear regression because of the "messiness" of implementation [cited from ROBINSON and HAMANN (2011)]. When plotting tree size and tree biomass, the spread of points around the regression line is much greater with larger values than with small values (SPRUGEL, 1983). This heterogeneity in variance causes problems when applying non-linear regression to biomass data. To avoid this complication, HOSODA and IEHARA (2010) weighted each observation by the inverse of the variance of the variable when applying non-linear regression to aboveground biomass equations for coniferous species in Japan.

The objective of the present study was to examine the use of non-linear and linear regression methods for estimating parameters of allometric equations fitted to biomass values for tree components. The subject of this study was mizunara oak (*Quercus crispula* Blume) growing in deciduous secondary

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forests that are dominated by the species in the cool-temperate zone of Japan. Typical allometric equations that are used to estimate biomass were chosen and fitted to mass measurements for each tree component and for the sum of some components, using different regression methods. Errors in the predictions were compared among the regression methods. The fitted allometric equations were applied to tree census data from experimental plots and stand biomass values for tree components were estimated to examine differences in stand biomass estimates among the different regression methods.

STUDY SITE AND METHODOLOGY

Study Site

The study was conducted in the Niigata University Forest on Sado Island (hereafter called Sado Forest), located in the northern part of Sado Island (38°12′N; 138°26′E) at 250-970 m above sea level. According to data from a weather survey site established within Sado Forest, mean annual temperature is 8.9°C and mean annual precipitation is 1,312 mm. Sado Forest is located in Japan's cool-temperate zone. Experimental plots (plots 1 to 4) were established in a secondary forest that was dominated by mizunara oak in Compartment No. 1 of Sado Forest (Tatsuhara *et al*., 2002). The secondary forest showed variation in stand condition components, such as density, tree size, and species composition, and the experimental plots were established so that each plot had different stand conditions (Table 1). Diameter at breast height (DBH) was recorded for standing trees that had diameters of 5 cm or greater in each plot; measurements were taken in 1999, 2002, and 2004. Total height was measured for trees sampled in 1999 and 2002, and all of the trees within each plot were measured in 2004

Data Collection

Field investigation

After examining the distribution of tree diameters, five trees were sampled outside each plot to cover the entire range of diameter values. DBH measurements were arranged in ascending order, the values were categorized into five classes, and means were calculated for each class. In each group, a mizunara oak tree with a DBH value that was close to the group mean was chosen for measurement. Table 2 provides a summary of the sampled trees.

In 1999, the chosen mizunara oak trees were felled, leaving 0.3-m-high stumps. The trees were then measured to obtain their heights before felling. The trees were separated into stem, branches, and leaves, and their fresh weights were measured using spring balances according to each stratum, i.e. 0.3, 1.3, 3.3 m, and then every 2 m. If the last stratum was smaller than 3 m, it was cut at 1 m nearest the end. A disc was cut from the bottom of the stem in each stratum. Then, samples of the stem, branches, and leaves were taken from each stratum to estimate the mass of each sampled tree.

Saputro *et al.* (2003) collected belowground data as well as aboveground data from Plot 3 in 2002. In 2005, the same investigation was carried out in Plot 1 using the methods of Saputro *et al.* (2003) as follows. After the sample trees were felled, their root systems were excavated by hand. Then, the root systems were brought to the laboratory where they were washed to remove soil particles and exposed to the open air to dry. All of the soil was removed from the root plate using a high-pressure jet water stream and the stem was cut from the root plate at the root collar. For most sample trees, fresh weights for roots with diameters >5.0 cm were measured in the field without being washed because they were too heavy to move to the nearest road. Subsequently, the root mass was weighed according to the following diameter classes: < 0.2, 0.2-0.5, 0.5-2.0, 2.0-5.0, and >5.0 cm. Many roots were broken during excavation and remained in the soil. The diameters of broken root ends were measured outside the bark in two perpendicular directions. One sample tree had a rotten section in its coarse roots. Therefore, only aboveground data for this tree were used in the analyses and another tree was sampled in 2006. As a result, only aboveground data were sampled for

Table 1 Summary of experimental plots in 2004

Plot	1	2	3	4
Plot size (ha)	0.05	0.05	0.03	0.0225
Density (trees/ha)	1,260 (1,260)	2,040 (1,620)	2,567 (2,500)	3,556 (3,200)
Average DBH (cm)	16.6 (16.6)	15.5 (13.9)	12.7 (12.9)	11.6 (11.0)
Average height (m)	13.6 (13.6)	10.8 (10.5)	9.2 (9.4)	7.4 (7.4)
Basal area (m^2/ha)	31.0 (31.0)	47.6 (28.2)	36.4 (36.2)	46.2 (34.0)

Note: Values in parentheses indicate values for hardwood trees only.

Table 2 Summary of sample trees

Measured component	Plot	Age (years)	DBH (cm)	Height (m)	Number of sample trees
Aboveground only	1	37 – 71	6.5 – 22.6	5.2 – 15.4	6
	2	48 – 70	6.7 – 16.5	7.0 – 14.0	5
	3	51 – 69	7.5 – 16.8	6.6 – 14.2	5
	4	51 – 66	5.9 – 15.7	6.3 – 10.9	5
Whole tree	1	46 – 62	5.2 – 20.9	6.0 – 15.3	5
	3	49 – 70	5.9 – 16.2	6.6 – 13.8	5

six trees in Plot 1.

Sample measurement

The stems were analyzed by counting annual rings and measuring their diameters in stem cross sections taken from each stratum. Annual rings were measured from the centre to outside the bark at 1-year intervals across the radius in four directions that were perpendicular to each other. Stem volume was calculated from the measurement data.

Leaf samples were dried at 96°C for 48 hours. Stem and branch samples from different strata and roots from different diameter classes were dried to a constant weight at 105°C to determine conversion factors for fresh to dry weights.

The mass of missing roots was estimated following the method of SAPUTRO *et al.* (2003). The diameters of the broken ends were tallied and a regression equation was applied to correct for these root losses. To create the regression equation, the cross-sectional diameters and lengths of unbroken root ends were sampled and measured at each root branching or every 25 cm if the distance between branches exceeded 25 cm. Because the sample of unbroken roots was weighed completely, the biomass fraction was calculated using the ratio of root volume. Then, values were summed to each branching point to determine the proportion of lost roots. Finally, the regression equation for the cross-sectional diameter of unbroken root ends versus root mass was developed for each root diameter class (0.2-0.5 and 0.5-2.0 cm).

Data analysis

Allometric equations for the mass of each tree component, stem and branch mass, and aboveground biomass versus variables such as DBH (D) and total height (H) were developed from the sampled trees. The following common allometric equations were applied to the data:

$$y = a\,D^b, \tag{1}$$

$$y = a\,(D^2H)^b, \tag{2}$$

$$y = a\,D^b\,H^c, \tag{3}$$

where the dependent variable y represents the mass of each component, stem and branch mass, and aboveground biomass, and a, b and c are parameters. Equation (1) can be used when only DBH is measured; the equation fits root mass well (DREXHAGE and COLIN, 2001). Equation (2) has often been used by Japanese researchers to estimate tree biomass (e.g. RESEARCH GROUP OF THE FOUR UNIVERSITIES, 1960, SHIBUYA and MATSUDA, 1993; GOTO *et al*., 2003). Equation (3) is used as a volume equation and is referred to as the Yamamoto-Schumacher equation (YAMAMOTO, 1918; SCHUMACHER and HALL, 1933). HOSODA and IEHARA (2010) showed that Eq. (3) was the most suitable for determining the biomass of individual trees from plantations of three major coniferous species and all their aboveground components in Japan.

The parameters were estimated by :

(1) Fitting a function $y = f\,(x)$ to the data using non-linear regression with the assumption that all of the errors had the same variance (hereafter called unweighted non-linear regression),

$$y_i = f\,(x_i) + \varepsilon_i\,,\ \mathrm{var}(\varepsilon_i) = \sigma^2, \tag{4}$$

where x_i and y_i are the i-th observation of the independent and dependent variables, respectively, ε_i is the error corresponding to the i-th observation, and var(ε_i) is variance of ε_i,

(2) Fitting a function $y = f\,(x)$ to the data using non-linear regression with the assumption that the variance of each observation y_i was proportional to the 2θ-th power of the corresponding mean value $f\,(x_i)$ (RITZ and STREIBIG, 2008) (hereafter called generalized non-linear regression),

$$y_i = f\,(x_i) + \varepsilon_i\,,\ \mathrm{var}\,(\varepsilon_i) = \sigma^2\,[f\,(x_i)]^{2\theta}\,, \tag{5}$$

(3) Fitting a logarithmically transformed function to the logarithms of the data using linear regression and a natural logarithm with the assumption that the natural logarithms of all of the errors had the same variance (hereafter called logarithmic linear regression),

$$\ln\,(y_i) = \ln\,[f\,(x_i)] + \ln(\varepsilon_i),\ \mathrm{var}\,[\ln(\varepsilon_i)] = \sigma^2. \tag{6}$$

These regressions were carried out using (1) the function “nls” with the Gauss-Newton algorithm, (2) the function “gnls” in the package “nlme”, and (3) the function “lm”, respectively, in R version 2.13.0 (R DEVELOPMENT CORE TEAM, 2011). Variance parameter θ in the second regression method is estimated from data. It represents the degree of increase in variance according to the increase in the mean, and error variance is constant when $\theta = 0$. Generalized non-linear regression model (Eq. (5)) is transformed into regular non-linear regression model (Eq. (4)) and then function parameters and parameters, σ^2, and θ are estimated (RITZ and STREIBIG, 2008). The third regression method produces a systematic bias when the unbiased logarithmic estimates are converted back to arithmetic values, i.e. untransformed (FINNEY, 1941; BASKERVILLE, 1971). To eliminate this bias, the logarithmic estimates were multiplied by a correction factor (CF) when transforming them back into biomass values. The CF was calculated from the formula:

$$\mathrm{CF} = \exp\left[\frac{\sum_{i=1}^{n}(\log y_i - \log \hat{y}_i)^2}{2(n - p)}\right], \tag{7}$$

where n is the number of data, p is the number of parameters in the equation, log y_i is the observed value of the dependent variable, and log $\hat{y}_i$ is the value predicted from the regression equation (SPRUGEL, 1983). The CF calculated by Eq. (7) was shown to be an adequate approximation of the CF that FINNEY (1941) derived (FLEWELLING and PIENAAR, 1981). To compare the errors of the equations, root mean-square error (RMSE) and bias values were calculated from the applied data, as is shown in Eqs. (8) and (9):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}}\,, \tag{8}$$

$$\mathrm{bias} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n}\ . \tag{9}$$

The percentages of both values were calculated and divided by the averages of the observations. Akaike’s information criterion (AIC) was also calculated to compare the fitness of the first two regression methods, as follows:

$$\mathrm{AIC} = -\,2logLik + 2k, \tag{10}$$

where $logLik$ is the log-likelihood value of the regression model and k is the number of parameters in the model. The log-likelihood function for unweighted non-linear regression is

$$logLik = -\frac{n}{2}\left[\ln\left(2\pi\frac{n-p}{n}s^2\right)+1\right], \quad (11)$$

where s is residual standard error. The log-likelihood function for generalized non-linear regression is

$$logLik = -\frac{1}{2}\left\{n\left[\ln\left(2\pi\frac{n-p}{n}s^2\right)+1\right]+\sum_{i=1}^{n}\ln\left|f(x_i)^{2\theta}\right|\right\}, \quad (12)$$

where s corresponds to σ in Eq. (5) (Ritz and Streibig, 2008).

Additionally, stem and branch mass and aboveground biomass were estimated by summing the masses of the components. To compare the errors of the estimates with those from direct relationship equations for the case of best-fit allometric equation in the three, the RMSE was calculated from the applied data.

Finally, the fitted allometric equations were applied to tree census data from Plots 1 to 4 to estimate the stand biomass in each plot. Maximum and minimum estimated stand biomass values were calculated among cases in which the same allometric equation was applied. The percentage of the difference between the maximum and minimum to the average was calculated to compare the three regression methods.

RESULTS

The scatter diagrams for the masses of each component against D^2H on log-log scales showed that branch mass and foliage mass had larger scatter around their regression lines than did stem mass and root mass (Fig. 1). Branch mass had more scatter around the regression line for smaller and larger trees than for mid-sized trees. Foliage mass had less scatter around the regression line as tree size increased. Stem and branch mass and aboveground biomass had similar tendencies to stem biomass.

The estimated parameters for the allometric equations, residual standard error s, CF, and variance parameter θ are shown in Table 3, and RMSE, bias, and AIC values are shown in Table 4. All of the model scenarios were carried out, except the fitting of Eq. (3) to branch mass using unweighted non-linear regression with the assumption of variance homogeneity. In this case, the parameters of Eq. (3) could not be obtained using non-linear regression within 50 iterations. For root mass, one sample tree was omitted from the analysis because the tree's root mass was unusually large for its DBH and height, and it was therefore considered to be an outlier.

Comparing RMSE values among the three methods, the unweighted non-linear regression had the lowest RMSE for all of the allometric equations and all of the dependent variables. Generalized non-linear regression had the second smallest RMSE for all of the components' mass, except branch mass, for which the logarithmic linear regression had the second smallest RMSE value. For branch mass, which had the largest θ value, around 1, the logarithmic linear regression had a smaller RMSE value than did the generalized non-linear regression. For the other dependent variables, which had θ values that were smaller than 1, generalized non-linear regression produced smaller RMSE values than did logarithmic linear regression, except the fitting of Eq. (1) to stem and branch mass and aboveground biomass. Generalized non-linear regression had better precision with decreasing θ compared to logarithmic linear regression. Especially for root mass, which had a smaller θ value that was relatively close to 0, generalized non-linear regression resulted in a clearly smaller RMSE compared to logarithmic linear regression. When comparing AIC values between the two non-linear regression methods, generalized non-linear regression yielded smaller AIC values than unweighted non-linear regression for all dependent variables, except root mass. For root mass, unweighted non-linear regression yielded smaller AIC values in the cases of Eqs. (1) and (3).

Stem mass had the smallest relative RMSE value among the five dependent variables, except for root mass, followed by stem and branch mass, aboveground biomass, foliage mass, and branch mass. Stem mass, stem and branch mass, and aboveground biomass had relative RMSE values of 13 to 16%, and the value for foliage mass was 35%. Branch mass had a relative RMSE of 130%. Root mass had relative RMSE values of 7 to 9%, except in one case with nine sample trees, although it was about 20% for ten trees.

Relative bias was less than 5% for stem mass, stem and branch mass, aboveground biomass, and root mass. Branch mass had large relative bias when using generalized non-linear regression and logarithmic linear regression, and foliage biomass had a relative bias of about 5% when using logarithmic linear regression. Excluding branch mass, the two non-linear regression methods had slightly lower bias than did logarithmic linear regression. For branch mass, which had a large θ value near 1, logarithmic linear regression had lower bias than generalized non-linear regression. For the other dependent variables, which had θ values smaller than 1, generalized non-linear regression produced lower bias than did logarithmic linear regression. For root mass and foliage mass, which had relatively small θ values, generalized non-linear regression had almost no bias. The relationships between the dependent variables and their residuals showed that larger trees had larger residuals (Fig. 2). For branch mass, the largest tree had the largest absolute bias value (Fig. 2). Comparing the relationships between the dependent variables and their residuals among the three regression methods, the three methods had slightly different bias tendencies for larger trees.

For stem and branch mass and aboveground biomass, the RMSE and bias of Eq. (2) were calculated for predictions made using direct allometric equations and for predictions created by summing the masses of the components with each allometric equation (Table 5). The direct estimation method had slightly smaller RMSE values than those of the summation method in all cases. The direct estimation method produced slightly smaller bias than did the summation method in half of the cases and slightly larger bias in the remaining cases.

Table 6 shows stand biomass estimates created by applying the fitted allometric equations to the four experimental plots. Differences in the total biomass estimates among the regression methods were less than 7% (Table 7). Stem mass had the smallest difference (less than 5%), followed by total biomass, root mass, foliage mass, and branch mass. For Eqs. (1) and (3), Plot 1 had the smallest differences for estimates of total biomass, followed by Plots 2, 3, and 4. For

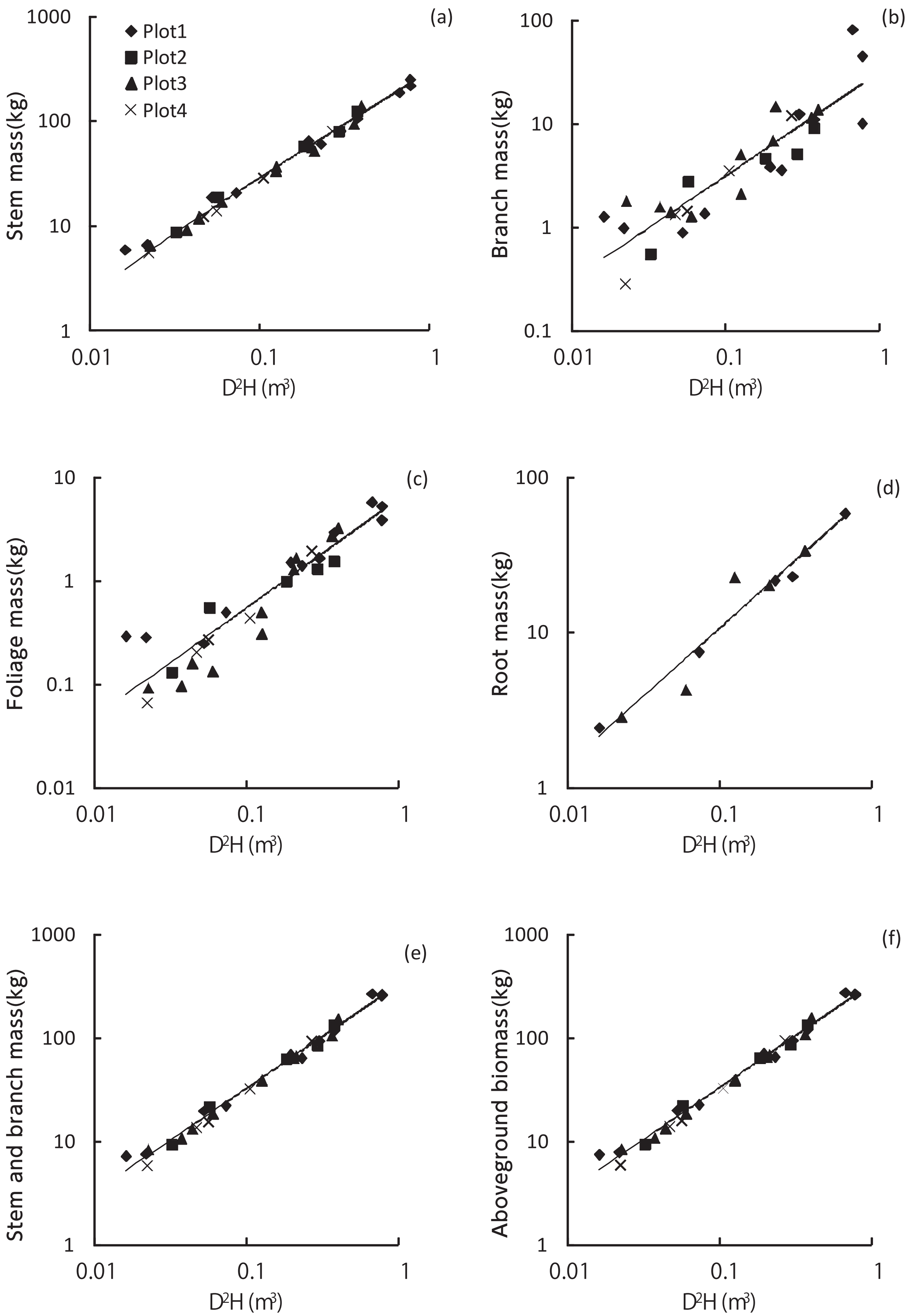

Fig. 1 Scatter plots of (a) stem mass, (b) branch mass, (c) foliage mass, (d) root mass, (f) stem and branch mass, and (e) aboveground biomass against D^2H

Table 3 Estimated parameters for allometric equations

Dependent variable	Equation	Regression method	*a*	*b*	*c*	*s*	*θ*	CF
Stem	Eq. (1)	UN	0.07745	2.574	–	9.306	–	–
		GN	0.04931	2.734	–	0.318	0.791	–
		LL	0.04642	2.754	–	0.155	–	1.013
	Eq. (2)	UN	0.02448	1.022	–	8.026	–	–
		GN	0.02727	1.008	–	0.186	0.865	–
		LL	0.02780	1.005	–	0.113	–	1.007
	Eq. (3)	UN	0.02687	2.085	0.940	8.158	–	–
		GN	0.02808	2.061	0.947	0.194	0.857	–
		LL	0.02798	2.020	0.990	0.115	–	1.007
Branch	Eq. (1)	UN	0.00138	3.321	–	11.086	–	–
		GN	0.00586	2.754	–	0.619	1.047	–
		LL	0.00453	2.796	–	0.556	–	1.181
	Eq. (2)	UN	0.00019	1.379	–	10.954	–	–
		GN	0.00477	0.961	–	0.526	1.152	–
		LL	0.00293	1.008	–	0.575	–	1.195
	Eq. (3)	UN	–	–	–	0.000	–	–
		GN	0.00591	2.776	–0.027	0.632	1.045	–
		LL	0.00565	3.116	–0.432	0.564	–	1.179
Foliage	Eq. (1)	UN	0.00154	2.612	–	0.473	–	–
		GN	0.00072	2.876	–	0.342	0.569	–
		LL	0.00057	2.940	–	0.452	–	1.116
	Eq. (2)	UN	0.00046	1.042	–	0.462	–	–
		GN	0.00033	1.081	–	0.348	0.528	–
		LL	0.00035	1.061	–	0.474	–	1.128
	Eq. (3)	UN	0.00052	2.140	0.931	0.470	–	–
		GN	0.00059	2.693	0.278	0.347	0.558	–
		LL	0.00066	3.171	–0.311	0.459	–	1.115
Root	Eq. (1)	UN	0.03305	2.464	–	1.564	–	–
		GN	0.03153	2.480	–	0.638	0.334	–
		LL	0.03951	2.389	–	0.179	–	1.004
	Eq. (2)	UN	0.01048	0.980	–	1.870	–	–
		GN	0.01296	0.954	–	0.642	0.389	–
		LL	0.01066	1.455	–	0.191	–	1.005
	Eq. (3)	UN	0.03528	2.493	–0.056	1.688	–	–
		GN	0.03235	2.495	–0.026	0.687	0.335	–
		LL	0.04792	2.598	–0.296	0.193	–	1.004
Stem and branch	Eq. (1)	UN	0.06676	2.675	–	11.481	–	–
		GN	0.04993	2.776	–	0.361	0.751	–
		LL	0.05044	2.768	–	0.153	–	1.013
	Eq. (2)	UN	0.01897	1.069	–	9.651	–	–
		GN	0.02724	1.024	–	0.262	0.789	–
		LL	0.03034	1.009	–	0.122	–	1.008
	Eq. (3)	UN	0.01776	2.111	1.124	9.818	–	–
		GN	0.03068	2.224	0.789	0.283	0.768	–
		LL	0.03230	2.123	0.872	0.124	–	1.008
Aboveground	Eq. (1)	UN	0.06829	2.674	–	11.754	–	–
		GN	0.05061	2.778	–	0.375	0.743	–
		LL	0.05130	2.769	–	0.154	–	1.013
	Eq. (2)	UN	0.01943	1.069	–	9.910	–	–
		GN	0.02728	1.027	–	0.291	0.767	–
		LL	0.03090	1.009	–	0.126	–	1.009
	Eq. (3)	UN	0.01826	2.112	1.120	10.081	–	–
		GN	0.03122	2.242	0.770	0.309	0.750	–
		LL	0.03321	2.139	0.851	0.127	–	1.008

Note: UN, unweighted non-linear regression; GN, generalized non-linear regression; LL, logarithmic linear regression.

Table 4 Error evaluations for allometric equations

Dependent variable	Equation	Regression method	DF	RMSE	(%)	Bias	(%)	AIC	*k*
Stem	Eq. (1)	UN	29	9.00	14.7	−0.697	−1.1	230.21	3
		GN	29	9.69	15.8	−0.232	−0.4	197.64	4
		LL	29	10.07	16.4	−0.716	−1.2	–	–
	Eq. (2)	UN	29	7.76	12.7	0.033	0.1	221.03	3
		GN	29	7.83	12.8	0.201	0.3	180.01	4
		LL	29	7.87	12.8	0.316	0.5	–	–
	Eq. (3)	UN	28	7.75	12.6	−0.033	−0.1	222.96	4
		GN	28	7.78	12.7	0.160	0.3	182.01	5
		LL	28	7.86	12.8	0.302	0.5	–	–
Branch	Eq. (1)	UN	29	10.72	121.8	−0.167	−1.9	241.06	3
		GN	29	11.27	128.0	1.059	12.0	160.25	4
		LL	29	11.16	126.7	0.864	9.8	–	–
	Eq. (2)	UN	29	10.60	120.3	0.041	0.5	240.32	3
		GN	29	11.72	133.1	1.494	17.0	159.52	4
		LL	29	11.35	128.9	0.958	10.9	–	–
	Eq. (3)	UN	–	–	–	–	–	–	–
		GN	28	11.26	127.9	1.050	11.9	162.29	5
		LL	28	11.12	126.3	0.816	9.3	–	–
Foliage	Eq. (1)	UN	29	0.46	34.3	−0.037	−2.7	45.49	3
		GN	29	0.47	35.4	0.000	0.0	15.95	4
		LL	29	0.51	38.0	−0.068	−5.1	–	–
	Eq. (2)	UN	29	0.45	33.5	−0.018	−1.3	44.00	3
		GN	29	0.45	33.6	0.000	0.0	17.09	4
		LL	29	0.45	33.8	−0.048	−3.6	–	–
	Eq. (3)	UN	28	0.45	33.4	−0.020	−1.5	45.98	4
		GN	28	0.46	34.7	0.000	0.0	17.71	5
		LL	28	0.53	40.1	−0.075	−5.6	–	–
Root	Eq. (1)	UN	7	1.38	7.1	−0.035	−0.2	37.33	3
		GN	7	1.38	7.1	0.003	0.0	37.96	4
		LL	7	1.66	8.5	0.379	2.0	–	–
	Eq. (2)	UN	7	1.65	8.5	0.123	0.6	40.55	3
		GN	7	1.68	8.7	0.013	0.1	40.33	4
		LL	7	2.97	15.3	0.608	3.1	–	–
	Eq. (3)	UN	6	1.38	7.1	−0.043	−0.2	39.32	4
		GN	6	1.38	7.1	0.002	0.0	39.96	5
		LL	6	1.52	7.9	0.317	1.6	–	–
Stem and branch	Eq. (1)	UN	29	11.10	15.8	−0.710	−1.0	243.23	3
		GN	29	11.35	16.2	−0.025	0.0	201.84	4
		LL	29	11.31	16.1	−0.059	−0.1	–	–
	Eq. (2)	UN	29	9.33	13.3	0.253	0.4	232.47	3
		GN	29	9.86	14.1	0.400	0.6	190.39	4
		LL	29	10.57	15.1	1.092	1.6	–	–
	Eq. (3)	UN	28	9.33	13.3	0.309	0.4	234.44	4
		GN	28	9.63	13.7	0.256	0.4	191.30	5
		LL	28	10.21	14.6	0.949	1.4	–	–
Aboveground	Eq. (1)	UN	29	11.37	15.9	−0.748	−1.0	244.69	3
		GN	29	11.63	16.3	−0.026	0.0	203.22	4
		LL	29	11.58	16.2	−0.043	−0.1	–	–
	Eq. (2)	UN	29	9.58	13.4	0.234	0.3	234.10	3
		GN	29	10.05	14.1	0.351	0.5	192.76	4
		LL	29	10.83	15.2	1.125	1.6	–	–
	Eq. (3)	UN	28	9.58	13.4	0.287	0.4	236.08	4
		GN	28	9.86	13.8	0.220	0.3	193.47	5
		LL	28	10.43	14.6	0.957	1.3	–	–

Note: DF, degrees of freedom; UN, unweighted non-linear regression; GN, generalized non-linear regression; LL, logarithmic linear regression.

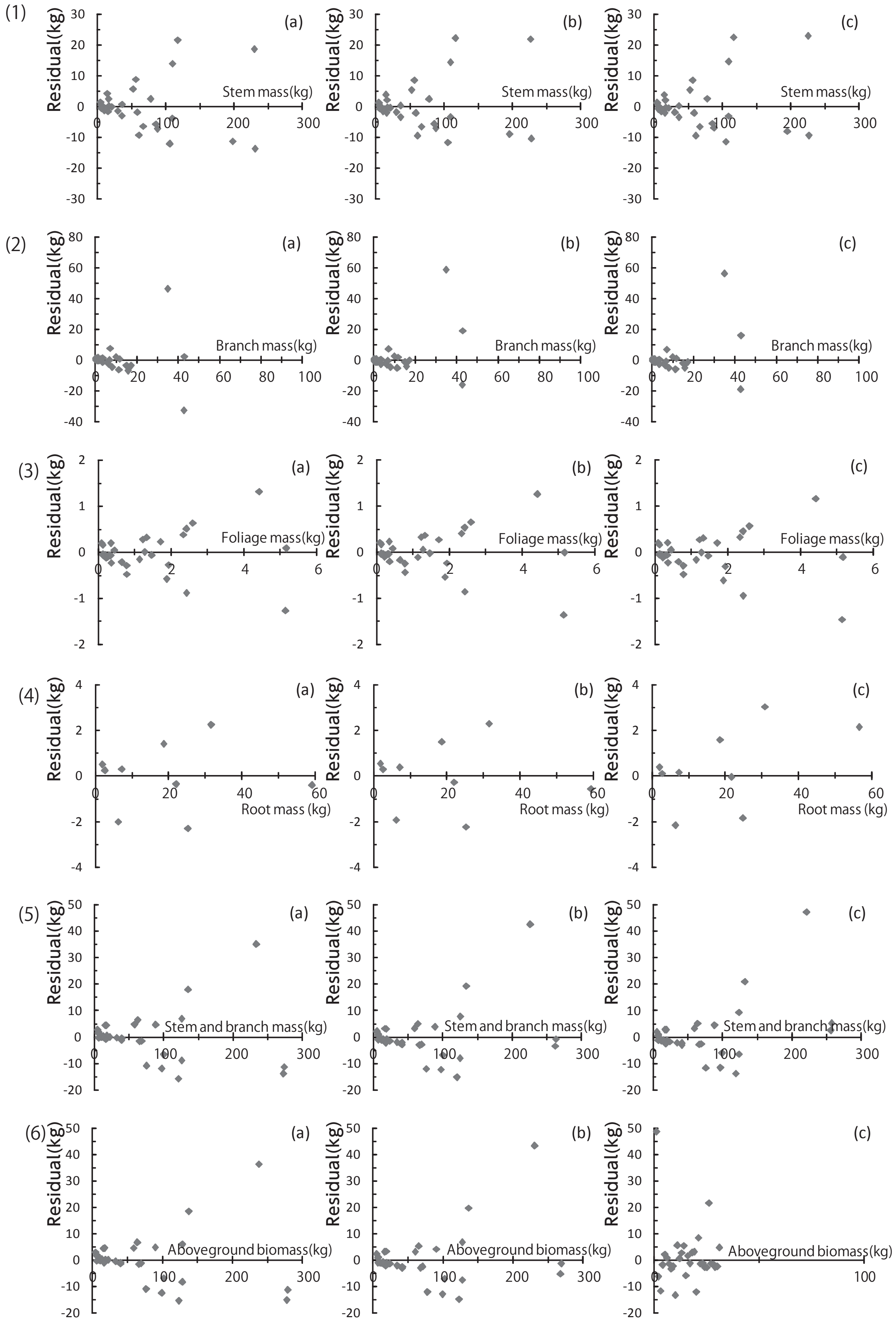

Fig. 2 Scatter plots of residuals against predictions when applying allometric equations to (1) stem mass, (2) branch mass, (3) foliage mass, (4) root mass, (5) stem and branch mass, and (6) aboveground mass with (a) unweighted non-linear regression, (b) generalized non-linear regression, and (c) logarithmic linear regression. Eq. (1) was applied to root mass and Eq. (2) was applied to other dependent variables.

Table 5 Comparison of errors when estimating stem and branch mass and aboveground biomass

Dependent variable	Equation	Regression method	Sum of component biomasses				Direct allometric equation			
			RMSE	(%)	Bias	(%)	RMSE	(%)	Bias	(%)
Stem and branch	Eq. (2)	UN	9.35	13.32	0.074	0.11	9.33	13.30	0.253	0.36
		GN	11.10	15.82	1.695	2.41	9.86	14.05	0.400	0.57
		LL	10.79	15.37	1.273	1.81	10.57	15.06	1.092	1.56
Aboveground	Eq. (2)	UN	9.60	13.42	0.056	0.08	9.58	13.40	0.234	0.33
		GN	11.30	15.80	1.695	2.37	10.05	14.05	0.351	0.49
		LL	10.98	15.35	1.226	1.71	10.83	15.15	1.125	1.57

Note: UN, unweighted non-linear regression; GN, generalized non-linear regression; LL, logarithmic linear regression

Table 6 Stand biomass estimates from fitted equations for experimental plots

Plot	Equation	Regression	Estimated stand biomass (t/ha)								
			Stem	Branch	Foliage	Root	Total*	Stem and branch	Total**	Above-ground	Total***
1	Eq. (1)	UN	172.3	30.5	3.8	52.7	259.4	202.5	259.0	206.3	259.0
		GN	178.8	22.6	4.0	52.8	258.3	206.2	263.1	210.2	263.0
		LL	181.2	23.5	4.3	50.8	259.8	205.9	261.0	209.8	260.5
	Eq. (2)	UN	178.7	32.5	4.0	52.9	268.0	210.5	267.4	214.5	267.4
		GN	176.5	20.4	4.1	52.2	253.1	203.6	259.9	208.0	260.2
		LL	175.7	22.6	4.1	48.0	250.5	199.4	251.6	203.3	251.3
	Eq. (3)	UN	178.1	–	4.0	52.7	257.4	211.0	267.6	214.9	267.6
		GN	176.7	22.7	4.0	52.8	256.2	204.6	261.4	208.8	261.7
		LL	175.8	23.8	4.4	51.7	255.7	200.3	256.3	204.1	255.8
2	Eq. (1)	UN	144.9	23.4	3.2	45.0	216.6	167.9	216.1	171.1	216.1
		GN	147.1	18.6	3.3	45.0	214.0	168.7	217.0	172.0	217.0
		LL	148.7	19.1	3.5	43.8	215.2	168.7	215.9	171.8	215.6
	Eq. (2)	UN	126.1	19.2	2.8	38.2	186.2	144.8	185.8	147.6	185.8
		GN	125.4	14.9	2.8	38.2	181.3	143.5	184.5	146.4	184.6
		LL	125.2	16.1	2.9	34.2	178.3	141.7	178.8	144.4	178.7
	Eq. (3)	UN	127.4	–	2.8	45.4	194.4	143.8	192.0	146.6	192.1
		GN	126.6	18.7	3.1	45.2	193.6	148.8	197.2	152.3	197.5
		LL	125.4	20.8	3.7	46.6	196.5	144.9	195.2	148.1	194.7
3	Eq. (1)	UN	102.6	14.7	2.3	32.4	151.9	117.0	151.7	119.3	151.7
		GN	101.7	12.8	2.2	32.3	148.9	115.8	150.3	118.0	150.3
		LL	102.4	13.1	2.3	31.9	149.7	115.9	150.1	118.1	149.9
	Eq. (2)	UN	81.8	10.4	1.8	25.2	119.2	91.9	119.0	93.7	119.0
		GN	81.9	9.9	1.7	25.6	119.1	93.0	120.3	94.8	120.3
		LL	81.8	10.5	1.8	22.9	117.1	92.5	117.2	94.3	117.2
	Eq. (3)	UN	83.3	–	1.8	32.8	130.8	90.8	125.5	92.7	125.5
		GN	82.9	12.9	2.1	32.5	130.4	97.6	132.2	99.9	132.4
		LL	82.1	14.5	2.5	34.5	133.6	95.2	132.2	97.4	131.9
4	Eq. (1)	UN	66.6	8.6	1.5	21.3	98.0	74.9	97.7	76.4	97.7
		GN	64.6	8.1	1.4	21.2	95.3	73.1	95.7	74.5	95.7
		LL	64.9	8.2	1.4	21.2	95.8	73.3	95.9	74.6	95.8
	Eq. (2)	UN	45.7	4.9	1.0	14.4	66.0	50.2	65.6	51.2	65.6
		GN	46.1	5.7	1.0	14.8	67.5	51.9	67.6	52.8	67.6
		LL	46.1	5.9	1.0	13.0	66.0	52.0	66.0	53.0	66.0
	Eq. (3)	UN	47.1	–	1.0	21.8	78.1	49.2	72.0	50.2	72.0
		GN	47.0	8.2	1.2	21.5	77.8	56.0	78.7	57.4	78.9
		LL	46.3	9.6	1.6	23.8	81.3	54.4	79.8	55.8	79.6

Note: UN, unweighted non-linear regression; GN, generalized non-linear regression; LL, logarithmic linear regression.
* Estimates of total biomass were calculated by summing stem mass, branch mass, foliage mass, and root mass. Estimates of branch mass calculated from Eq. (3) using GN were used to calculate the estimates of total biomass from Eq. (3) using UN because Eq. (3) could not be fitted to branch biomass using UN.
** Estimates of total biomass were calculated by summing stem and branch mass, foliage mass, and root mass.
*** Estimates of total biomass were calculated by summing aboveground biomass and root mass.

Table 7 Differences among stand biomass estimates from fitted equations applied to experimental plots

Plot	Equaiton	Difference among regression methods (%)								
		Stem	Branch	Foliage	Root	Total*	Stem and branch	Total**	Above-ground	Total***
1	Eq. (1)	5.0	29.8	11.3	3.9	0.6	1.8	1.6	1.9	1.6
	Eq. (2)	1.7	45.7	3.5	9.6	6.7	5.4	6.1	5.4	6.2
	Eq. (3)	1.3	4.9	9.1	2.2	0.7	5.2	4.3	5.2	4.5
2	Eq. (1)	2.6	23.2	7.0	2.6	1.2	0.5	0.5	0.5	0.6
	Eq. (2)	0.7	25.1	3.2	11.1	4.3	2.2	3.8	2.2	3.9
	Eq. (3)	1.6	10.6	25.7	3.1	1.5	3.5	2.6	3.8	2.8
3	Eq. (1)	0.9	13.9	4.8	1.5	2.0	1.1	1.1	1.1	1.2
	Eq. (2)	0.1	5.8	4.1	10.9	1.8	1.1	2.6	1.1	2.7
	Eq. (3)	1.4	12.0	30.1	5.9	2.4	7.2	5.2	7.5	5.4
4	Eq. (1)	3.1	6.4	6.5	0.5	2.8	2.4	2.1	2.5	2.1
	Eq. (2)	0.9	18.0	5.0	12.6	2.2	3.5	3.0	3.4	3.0
	Eq. (3)	1.7	15.9	42.4	10.3	4.3	13.0	10.2	13.4	9.9

Note: * Estimates of total biomass were calculated by summing stem mass, branch mass, foliage mass, and root mass. Estimates of branch mass calculated from Eq. (3) using GN were used to calculate the estimates of total biomass from Eq. (3) using UN because Eq. (3) could not be fitted to branch biomass using UN.
** Estimates of total biomass were calculated by summing stem and branch mass, foliage mass, and root mass.
*** Estimates of total biomass were calculated by summing aboveground biomass and root mass.

Eq. (2), Plot 3 had the smallest differences in estimates of total biomass, followed by Plots 4, 2, and 1. No clear tendency was found in the relationships between the differences in the estimates of each biomass component and the plots. Stem and branch mass and aboveground biomass had smaller differences than branch mass and foliage mass, although the difference was slightly larger than for stem mass. The difference in total stand biomass showed almost no change when estimates created from equations for tree components were replaced with estimates from stem and branch mass equations or aboveground biomass equations.

DISCUSSION

Generalized non-linear regression was the best of the three examined regression methods for all three allometric equations from analyses of RMSE, bias, and AIC. It is theoretically true that unweighted non-linear regression had the lowest RMSE because this method did not weight the data for fitting equations and the errors were evaluated for all of the data without any weights. Because the biomass data showed heterogeneity of variance (Figs. 1 and 2), generalized non-linear regression or logarithmic linear regression would be preferable to unweighted non-linear regression. Generalized non-linear regression was better than logarithmic linear regression in terms of both RMSE and bias when the variances showed relatively little heterogeneity, as occurred with all of the dependent variables except branch mass, and the difference between the estimates became smaller as heterogeneity of the variance increased. This finding is consistent with the results for stem mass in sugi (*Cryptomeria japonica* D. Don; Hosoda and Iehara, 2007). Logarithmic linear regression was better than generalized non-linear regression when the error variance increased more rapidly with the increase in tree size, or when the variance parameter was larger than 1.0, as with branch mass, when the assumptions of logarithmic linear regression are more suitable for the error variance.

Baskerville (1971) described a method for selecting a regression model when the variance of the dependent variable is not constant across the range of independent variables: If the variance of the logarithm of a dependent variable over the independent variables is horizontal with random deviation, it is reasonable to assume the model in Eq. (6); If both the arithmetic and logarithmic variances of the dependent variable are not constant, it is necessary to weight each observation of the dependent variable by the inverse of the variance of the observation and then fit the equation using the weighted logarithms. Also, when applying a non-linear regression model, if the variance of the dependent variable is not constant, the same method needs to be applied. It is possible to calculate the variance of each class of the dependent variable and to apply the weighting method when the number of data is large. However, it is difficult to calculate the variance of the dependent variable from observations when the number of data is small, as in this paper. In such a case, the model of Eq. (5) can be applied to non-linear regression.

Branch mass and foliage mass showed larger variation around their regression lines than did stem mass (Fig. 1). Equation (3) could not be fitted to branch mass in this study. Branch mass had the largest bias because the largest tree sampled had a considerably larger branch mass. Stem mass can be estimated from DBH and tree height with great accuracy (Kira and Shidei, 1967). In contrast, branch mass and foliage mass can be estimated from DBH and height, but the accuracy is lower than with stem mass because the parameters of their allometric relationships differ among stands (Ogawa *et al.,* 1965; Tadaki, 1966; Kira and Shidei, 1967). Moreover, in comparison to conifers, mizunara oak have larger variation in tree form and in the number of large branches. As tree size increases, the number of large branches tends to increase and its variation also tends to increase. Some large trees are forked and their stems are difficult to identify. Therefore the error variance of branch mass is proportional to the square of its mean value. Conversely, OGAWA *et al.* (1965) found that foliage mass tends to approach a certain asymptotic value as tree size increases and the following equation is preferable for estimating foliage mass:

$$\frac{1}{w_L}=\frac{\alpha}{w_S}+\beta, \tag{13}$$

where w_L is foliage mass, w_S is stem mass, and α and β are parameters. The error variance of foliage mass was therefore much smaller than that of branch mass; it was even smaller than the error variance of stem mass and was proportional to its mean value.

Differences in the estimates of stand stem mass among the regression methods were less than 5%, but some of the differences in the estimates of branch mass and foliage mass were large. Although the difference in fit among the regression methods was not large, estimates of branch mass and foliage mass varied among the regression methods. Differences in stand estimates were caused by differences in parameter values and in the tree size distributions among stands. The differences in parameter values led to differences in the relationships between tree size and biomass estimates. For instance, one regression method produced larger estimates than another for small trees and smaller estimates for larger trees. The differences in the parameter values among the regression methods were caused by weighting the data when fitting the allometric equation. The weights of larger trees were greatest with unweighted non-linear regression, followed by generalized non-linear regression, and then logarithmic linear regression. More variation was found in observations for large trees than in those for small trees. However, when applying a fitted equation to other data to estimate stand biomass, the fit of the equation with larger trees affected the estimates of stand biomass more than the fit with small trees (HOSODA and IEHARA, 2008). After the trees measured in a plot were categorized into five classes in ascending order of DBH so that the number of trees in each class was nearly equal, a sample tree with a DBH value that was close to the mean of the class was chosen from each DBH class. It might have been better to choose more sample trees from larger size classes to obtain well-fitted allometric equations.

Direct estimates are expected to produce smaller RMSE values than are estimates created by adding the biomass values of individual components, and the former actually produced slightly smaller RMSE values. The biases in both estimates were small in all cases, and no clear tendency was found in the relationships between the two methods and bias. However, the differences among the regression methods for estimating total stand biomass showed almost no change when estimates from equations for individual components were replaced with estimates from stem and branch mass equations or aboveground biomass equations, which did not demonstrate the accuracy of the estimates from the two methods. Thus, the estimates from the two methods were quite close. Even if the masses of two components, y and z, have allometric relationships with x, the sum of the two masses w $(= y + z)$ does not necessarily have an allometric relationship with x. Theoretically, the allometric relationship between w and x can hold, but only when the values of the exponents of power functions for the two components are equal. The RESEARCH GROUP OF THE FOUR UNIVERSITIES (1960) showed three conditions when we can assume that an allometric relationship will hold: (1) when the range of x is small; (2) when either y or z is much larger than the other and the exponent of w is nearly equal to the exponent of the larger mass; or (3) when the two exponents of y and z are similar. In this study, the exponents of Eq. (2) were slightly larger than 1.0 and were almost the same, and stem and branch mass and aboveground mass were dominated by stem mass. Therefore, this study met conditions (2) and (3) above, which explains why the estimates from the methods for stem and branch mass and aboveground biomass were quite close. Moreover, stem and branch mass had a smaller θ value than both stem mass and branch mass. Branch mass had a large bias when using generalized non-linear regression or logarithmic linear regression, although stem and branch mass had little bias. Therefore, estimating both stem and branch mass at once would be effective for obtaining less biased estimates of woody aboveground biomass for individual trees.

CONCLUSIONS

This study examined the use of non-linear and linear regression methods for estimating the parameters of allometric equations for the biomass of mizunara oak trees grown in a deciduous secondary forest that was dominated by the species. Generalized non-linear regression proved to be slightly preferable to logarithmic linear regression or unweighted non-linear regression with respect to error. Branch mass and foliage mass had different variance parameters, although both had large variation around their regression lines. When the variance parameter was greater than 1.0, as occurred with branch mass, logarithmic linear regression was slightly better than generalized non-linear regression. When applying fitted allometric equations to other data, the choice of regression method caused only small differences in the estimates of stem mass. However, the choice of method may cause large differences in estimates of branch mass and foliage mass.

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Article

Utility of Very High Resolution Imagery for Forest Type Classification and Stand Structure Estimation

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ABSTRACT

We compared the relative utilities of very high resolution imagery (VHRI) and medium resolution imagery (MRI) for forest type classification and stand structure estimation. We used QuickBird imagery for the VHRI with object-based classification and LANDSAT/ETM+ imagery for the MRI with pixel-based classification. The study site contained even-aged plantations of Japanese cedar (*Cryptomeria japonica* D. Don) and Japanese cypress (*Chamaecyparis obtusa* (Sieb. et Zucc.) Endl.) and natural broad-leaved forests. The overall accuracy of forest classification was 81% with the VHRI and 72% with the MRI; the VHRI was more accurate in discriminating Japanese cypress from natural broad-leaved forest. Stem density was not correlated with any features measurable from VHRI, whereas the texture measures had significant curvilinear relations with the stand volume of both Japanese cedar and Japanese cypress (the relative root mean square error was 8.6% and 18.0%, respectively). The pixel values of MRI were not correlated with either stem density or stand volume. We conclude that MRI is virtually not enough to use in forest management planning for practical use in Japan and the use of VHRI is recommended for it. Texture information is important for both classification and stand structure estimation to exert the potential of VHRI.

Keywords: LANDSAT/ETM+, medium resolution imagery (MRI), QuickBird, texture, very high resolution imagery (VHRI)

INTRODUCTION

Sustainable forest management depends on accurate forest information from periodic and systematic measurements. Remote sensing is a powerful tool for obtaining forest information for sustainable forest management (Franklin, 2001). Although manual interpretation of aerial photographs has traditionally been used to acquire forest information, it is time consuming, subjective, and highly dependent on the skill of the interpreter (Wulder, 1998; Kayitakire *et al.*, 2006). Semi-automated processing of optical remotely sensed imagery provides a faster alternative method for collecting forest information (Kayitakire *et al.*, 2006). However, the error of estimates of processing such imagery has been very high at the field plot and forest stand levels (Mäkelä and Pekkarinen, 2001). A reason for the large error at the stand and plot levels is the limited spatial resolution of the remotely sensed data employed (Tuominen and Pekkarinen, 2005). The spatial resolution of medium resolution imagery (MRI) is about 20–30 m. However, the average stand size is often small; for example, 50% of Japanese forest owners have less than 3 ha of forest. Such small forest stands are represented by very few pixels if 20–30 m spatial resolution imagery is used. In addition, a considerable proportion of these pixels also carry spectral information from adjacent stands, and thus may poorly represent the target stand's spectral properties (Tuominen and Pekkarinen, 2005).

The spatial resolution of remotely sensed imagery has improved dramatically with the launch of new-generation satellites since 1999, when the IKONOS satellite was launched. Very high resolution imagery (VHRI) with spatial resolution of 0.5–5 m is now available. Even small forest stands are represented by a large number of pixels if VHRI is used. Additionally, VHRI reduces the problem of pixels that represent a mixture of stands. VHRI might therefore be more suitable for stand level estimation than MRI and has the potential to raise the value of remotely sensed imagery for forest management.

The use of remotely sensed imagery in forest management provides three levels of information: (1) the spatial extent of forest cover, (2) forest type and (3) variables that represent forest stand structure (Boyd and Danson, 2005). Many studies have been conducted using VHRI for forest cover estimation (Goetz *et al.*, 2003, Eroğlu *et al.*, 2010), forest type classification (Franklin *et al.*, 2000; Coburn and Roberts, 2004; Zhang *et al.*, 2004; Johansen *et*

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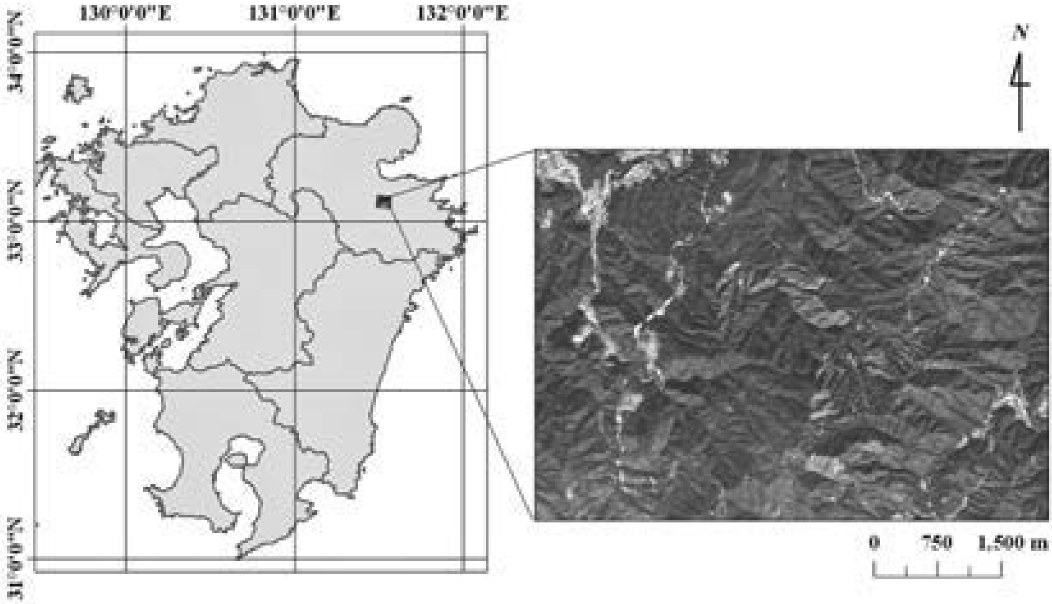

Fig. 1 Study area in Kyushu, Japan used to compare the utility of very high resolution and medium resolution imagery for forest type classification and stand structure estimation

al., 2007; MALLINIS *et al*., 2008) and estimation of variables representing forest stand structure (FRANKLIN *et al*., 2001; TUOMINEN and PEKKARINEN, 2005; KAYITAKIRE *et al*., 2006; OTA *et al*., 2007; KANEKO *et al*., 2008; OZDEMIR, 2008; FUCHS *et al*., 2009). However, few studies have simultaneously acquired information at different resolutions and compared the accuracy of using VHRI and MRI. A problem is that the accuracy of analysis depends not only on the spatial resolution of the imagery but also on other factors such as the season when the imagery data were acquired (MURAKAMI, 2004), stem density (KATOH *et al*., 2008), tree crown size (POULIOT *et al*., 2002), or stand age class (HIRATA, 2008). Thus, it is still unclear how effective VHRI is at detecting different levels of forest information as compared to MRI.

The objective of this study was to compare the effectiveness of VHRI and MRI for forest type classification and stand structure estimation. We focused on the potentially efficacy of VHRI and MRI to collect forest information at the stand level for forest management planning. We selected imageries acquired over the same study area on close days in order to eliminate problems arising from the difference in stand types and the seasons when the imagery data were acquired, using QuickBird panchromatic and multispectral for the VHRI and LANDSAT/ETM+ for the MRI. The applications of VHRI and MRI to forest management were discussed.

STUDY AREA

The study area was a 4 km by 6 km forested site in Oita Prefecture, Kyushu, Japan (Fig. 1). The elevation of the area ranged from 570 to 800 m. The natural vegetation was warm-temperate broad-leaved forest. Forests within the study area consisted mainly of even-aged plantations of Japanese cedar (*Cryptomeria japonica* D. Don) and Japanese cypress (*Chamaecyparis obtusa* (Sieb. et Zucc.) Endl.). The other areas were remnants of natural broad-leaved forest, consisting mainly of *Acer rufinerve* Sieb. et Zucc., *Swida controversa* (Hemsl.) Soják and *Carpinus japonica* Bl. as determined from the measurement of permanent plots in this area. We focused on classifying three forest-cover types: Japanese cedar, Japanese cypress and natural broad-leaved forest. We also focused on estimating stand variables for the Japanese cedar and Japanese cypress stands. For forest type classification, we selected 30 points of each of the three forest types for training and another 30 points each for accuracy assessment from orthorectified IKONOS-2 pan-sharpened imagery of IKONOS-2 multispectral and panchromatic imagery with 1-m spatial resolution acquired in March 2003.

MATERIALS AND METHODS

Data Acquisition

The digital image data were acquired over the study area by the QuickBird satellite on 13 November 2006 and by LANDSAT/ETM+ on 12 November 2006 (Path 112, Row 37, Level-1T geometrically corrected product). The QuickBird data set consisted of single-band panchromatic imagery (*PAN*, 450-900 nm) with a spatial resolution of 0.6 × 0.6 m and 4-band multispectral imagery with a spatial resolution of 2.4 × 2.4 m. The four spectral bands were blue (*B*, 450-520 nm), green (*G*, 520-600 nm), red (*R*, 630-690 nm) and near-infrared (*NIR*, 760-900 nm). The QuickBird data were geometrically corrected using ground control points extracted from a 1:25,000 digital map and a digital elevation model with a 10-m grid published by the Geographical Survey Institute of Japan.

The LANDSAT/ETM+ data set consisted of 7-band multispectral imagery with a spatial resolution of 30 × 30 m. The seven spectral bands were blue (*B*, 450-520 nm), green (*G*, 520-600 nm), red (*R*, 630-690 nm), near-infrared (*NIR*,

Table 1 Summary of stand parameters

	Stem density (stems ha^{-1})		Stand volume (m^3 ha^{-1})	
	Mean	Standard deviation	Mean	Standard deviation
Japanese cedar	2070	457	493.08	69.32
Japanese cypress	1665	368	394.39	92.25

760-900 nm), mid-infrared (*MIR1*, 1550-1750 nm), thermal infrared and mid-infrared (*MIR2*, 2080-2350 nm). The data from band 6, the thermal infrared band, were not considered in this study. Parts of the LANDSAT/ETM+ imagery from 12 November 2006 near the study area were missing because of a failure of the Scan Line Corrector. However, no part of the study area used in this research was affected. Although LANDSAT/ETM+ Level-1T was a geometrically corrected product, the imagery we used retained some geometrical error. We therefore geometrically corrected the imagery using ground control points extracted from a 1:25,000 digital map and a digital elevation model with a 10-m grid published by the Geographical Survey Institute of Japan. The projective transform was applied to perform the geometric correction.

Field Sampling

We selected 11 even-aged Japanese cedar stands and 11 even-aged Japanese cypress assessment plots for field-level forest classification. Each plot was 20 × 20 m (0.04 ha). The plot center coordinates were recorded using a differential global positioning system (MobileMapper CX, Megellan Navigation, Inc.), which produced sub-meter accuracy. Diameter at breast height (dbh) and the number of trees of all trees in each plot were recorded. The heights of a random selection of one-third of the trees in each plot were also measured.

Stand volume and stem density (number of stems per hectare) were selected for stand structure estimation. The heights of unmeasured trees were estimated using the Näslund equation in order to calculate stand volume:

$$H = 1.2 + \frac{D^2}{(a+bD)^2}, \tag{1}$$

where H is tree height, D is dbh, and a and b are parameters to be estimated. We estimated a and b based on paired observations of dbh and height of each species. The estimated values of parameters of Japanese cedar were a = 1.98 and b = 0.18. Those of Japanese cypress were a = 2.00 and b = 0.18. The volume of individual trees was estimated using local two-way volume equation for Japanese cedar and Japanese cypress (Forest Planning Section of The Japanese Forestry Agency, 1970). Table 1 shows a summary of stand parameters.

Image Processing for QuickBird Imagery

Extracting forest information from VHRI involves relatively new techniques (Falkowski *et al.*, 2009) because single pixels of VHRI represent individual elements of the stand, such as tree apices or stand floor rather than forest stand-level samples that integrate such elements. One of the most promising techniques for extracting forest information from VHRI is the object-based approach, which partitions an image into spatial units that are homogenous (Falkowski *et al.*, 2009). We used the object-based approach for the QuickBird imagery. The object-based approach consists of two stages, image segmentation into objects and classification or estimation using information derived from the objects. Segmentation is the partitioning of an image into a set of jointly exhaustive, mutually disjoint regions that are more uniform within themselves than adjacent regions (Castilla and Hay, 2008).

We used eCognition (Definiens Imaging, Munich, Germany), an object-based classification software package used for segmentation. In eCognition, segmentation is performed using the scale parameter and homogeneity criteria (Ozdemir, 2008). The scale parameter indirectly influences the average object size-the larger the value, the larger the object (Baatz *et al.*, 2004). Murakami *et al.* (2010) found that the homogeneity criteria for color and shape affect the accuracy of forest stand type classification in forests relatively similar to our sites in southern Kyushu, with the best combination being 0.8 for color and 0.2 for shape. The weighting of each input layer also influences the segmentation process (Chubey *et al.*, 2006). In this study, we set the segmentation parameter to a scale parameter of 200 and the homogeneity criteria for color and shape at 0.8 and 0.2, respectively. The smoothness and compactness criteria for shape were both set at 0.5. The relative weights of the segmentation input layers of QuickBird are summarized as:

$$(W_{Rq} + W_{Gq} + W_{Bq} + W_{Nq}) = W_{panq} \tag{2}$$

and

$$W_{Rq} = W_{Gq} = W_{Bq} = W_{Nq}, \tag{3}$$

where W_{Rq} is the weighting factor for the red layer, W_{Gq} is the weighting factor for the green layer, W_{Bq} is the weighting factor for the blue layer, W_{Nq} is the weighting factor for the near infrared layer and W_{panq} is the weighting factor for the panchromatic layer. We selected a different weight for W_{panq} than the others because of the difference in spatial resolution.

The feature attributes of each object were calculated using *R*, *G*, *B*, *NIR* and *PAN*. We calculated the mean, standard deviation (SD), and second order texture features derived from grey-level co-occurrence matrices (GLCM; Haralick *et al.*, 1973). Texture is a function of patterns in the spatial variation of pixel values in the imagery. Texture retrieval from VHRI is effective for land cover classification (Franklin *et al.*, 2000; Rao *et al.*, 2002; Coburn and Roberts, 2004; Zhang *et al.*, 2004) and stand structure estimation (e.g. Tuominen and Pekkarinen, 2005; Kayitakire *et al.*, 2006). GLCM is a widely used measure of texture for the extraction of information on forest structure (Franklin *et al.*, 2001; Kayitakire *et al.*, 2006). The definition of GLCM is a tabulation of how often different combinations of pixel brightness values (grey levels) occur in an image. The assumption underlying GLCM is that texture information on an image contains the overall or average spatial relationship of the gray tones to one another (Franklin, 2001). We considered six texture measures from GLCM: Homogeneity (HOM), Contrast (CON), Dissimilarity (DIS), Entropy (ENT), Angular second moment (ASM), and correlation (COR). Thus we examined 40 feature attributes for each object: five layers multiplied by eight features (SD, mean and the six texture measures).

Image Processing for LANDSAT/ETM+ Imagery

We used a pixel-based approach for the Landsat/ETM+ imagery because it was the typical approach used to analyze LANDSAT/ETM+ imagery (e.g., Salajanu and Olson, 2001; Kajisa *et al.*, 2007). It is not realistic to adopt an object-based approach for LANDSAT/ETM+ imagery with a 30 m spatial resolution for managed forests in Japan because of the small stand size. Also, the objective of this study was to compare detailed forest information collected from VHRI with that obtained from traditional remote sensing methods, i.e., LANDSAT/ETM+ and a pixel-based approach. The pixel-based approach extracts forest information based on individual pixel values.

Classification

Classification and regression tree (CART) analysis was used for forest type classification. The CART method recursively divides the response variable into increasingly homogeneous subsets based on critical thresholds of the predictor variables (Kelly and Meentemeyer, 2002; Lozano *et al.*, 2008). We selected the CART method because it was capable of handling high-dimensional data sets. We selected the Gini index of impurity for node splitting (Breiman *et al.*, 1984). The Gini index of impurity is defined as

$$i(t) = 1-p^2(j|t), \tag{4}$$

where $p(j|t)$ is the proportion of class j at node t. To avoid over-fitting the tree model, an iterative cross-validation procedure was used that identifies an optimal tree size, beyond which validation performance drops as additional br$\hat{K}$ches “grow” in response to peculiarities in the development data without further accounting for variance in the test data (Kelly and Meentemeyer, 2002).

Kappa analysis (Cohen, 1960; Congalton, 1991) was used for accuracy evaluation. The Kappa coefficient, , was defined as

$$\hat{K} = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+} \times x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+} \times x_{+i})} , \tag{5}$$

where r is the number of rows in the matrix, x_{ii} is the number of observations in row i and column i, x_{i+} and x_{+i} are the marginal totals of row i and column i, respectively, and N is the total number of observations (Murakami, 2004). User’s accuracy and producer’s accuracy were also used for accuracy evaluation. User’s accuracy is indicative of the probability that a classified object on a map actually represents that category on the ground, and producer’s accuracy indicates the probability of a reference object being correctly classified (Congalton, 1991).

Stand Structure Estimation

Relationships between forest stand variables (stem density and stand volume) and imagery features were analyzed by Pearson’s correlation coefficient. For each stand variable, the feature with the highest absolute correlation coefficient was identified and, if statistically significant (p < 0.05), used in a generalized linear model (GLM) to determine values of forest variables. Stand volume and stem density were used as the dependent variables and features from pixels or objects were used as the independent variables. Further, log was used as a link function in the GLM because stand volume and stem density values must be positive.

We used root mean squared error (RMSE) and relative root mean squared error (RMSEr) to evaluate the performance of models. RMSE and RMSEr were defined as

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(y_i \times \hat{y}_i)^2}{n}} \tag{6}$$

$$\mathrm{RMSE_r} = \frac{\mathrm{RMSE}}{\bar{y}} \times 100 \tag{7}$$

where y_i is the observed value of y, $\hat{y}_i$ is the estimate of y, $\bar{y}$ is the average of observed values of y, and n is the number of observations.

RESULTS

Forest Type Classification

Fig. 2(a) shows the optimal classification tree model for forest type classification using QuickBird imagery. Although 40 features were identified, only mean derived from near-infrared and standard deviation derived from blue were retained in the optimal classification tree. In the first split, standard deviation of objects derived from analysis of blue reflectance discriminated natural broad-leaved forest from other categories. For the second node, the mean of objects derived from near-infrared discriminated between Japanese cypress and Japanese cedar. Table 2 shows the error matrix for forest type classification using data derived from QuickBird VHRI. The overall accuracy for the forest classification was 81% and the Kappa coefficient was 0.72. The user’s accuracy of each category was between 79% and 86% and producer’s accuracy of each category was between 73% and 87%.

Fig. 2(b) shows the optimal classification tree model for forest type classification using LANDSAT/ETM+ imagery. Only mid-infrared 1, near-infrared and blue were used in the optimal classification tree. Table 3 shows the error matrix for forest type classification using LANDSAT/ETM+ imagery. The overall accuracy for the forest classification was 72% and the Kappa coefficient was 0.58. The user’s accuracy of each category was between 59% and 85% and the producer’s accuracy of each category was between 57% and 97%. The user’s accuracy for Japanese cypress was appreciably lower than that of Japanese cedar and natural broad-leaved forest because 40% of natural broad-leaved forest pixels were classified as Japanese cypress.

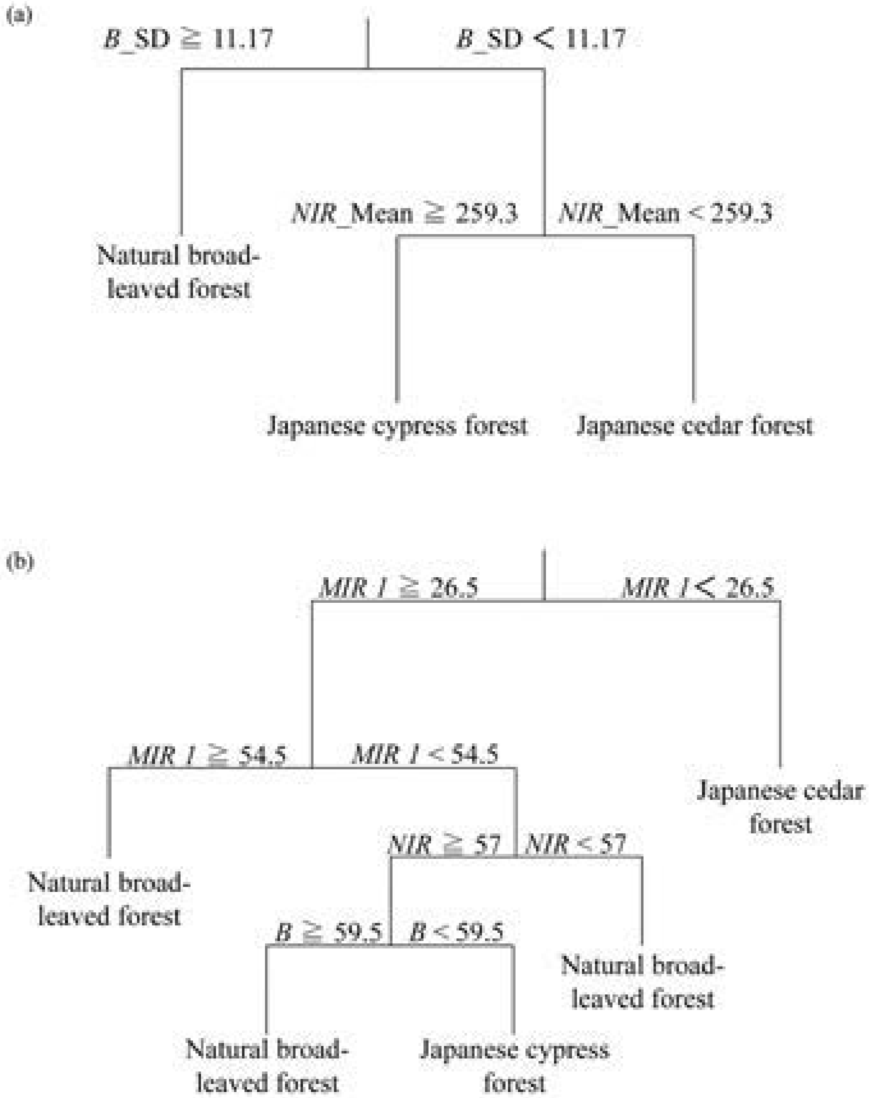

Fig. 2 Classification tree models of forest type classification using the features derived from (a) QuickBird imagery and (b) LANDSAT/ETM+ imagery

Table 2 The error matrix for forest type classification using QuickBird imagery

	Japanese cedar forest	Japanese cypress forest	Natural broad -leaved forest	User's accuracy (%)
Japanese cedar forest	26	5	2	79
Japanese cypress forest	3	22	3	79
Natural broad-leaved forest	2	3	25	86
Producer's accuracy (%)	87	73	83	
		Overall accuracy (%)		81
		Kappa Coefficient		0.72

Table 3 The error matrix for forest type classification using LANDSAT/ETM+ imagery

	Japanese cedar forest	Japanese cypress forest	Natural broad -leaved forest	User's acccuracy (%)
Japanese cedar forest	29	8	1	76
Japanese cypress forest	1	19	12	59
Natural broad-leaved forest	0	3	17	85
Producer's accuracy (%)	97	63	57	
		Overall accuracy (%)		72
		Kappa Coefficient		0.58

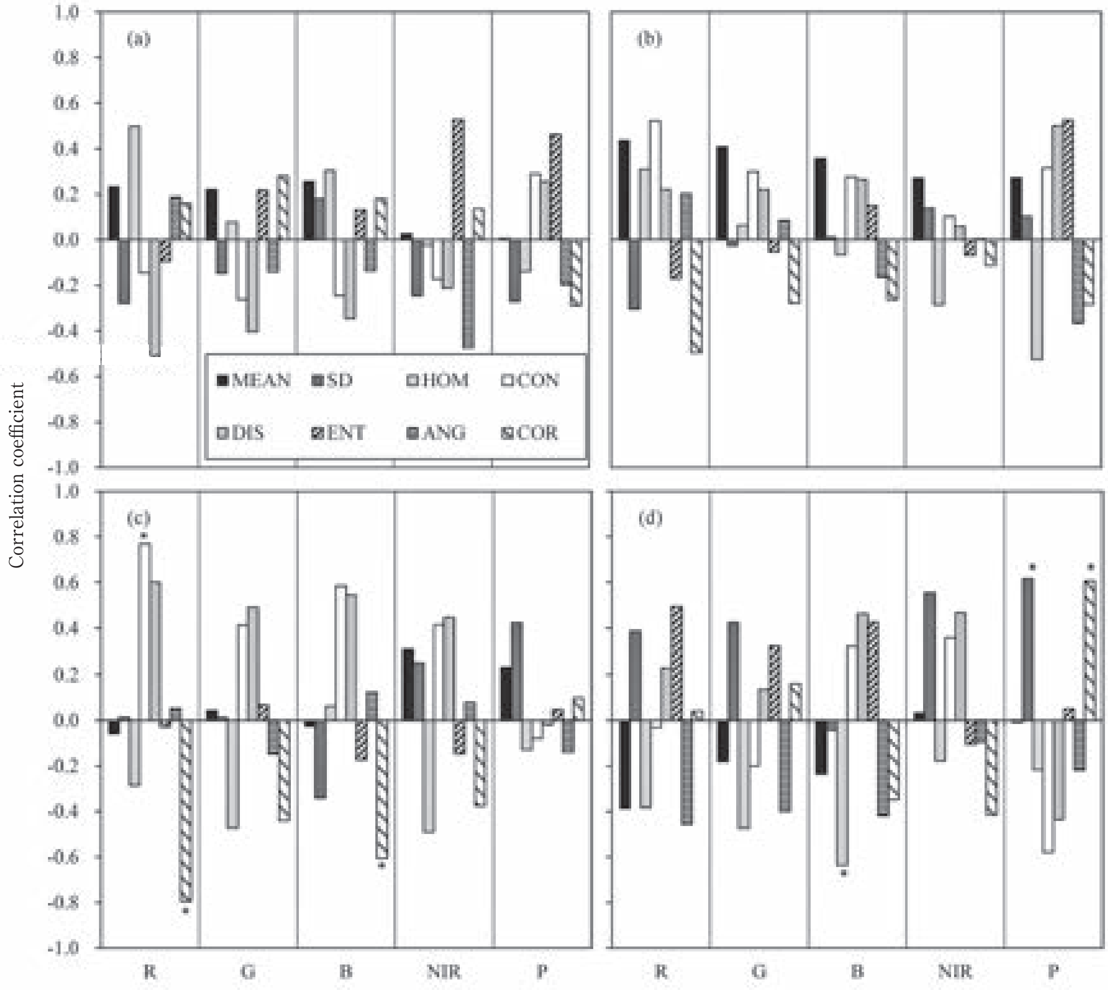

Fig. 3 Correlation coefficients between stand structure variables and features derived from QuickBird imagery. (a) stem density of Japanese cedar, (b) stem density of Japanese cypress, (c) stand volume of Japanese cedar, (d) stand volume of Japanese cypress. Asterisk marks indicate significant correlation ($p > 0.05$).

Stand Structure Estimation

Fig. 3 shows the relationship between stand variables and features from QuickBird imagery. The stem density of both Japanese cypress and Japanese cedar were not significantly correlated with any features ($p > 0.05$, Figs. 3(a) and 3(b)). However, the stand volume of Japanese cedar (Fig. 3(c)) had a relatively high correlation with many of the features. The correlation derived from red reflectance was best correlated with the stand volume (Fig. 3(c), $r = -0.80$, $p < 0.05$). The stand volume of Japanese cypress (Fig. 3(d)) was more highly correlated with many of the features than stem density (Figs. 3(a), 3(b) and 3(d)). The homogeneity derived from blue reflectance was best correlated with the stand volume of Japanese cypress (Fig. 3(d), $r = -0.64$, $p < 0.05$).

Fig. 4 shows the relationship between stand volume of Japanese cedar and correlation derived from red reflectance (R_{COR}). The equation for this relationship was

$$V = \exp(1.033\times10-5.226\ R_{COR}). \quad (8)$$

where V is stand volume. The RMSE was 42.4 $m^3\ ha^{-1}$ and RMSEr was 8.6%. Fig. 5 shows the relationship between stand volume of Japanese cypress and homogeneity derived from blue reflectance (BHOM). The equation for this relationship was

$$V = \exp(9.783-6.343\ B_{HOM}). \quad (9)$$

The RMSE was 70.8 $m^3\ ha^{-1}$ and the RMSEr was 18.0%.

Fig. 6 shows the relationship between forest variables and features (pixel spectral values) from LANDSAT/ETM+ imagery. The stem densities (Figs. 6(a) and (b)) and stand volumes (Figs. 6(c) and (d)) of Japanese cypress and Japanese cedar were not significantly correlated with any features ($p > 0.05$ for all).

DISCUSSION

The overall accuracy of forest type classification using QuickBird imagery was 9 percentage points higher than that using LANDSAT/ETM+ imagery (Tables 2 and 3). QuickBird imagery improved the accuracy of classifying natural broad-leaved forests, many of which were mis-classified as Japanese cypress using LANDSAT/ETM+ imagery. Although spectral features are the most important and widely used information for image classification, the importance of introducing texture information increases as spatial resolution increases (LU and WENG, 2007). OTA *et al.* (2011) found that texture information derived from VHRI improved the discrimination between plantation forests and natural forests. In the present study, standard deviation (SD), which is one of the measures of texture, derived from blue reflectance in QuickBird imagery was used to discriminate between natural broad-

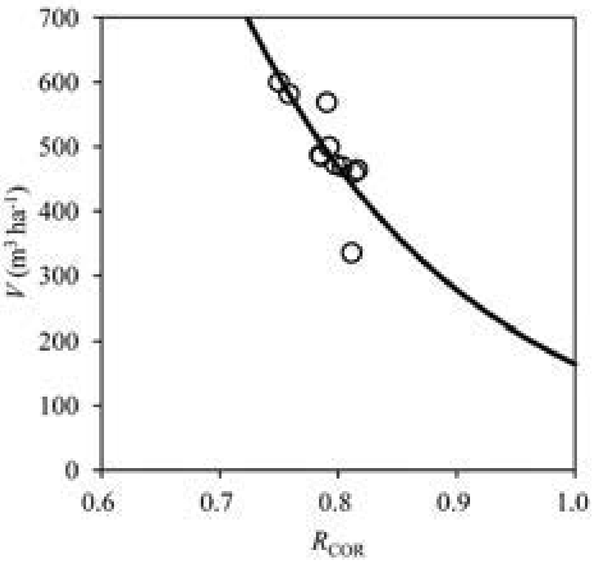

Fig. 4 The relationship between stand volume of Japanese cedar (V) and correlation derived from red reflectance of QuickBird imagery (RCOR)

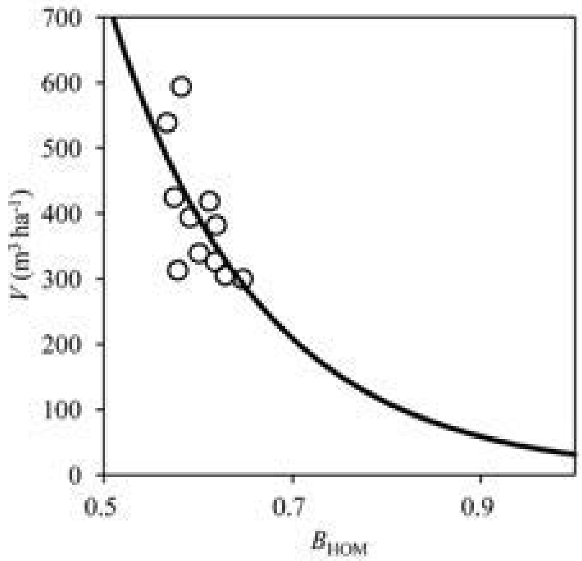

Fig. 5 The relationship between stand volume of Japanese cypress (V) and homogeneity derived from blue reflectance of QuickBird imagery (BHOM)

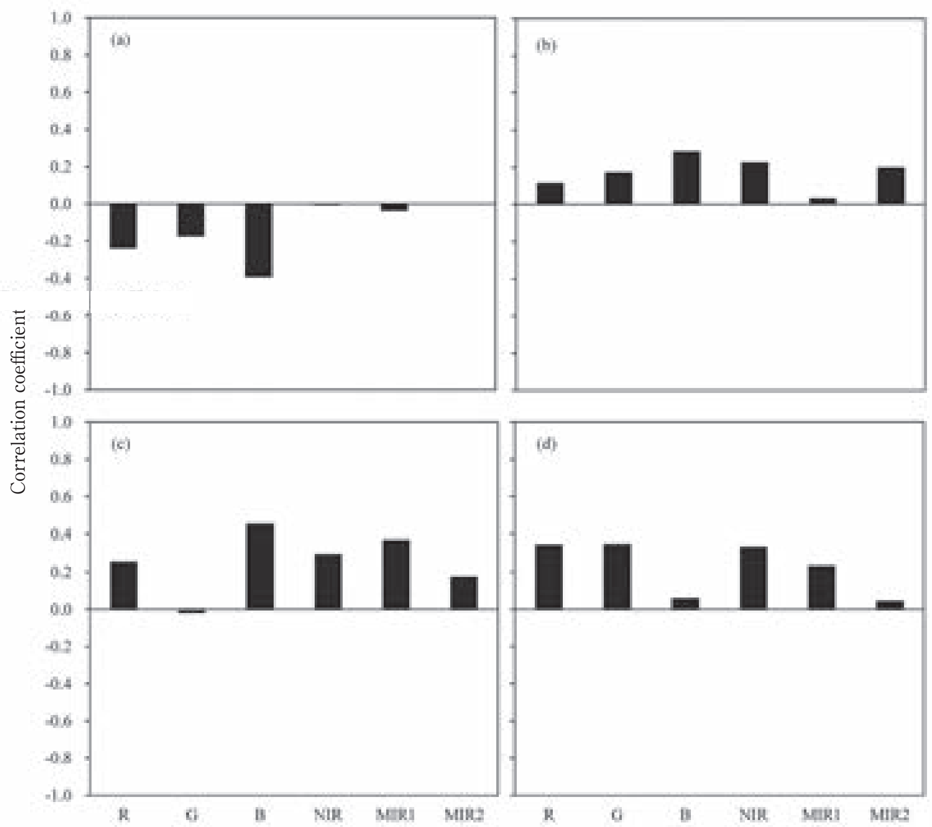

Fig. 6 Correlation coefficients between stand structure variables and features derived from LANDSAT/ETM+ imagery. (a) stem density of Japanese cedar, (b) stem density of Japanese cypress, (c) stand volume of Japanese cedar, (d) stand volume of Japanese cypress.

leaved forest (larger SD) and artificial forests (lower SD) (Fig. 2(a)). SD expresses the difference in crown complexity between even-aged plantations with a single-layer canopy and uneven-aged natural broad-leaved forests with a multi-layer canopy. This indicates that texture information from VHRI can be considered for forest classification where there are several forests with different crown complexities in a forest management area.

The lowest user's accuracy using LANDSAT/ETM+ imagery was for Japanese cypress (Table 3). Some 12 out of 32 pixels that were classified as Japanese cypress were Japanese cedar or natural broad-leaved forest. The log price of Japanese cypress is almost twice that of Japanese cedar (Forest Agency of Japan 2008), so accurate estimation of the area of Japanese cypress is important for forest managers. Forest type classifications performed using QuickBird imagery are therefore of greater utility for Japanese forest management than those performed using LANDSAT/ETM+ imagery.

Although we did not find any correlation between stem density and any of the features from QuickBird imagery (Figs. 3(a) and (b)), Kayitakire *et al.* (2006) found a strong correlation between stem density and texture features derived from VHRI. A reason for the two different results may be that the relationship between stem density and features from VHRI is not linear. Ota *et al.* (2007), using VHRI, found that differentiation of the features of objects began to be saturated when stem density was more than 1500 trees ha^{-1} (Ota *et al.*, 2007). In the present study, most of the Japanese cedar and Japanese cypress stands had stem densities >1500 trees ha^{-1}. Hence, stem density was weakly correlated with the measured features. Because stands are usually established at planting densities of 3000 trees ha^{-1} in Japan, stem densities of more than 1500 trees ha^{-1} are common at younger ages. Hence, it is difficult to estimate stem density using features derived from VHRI for many stands at this time. However, it is conceivable that stem densities of less than 1500 trees ha^{-1} become more common. Recently, planting density less than 3000 trees ha^{-1} starts to garner attention to reduce planting cost. Also, forest rotation age is extended because of the fall in the timber price, and there are increasing areas of older stands with lower stem density. Therefore, the applicability of VHRI to estimate stem density could be increased in the future.

The significant correlations between features extracted from QuickBird imagery (Figs. 3(c) and (d)) and stand volume provided favorable estimation performance compared with other studies using VHRI. Tuominen and Pekkarinen (2005) reported a RMSEr of 58% from aerial photographs with a spatial resolution of 0.5 m from forests in Finland. Hyvönen *et al.* (2005) also reported a RMSEr of 58.1% from aerial photographs with 0.5-m spatial resolution in Finland. On the other hand, in our study, stand volume was not correlated to pixel values of LANDSAT/ETM+ imagery (Figs. 6(c) and (d)). Some studies have reported a negative correlation between stand volume and pixel values of LANDSAT imagery (e.g., Kajisa *et al.*, 2007, 2009). One explanation for the two different results may be that the relationship between stand volume and pixel values from medium resolution imagery is not linear, similar to the relationship between stem density and features from VHRI (Kajisa *et al.*, 2007, 2009). Pixel values reached near saturation at higher levels of stand volume development (Kajisa *et al.*, 2007). In this study, all plots had stand volumes of more than 300 m^3 ha^{-1}. Hence, stem density was weakly correlated with the imagery features.

Stand volume was well estimated using QuickBird imagery, but could not be estimated using LANDSAT/ETM+ imagery. This result indicated that VHRI is superior to MRI for stand structure estimation. On the other hand, stem density could not be estimated by either technique in this research. This indicates that there are limitations to stand structure estimation using VHRI, and serves as a caution that not necessarily all stand structures can be well estimated even if VHRI is used.

The main conclusion of this study is that VHRI is more informative than MRI in forest stand delineation and characterization in Japan. The reason includes that the size of forest stand is small in Japan. One forest stand is often represented by a few pixels if MRI is used. Also, a considerable proportion of these pixels carry spectral information from adjacent stands. Therefore, MRI is virtually not enough to use in forest management planning for practical use in Japan, and we have no choice but to select VHRI for it. When we use VHRI for forest classification, the addition of texture improves classification accuracy (Franklin *et al.*, 2000; Berberoglu *et al.*, 2007; Ota *et al.*, 2011). This study also indicated the importance of texture information, especially to discriminate natural broad-leaved forest from artificial forests. Additionally, texture information correlated with forest variables stronger than spectral information did (Fig. 3). Hence, this research showed texture information was important for both classification and stand structure estimation. In contrast, Tuominen and Pekkarinen (2005) showed spectral information correlates moderately well with forest variables whereas texture information generally correlates weakly with forest variables. Further research is needed to reveal the relationship between forest variables and texture information. Also, we identified limitations to stand structure estimation using VHRI. Recently, more complex methods than those used in the current study have come under development, e.g., the integration of VHRI and LiDAR data (Ke *et al.*, 2010; Arroyo *et al.*, 2010). These new technologies have the potential to provide accurate information to forest managers because LiDAR provides detailed information about various measures of stand structure. Hence, further work to collect forest information from VHRI for use in forest management planning is required.

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Article

Does the Relationship between Quadratic Mean Diameter and Stem Density in Old Thinned and Unthinned *Cryptomeria japonica* Forests Deviate from a Power Function?

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ABSTRACT

In approximately 100-year-old forest stands, we investigated whether the relationship between quadratic mean diameter (D_q) and stem density in thinned and unthinned stands (N_t and N_u) deviates from a power function. We also examined the effects of changes in stand leaf mass during stand development on the form of these two relationships. To answer these questions, we used data from 29 long-term experimental monitoring plots established in Japanese cedar (*Cryptomeria japonica* D. Don) plantations in northeastern Japan. In old thinned stands, the D_q-N_t relationship deviated from the power function, whereas the D_q-N_u relationship in unthinned stands did not deviate from this function during the self-thinning period. These results were strongly affected by changes in total leaf mass with stand development. Comparison of stand development in unthinned and thinned forests indicated that thinning delayed forests from entering the self-thinning period, leading to an apparent rejuvenation effect.

Keywords: allometric model, REINEKE equation, self-thinning, stand leaf mass, thinned and unthinned forests

INTRODUCTION

The self-thinning law, which is also referred to as the 3/2 power law of self-thinning (YODA *et al*., 1963), describes an increase in mean plant weight (w) with decreasing plant density (N_u) in unthinned (overcrowded) pure stands:

$$w = kN_u^{\alpha} \quad (1)$$

where k and α are constants that represent the self-thinning coefficient and the self-thinning exponent, respectively. The name of the law derives from the fact that $\alpha = 3/2$ for many plants. A comparable law has been applied to the relationship between other measurements of mean size and plant density. REINEKE (1933) described the decrease in N_u with increasing quadratic mean diameter (D_q, which equals the diameter at breast height for a tree with the mean basal area) in overcrowded pure stands as follows:

$$\ln N_u = \beta - \gamma \ln D_q \quad (2)$$

where β and γ are constants. REINEKE (1933) considered the exponent γ to be universal constant (i.e. γ is 1.605). Many researchers have debated the mechanisms responsible for generating the self-thinning exponents α and γ (e.g., SATOO, 1962; WELLER, 1987; OSAWA and ALLEN, 1993; ENQUIST *et al*., 1998). These studies have adopted three main approaches: an early isometric approach (YODA *et al*., 1963), an allometric approach (SATOO, 1962; WELLER, 1987; OSAWA and ALLEN, 1993), and more recently a fractal approach (ENQUIST *et al*., 1998). It should be noted that all three approaches share the assumption that total stand leaf mass remains constant during stand development.

These studies also assumed that the power relationships in equations (1) and (2) are valid, although the values of α and γ vary slightly rather than being universally valid constants. However, several studies have questioned the validity of the power relationship for the D_q-N_u relationship (e.g., MEYER, 1938; LAASASENAHO and KOIVUNIEMI, 1990; ZEIDE, 1995, 2005, 2010; del RÍO *et al*., 2001; CHARRU *et al*., 2012). These studies have reported nonlinearity of the D_q-N_u relationship on a log-log scale even though equation (2) indicates that the relationship should be linear on a log-log scale. The nonlinearity may be due to temporal variability in crown closure and stand leaf mass (ZEIDE, 1995, 2005; del RÍO *et al*., 2001). This can be understood if we consider three phases of stand development that are related to a stand's self-thinning and crown closure dynamics (del RÍO *et al*., 2001; VANDER SCHAAF and BURKHART, 2008) (Fig. 1): (1) From the young stage until crown closure (Phase B in Fig. 1), self-thinning is less than the mortality rate that occurs at the maximum competition for light between individual

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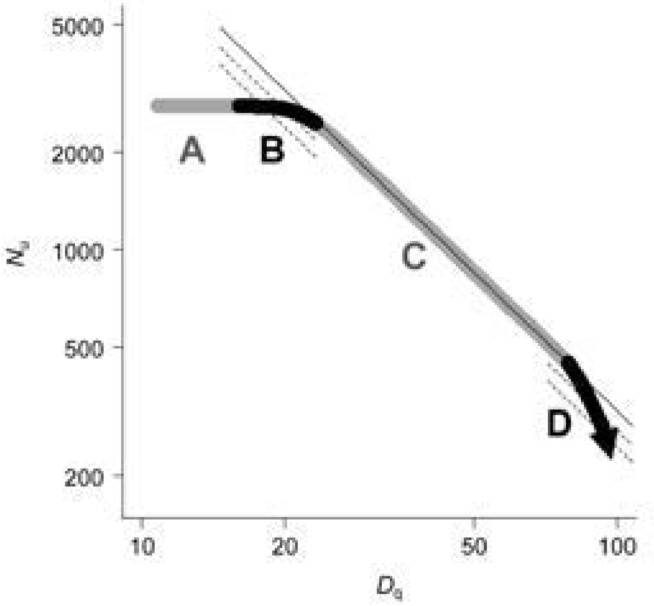

Fig. 1 Schematic diagram of the change in the relationship between quadratic mean diameter (D_q) and maximum stem density (N_u) in an unthinned stand. The solid thin line shows the size-dependent maximum stem density described by equation (2). The dashed lines have the same slopes as the solid thin line but different intercepts. The bold curve shows the D_q-N_u trajectory with four phases. Phase A is a stage of stand development under which only density-independent mortality occurs (VANDER SCHAAF and BURKHART, 2008), without competition for light among individual tress. The subsequent three phases can be interpreted as follows (del RÍO *et al.*, 2001; VANDER SCHAAF and BURKHART, 2008): In Phase B, from the young stage until crown closure, self-thinning is less than the mortality rate at the time of maximum competition for light between individual trees in a stand. In Phase C, an intermediate phase of stand development, competition between individual trees is severe and the D_q-N_u relationship on a log-log scale follows the straight line of size-dependent maximum density. Maximum stem density decreases with increasing tree size, because the requirement of individual trees for light resources increases with increasing tree size, and the total light resources available for capture by the stand's constant leaf mass are limited. Phase D represents old stands, which have lost their capacity to fill the gaps left by dead trees, and maximum stem density decreases more with increasing tree size than in Phase C, due to a decrease in the light resources that can be captured as a result of the increasing gap area.

trees in a stand, and the D_q-N_u relationship on a log-log scale is concave downward. (2) During the intermediate phase of stand development (Phase C in Fig. 1), the relationship follows a straight line with a negative slope that represents the size-dependent maximum density caused by competition for light between trees. During this phase, maximum stem density decreases with increasing tree size, because the requirement of an individual tree for light resources increases with increasing tree size, although the total light resources captured by individuals is limited by the constant leaf mass in the stand. (3) In old stands (Phase D in Fig. 1), when the capacity to fill the gaps created by dead trees has been lost, the relationship becomes concave downward again, because maximum stem density decreases more with increasing tree size than in Phase C, due to a decrease in the proportion of the total light resources captured by the existing leaf mass due to the increasing gap area in the stand. The proposed variability in total leaf mass that occurs during stand development is expected to result in the two phases of nonlinearity of the D_q-N_u relationship.

The size-density relationship in equation (2) is, in a precise sense, considered valid only for overcrowded stands (i.e., unthinned stands). However, several forestry studies (e.g., SHIRAISHI, 1986; SCHÜTZ and ZINGG, 2010) have found that the power law is also applicable to the relationship between D_q and tree stem density (N_t) in thinned pure stands. The power law has therefore been used for developing stand yield tables (SASAKAWA *et al.*, 2004) or complex stand growth simulators (SHIRAISHI, 1986). The horizontal size of individual trees in thinned stands (i.e., both D_q and crown size) is larger than that in unthinned stands. Thus, the gap size created by felling an old tree in a thinned stand is greater than that created by mortality of a tree of the same age caused by self-thinning in unthinned stands. As a result, the gaps in thinned stands may not be adequately filled, leading to a decrease in stand leaf biomass at an earlier age than in unthinned stands. Thus, stand development appears to proceed more rapidly in thinned stands than in unthinned stands. If constant stand leaf mass generates the power law that describes the size-density relationship in thinned stands in a way analogous to what occurs in unthinned stands, the possible temporal variability in stand leaf biomass brings into question the validity of the linear D_q-N_t relationship in old stands.

We can, therefore, predict the occurrence of nonlinearity in the D_q-N_u and D_q-N_t relationships in old stands at some point in time. However, the age at which the relationships deviate from the power function remains uncertain. As noted above, previous studies (e.g., MEYER, 1938; LAASASENAHO and KOIVUNIEMI, 1990; ZEIDE, 1995, 2005; del RÍO *et al*., 2001) addressed the decrease in a stand's capacity to fill canopy gaps in relation to nonlinearity in old stands. However, most of these studies used data obtained from yield tables or young stands and short-term monitoring, even though long-term monitoring data that includes old stands are essential for detecting nonlinearity in old stands; few analyses have used such data. The few studies that have used long-term data from old stands (del RÍO *et al*., 2001; PRETZSCH and BIBER, 2005; PRETZSCH, 2006; PRETZSCH and METTE, 2008; SCHÜTZ and ZINGG, 2010) reported conflicting results (e.g., linearity versus nonlinearity, concave versus convex curves). For instance, PRETZSCH (2006) analyzed the data from 28 non-thinned, fully stocked plots, and found nonlinearity in eight plots, of which six curves were concave downward and two concave upward. In other instance, del RÍO *et al.* (2001) analyzed the data from 23 untreated or control plots and found nonlinearity, which represented concave downward. However, they attributed the nonlinearity to the transition from Phases B to C in Fig. 1, but not to that from Phases C to D in Fig. 1 (and found no nonlinearity in the old stands). Thus, scientific consensus has not been reached on the nonlinearity of the D_q-N_u and D_q-N_t relationships in old stands.

In this study, we analyzed data from 29 long-term experimental monitoring plots established in Japanese cedar (*Cryptomeria japonica* D. Don) plantations in northeastern Japan. First, we addressed the following question: does the relationship between quadratic mean diameter (D_q) and stem density in thinned and unthinned stands (N_t and N_u, respectively) deviate from a power function?

We also examined the effects of changes in stand leaf mass during stand development on the form of the D_q-N_u and D_q-N_t relationships. By comparing the results obtained in unthinned and thinned forests, we examined the hypothesis that stand development proceeds faster in thinned stands than in unthinned stands. In Japan, the rotation periods of Japanese cedar plantations are generally becoming longer, and scientific information on these older plantations is needed (NISHIZONO *et al*. 2008a, b). Answering these questions and discussing the mechanisms responsible for the observed changes will improve our understanding of the self-thinning rule in old forests. In addition, our findings will provide valuable knowledge for managing plantations with an extended rotation.

DATA

Study Sites and Measurements

We used the same datasets used by NISHIZONO *et al.* (2008a, b) and NISHIZONO (2010). The data were obtained from 10 even-aged pure forests of Japanese cedar in the Akita District of the Tohoku region of northern Japan (Table 1). The forests ranged in elevation from 143 to 470 m a.s.l. The mean annual temperature in the forests ranged from 7.7 to 9.6°C (with monthly means ranging from –4.3 to –1.0°C in January and from 19.2 to 21.6°C in July), and mean annual precipitation ranged from 1283.7 to 2171.0 mm, with a maximum snow depth ranging from 0.3 to 2.1 m.

Three plots were established at each forest site between 1934 and 1940. The age at first measurement for each plot was between 27 and 39 years (Table 1). The plots ranged in size from 0.12 to 0.28 ha (with a median and mean both equal to 0.20 ha). The tree height and diameter at breast height (DBH, 1.2 m above the ground) of all living trees with DBH > 7.0 cm were periodically measured, at intervals of about 5 years in the young stands (up to about 60 years) and at intervals of about 10 years in older stands. At some measurement times, tree height was measured for only a sample of the trees. The age at the last measurement, which was conducted between 1998 and 2006, ranged between 88 and 104 years.

Before the establishment of these plots, all of the forests had experienced a series of conventional silvicultural treatments common to the time period, which included planting, supplementary planting (to obtain satisfactory regeneration density), weeding, weeding to remove epiphytes such as vines, improvement cutting (to remove trees of an undesirable species, form, or condition), pruning, and thinning (as described below). After the plots were established, thinning from below, which removed suppressed trees and preserved the dominant trees, was conducted two to seven times in each plot, with the exception of the three plots in the Ogayama Forest, which were not thinned during the study period (Table 1). At each of these thinnings, the stem density and volume were decreased by 0.8% to 40.8% and by 0.5% to 27.1%, respectively (Table 1). Thus, all thinning rates were relatively low. Although the Ogayama Forest was not thinned during the study period (after 1938), the forest underwent improvement cutting in 1932 and thinning at rates of 15.0% for stem density and 10.0% for stem volume in 1936. Thus, since its planting, the Ogayama Forest has not always been unthinned; however, hereafter we called it the unthinned forest because it had not been thinned for more than 60 years by the time of the last measurement.

Data were analyzed for 29 of the 30 plots that were available to us, excluding one plot in the Ozakure Forest for which no final measurements were obtained. We also excluded final data from measurements in plot 1 in the Kirinaizawa Forest because of severe damage to trees caused by a strong typhoon in 1991.

Calculation of Stand Attributes

We calculated D_q (cm), N_t and N_u (trees ha^{-1}), mean leaf mass (w_L; oven-dry t), and total leaf mass (W_L; oven-dry t ha^{-1}) at each measurement time. When thinning was conducted at the time of measurement, we calculated the stand attributes before and after the thinning. When thinning was conducted between successive measurements, we calculated the stand attributes before and after thinning based on the assumption that thinning was conducted at the beginning of the period (i.e., at the early measurement). D_q was calculated as $\left[\left[\sum_{i=1}^{n} d_i^2\right]/n\right]^{0.5}$

Table 1 Stand attributes of the pure forests of Japanese cedar (*Cryptomeria japonica*) examined during the first and last measurement periods

No.	Site	Treatment	Plot	First measurement						Last measurement					
				Age (years)	Stem density (trees ha^{-1})	Mean height (m)	D_q * (cm)	Stand volume (m^3 ha^{-1})	Stand leaf mass (oven-dry t ha^{-1})	Age (years)	Stem density (trees ha^{-1})	Mean height (m)	D_q (cm)	Stand volume (m^3 ha^{-1})	Stand leaf mass (oven-dry t ha^{-1})
1	Iwakawa	Thinned	1	35	853	18.0	29.2	491.6	25.4	93	326	36.6	57.7	1317.8	29.7
			2	35	1214	16.4	22.5	403.5	20.1	93	429	31.2	47.1	1038.8	26.7
			3	35	1158	17.1	21.7	370.2	16.7	93	358	35.2	51	1136.4	24.5
2	Kamionaizawa	Thinned	1	27	1311	11.8	16	163.3	12.3	88	483	32.6	45.2	1152.4	26
			2	27	1153	11.3	14.8	119.3	9.1	88	480	32.1	43.4	1052.3	23.6
			3	27	1027	11.2	15.3	111.6	8.9	88	560	31.6	44.2	1244.1	29.4
3	Kirinaizawa	Thinned	1†	39	609	20.5	32.8	517.8	21.6	101	346	40.4	61	1726.4	33.1
			2	39	923	14.4	22.9	275.4	17.9	101	488	33.1	47.6	1290.6	29.5
			3	39	1491	10.0	15.7	182.8	14.5	101	446	32.2	45.2	1065.9	24.4
4	Nibuna-Kokakeyama	Thinned	1	32	1276	13.8	20.4	304.2	18.8	104	432	31.4	48.9	1125.0	29.6
			2	32	1404	12.9	18.7	260.3	18	104	383	34.3	48.1	1072.6	23.2
			3	32	2179	10.6	14	197.8	15.9	104	538	30.3	40.3	986.4	23
5	Obiraki	Thinned	1	27	1055	15.9	22.4	335.6	17.7	90	355	36.9	52.9	1258.8	25.7
			2	27	1440	12.6	18.2	243.8	17.4	90	435	33.6	45.6	1093.3	23.4
			3	27	2645	8.4	12	138.8	16.5	90	640	26.4	34.5	784.1	20.6
6	Ogayama	Unthinned	1	31	1432	13.1	19.8	285.9	21.1	96	768	31.5	42.1	1568.7	35.7
			2	31	1530	12.3	18.4	259.0	19.6	96	787	30.9	39.4	1423.0	31.2
			3	31	2347	12.0	17.3	347.2	25.9	96	889	31.1	39.2	1604.4	34.8
7	Osawa	Thinned	1	31	715	15.4	25.4	284.9	16.8	94	240	37.3	57.4	985.3	21.2
			2	31	1459	12.8	19.1	302.5	19	94	264	38.9	55.4	1077.3	20.4
			3	31	2105	10.4	13.9	194.4	14.8	94	390	31.9	44.5	889.9	20.6
8	Ozakure	Thinned	1	33	780	16.1	27	348.7	21.2	96	215	37.4	65.4	1093.0	26.6
			2	33	1015	12.4	19.8	203.4	15.4	96	270	35.0	59.6	1093.9	27.9
9	Shimonaizawa	Thinned	1	37	522	20.0	29.2	333.6	14.2	102	204	39.0	62.2	1002.7	21.3
			2	37	757	16.2	23.1	256.7	13.6	102	291	35.1	52.9	976.4	22
			3	37	1117	12.9	18.2	199.7	13.2	102	279	33.7	53	893.7	22
10	Tozawayama	Thinned	1	35	914	15.5	22.4	273.3	15.9	100	443	28.6	44.3	881.3	25.6
			2	35	1100	11.8	18.5	180.4	14.9	100	460	25.1	42.6	742.3	27
			3	35	1532	9.3	13.5	115.0	11.2	100	686	26.1	36.7	912.2	26.3

* D_q is the quadratic mean diameter.
† Data from the final measurements were excluded because of severe damage to the trees caused by a strong typhoon in 1991.

Table 1 *Continued*

No.	Site	Treatment	Plot	Age at thinning (years)	Thinning rate of density	Thinning rate of volume
1	Iwakawa	Thinned	1	45, 55, 60, 80	0.19, 0.13, 0.17, 0.28	0.09, 0.08, 0.09, 0.18
			2	45, 55, 60, 80	0.23, 0.19, 0.16, 0.31	0.13, 0.10, 0.10, 0.24
			3	45, 55, 60, 80	0.20, 0.31, 0.13, 0.36	0.10, 0.21, 0.10, 0.27
2	Kamionaizawa	Thinned	1	37, 47, 52, 77	0.20, 0.27, 0.04, 0.34	0.10, 0.16, 0.02, 0.25
			2	47, 52, 77	0.31, 0.04, 0.35	0.15, 0.02, 0.24
			3	47, 52, 77	0.14, 0.02, 0.31	0.08, 0.01, 0.22
3	Kirinaizawa	Thinned	1†	54, 64	0.29, 0.05	0.14, 0.04
			2	54, 64	0.28, 0.21	0.13, 0.14
			3	54, 64	0.39, 0.26	0.11, 0.13
4	Nibuna-Kokakeyama	Thinned	1	37, 47, 57, 96	0.26, 0.25, 0.17, 0.14	0.16, 0.15, 0.11, 0.11
			2	37, 47, 57, 96	0.31, 0.31, 0.15, 0.27	0.16, 0.19, 0.10, 0.25
			3	37, 47, 57, 96	0.36, 0.23, 0.24, 0.30	0.17, 0.13, 0.15, 0.26
5	Obiraki	Thinned	1	27, 32, 47, 57, 77	0.27, 0.19, 0.11, 0.11, 0.13	0.20, 0.14, 0.06, 0.07, 0.11
			2	27, 32, 47, 57, 77	0.14, 0.30, 0.24, 0.16, 0.11	0.11, 0.22, 0.10, 0.09, 0.10
			3	27, 42, 47, 52, 57, 77	0.04, 0.02, 0.34, 0.34, 0.11, 0.20	0.04, 0.01, 0.16, 0.18, 0.06, 0.14
6	Ogayama	Unthinned	1			
			2			
			3			
7	Osawa	Thinned	1	31, 41, 51, 73, 83	0.05, 0.23, 0.11, 0.26, 0.27	0.01, 0.05, 0.04, 0.15, 0.25
			2	31, 41, 51, 73, 83	0.10, 0.38, 0.23, 0.25, 0.27	0.05, 0.13, 0.12, 0.16, 0.26
			3	31, 41, 51, 73, 83	0.17, 0.19, 0.34, 0.38, 0.27	0.10, 0.05, 0.19, 0.20, 0.25
8	Ozakure	Thinned	1	33, 38, 48, 53, 58, 73, 83	0.19, 0.07, 0.18, 0.07, 0.12, 0.16, 0.3	0.17, 0.06, 0.15, 0.03, 0.07, 0.12, 0.25
			2	33, 48, 53, 58, 73, 83	0.10, 0.16, 0.09, 0.18, 0.16, 0.25	0.09, 0.11, 0.04, 0.11, 0.09, 0.19
9	Shimonaizawa	Thinned	1	42, 57, 62, 67, 77, 87	0.20, 0.14, 0.08, 0.05, 0.17, 0.22	0.16, 0.09, 0.06, 0.04, 0.16, 0.20
			2	42, 57, 62, 67, 87	0.22, 0.18, 0.13, 0.01, 0.26,	0.20, 0.06, 0.10, 0.01, 0.21
			3	42, 57, 62, 67, 77, 87	0.2, 0.28, 0.19, 0.07, 0.01, 0.3	0.18, 0.08, 0.13, 0.04, 0.00, 0.23
10	Tozawayama	Thinned	1	50, 60	0.27, 0.26	0.15, 0.20
			2	50, 60	0.26, 0.35	0.14, 0.21
			3	50, 60	0.41, 0.05	0.17, 0.02

from the DBH (d_i) of individual tree i and total number of trees (n). The individual leaf mass of tree i (w_{Li}) was estimated from d_i and tree height (h_i) using an allometric equation developed by HOSODA and IEHARA (2010):

$$w_{Li} = 0.070348\, d_i^{2.596261}\, h_i^{-0.935245}. \quad (3)$$

W_L was estimated as $\sum_{i=1}^{N} w_{Li}$.

Equation (3) was developed using the data of which tree ages ranged from 10 to 82 years, and DBHs ranged from 2.8 to 55.7 cm (HOSODA and IEHARA, 2010). The maximum age and size in the data used by this study (104 years in stand age, 84.5 cm in DBH of individual tree) was older and larger than those of the trees used by HOSODA and IEHARA (2010). Therefore, someone will question the reasonability for extrapolating equation (3) to trees older and larger than the sample trees used to develop the equation. Unfortunately, we were unable to completely examine this issue, given the lack of available data on the leaf biomass of *C. japonica* trees having a size similar to that of the trees covered by our data. Nevertheless, we attempted to examine the validity of equation (3) by collecting all currently available data from literature (APPENDIX A), and obtained a degree of justification. The maximum age and DBH of trees in the dataset developed here from the literature were younger and smaller than those of the trees used in this study, but older and slightly larger than those of the trees used by HOSODA and IEHARA (2010). A comparison of observed leaf masses with estimated ones (Fig. A1) showed the validity of equation (3) for the data derived from literature. This examination provides some (albeit weak and incomplete) justification for extrapolating equation (3) to old and large trees. Therefore, in this study, we used equation (3) to estimate stand leaf mass.

METHOD OF ANALYSIS

Parameter Estimation and Model Selection for the D_q-N_u Relationship in Unthinned Stands

ZEIDE (2005) proposed the following equation for describing the nonlinearity in the D_q-N_u trajectory:

$$\ln N_u = \beta - \gamma \ln(D_q) - \eta D_q \quad (4)$$

According to ZEIDE's interpretation, β, γ, and η are positive constants; γ is the rate of tree mortality caused by an increase in crown size; and η is the mortality rate due to diminishing canopy closure. Three phases related to self-thinning and crown closure dynamics occur during the course of stand development (del RÍO *et al.*, 2001; VANDER SCHAAF and Burkhart, 2008) (Fig. 1). ZEIDE's equation is expected to describe the D_q-N_u trajectory that occurs when Phase C changes to Phase D (Fig. 1).

To examine whether the D_q-N_u trajectory deviated from the power law in aged stands, data from unthinned stands were fitted to equations (2) and (4). A linear mixed-effects model (PINHEIRO and BATES, 2000) was used for this fitting. The linear mixed-effects models based on equations (2) and (4) are described by equations (5) and (6), respectively:

$$\ln N_{u(i,j)} = (\beta_0+\beta_i)-(\gamma_0+\gamma_i)\ln(D_{q(i,j)})+\varepsilon_{ij}$$
$$\text{and} \begin{bmatrix}\beta_i\\ \gamma_i\end{bmatrix} \sim N(0,\Psi),\ \varepsilon_{ij} \sim N(0,\sigma^2\Lambda_i) \quad , \quad (5)$$

$$\ln N_{u(i,j)} = (\beta_0+\beta_i)-(\gamma_0+\gamma_i)\ln(D_{q(i,j)})-(\eta_0+\eta_i)D_{q(i,j)}+e_{ij}$$
$$\text{and} \begin{bmatrix}\beta_i\\ \gamma_i\end{bmatrix} \sim N(0,\Psi),\ \varepsilon_{ij} \sim N(0,\sigma^2\Lambda_i) \quad , \quad (6)$$

where $N_u(i, j)$ and $D_q(i, j)$ are the stem density and the quadratic mean diameter in the i-th plot at the j-th measurement time, respectively; ε_{ij} is a normally distributed within-plot error term; β_0, γ_0, and η_0 are model coefficients for the fixed effects; and β_i, γ_i, and η_i are within-plot random effects. In this study, we did not assume any special form for the random-effects variance-covariance matrices (Ψ). The variance-covariance structure of the within-plot error ($\sigma^2\Lambda_i$) was modeled using a suitable variance-covariance function by examining the standardized residuals (PINHEIRO and BATES, 2000). We then selected the best model based on AKAIKE's information criterion (AIC; AKAIKE, 1974). In this approach, the model with the smallest (or most negative) AIC is considered significantly more appropriate than competing models if the difference in AIC values between the models is greater than 2 (BURNHAM and ANDERSON, 2002).

For our regression analyses, we used all data for the period between the first and last measurements. This period will hereafter be called the "whole period." However, neither equations (2) nor (4) was originally intended to describe the portion of the D_q-N_u trajectory that includes phases A and B in Figure 1. Therefore, to exclude these data from our regression analysis, we only used data for the period when mortality was sufficiently great to indicate that the stand had entered phases C or D. This period was visually selected using plots of the changes in stem density with age. This period will hereafter be called the "self-thinning period." Fitting by the mixed-effects model was performed using the "lme" function in the "nlme" library created by PINHEIRO and BATES (2000) for use with the R software (R DEVELOPMENT CORE TEAM, 2012).

Parameter Estimation and Model Selection for the D_q-N_t Relationship in Thinned Stands

To examine whether the D_q-N_t trajectory deviated from the power law in old stands, data from thinned stands were fitted to equations (2) and (4). With a method similar to the one used for the D_q-N_u relationship in unthinned stands, data were fitted using the linear-mixed effects model approach (equations (5) and (6)). However, unlike in our analysis of the D_q-N_u relationship in unthinned stands, we used all data from the thinned stands and did not select data based on the degree of stand crowding.

Effects of Changes in Stand Leaf Mass during Stand Development on the Form of the D_q-N_u and D_q-N_t Relationships

Allometric models for the D_q-N_u relationship (SATOO, 1962; OSAWA and ALLEN, 1993) can explain how a change in stand leaf mass effects the form of the D_q-N_u relationship. We have assumed, as SATOO (1962) and OSAWA and ALLEN (1993) did, that a forest consists of individual trees of the same diameter (D_q) and the same leaf mass (w_L). By assuming an allometric relationship between D_q and w_L, we obtain the following equations:

$$w_L(t) = aD_q(t)^b \quad (7)$$

where a and b are regression coefficients, and t is the stand age. By definition, total leaf mass (W_L) is obtained as follows:

$$W_L(t) = w_L(t)N_u(t) \tag{8}$$

Combining equations (7) and (8) yields the following equation:

$$N_u(t) = [W_L(t)/a]\ [D_q(t)^{-b}] \tag{9}$$

Equation (9) indicates that the D_q-N_u relationship can be explained using a combination of temporal changes in stand leaf mass, $W_L(t)$, and the allometric relationship between D_q and w_L. When total leaf mass remains constant at K, as follows:

$$W_L(t) = K \tag{10}$$

Equation (9) can be rewritten as

$$N_u(t) = (K/a)\ [D_q(t)^{-b}]. \tag{11}$$

The power law in equation (2) is then valid because the mathematical expression of equations (2) and (11) are identical when equation (11) is expressed in logarithmic form. When total leaf mass is not constant, but decreases from K to K_1, $N_u(t)$ decreases from $(K/a)\ [D_q(t)^{-b}]$ to $(K_1/a)\ [D_q(t)^{-b}]$, as shown in Phase D of Fig. 1. Therefore, the D_q-N_u relationship deviates downward from the curve estimated by the power law. We can also derive ZEIDE's model to account for deviation from the power law using equation (8) and assuming that stand leaf mass changes with respect to D_q as follows:

$$W_L(t) = KD_q(t)^{b_0}\exp\left[\lambda D_q(t)\right] \tag{12}$$

where b_0 and λ are regression coefficients. Combining equations (9) and (12) yields the following equation:

$$N_u(t) = (K/a)D_q(t)^{b_0-b}\exp\left[\lambda D_q(t)\right] \tag{13}$$

When stand leaf mass changes with stand development as described in equation (12), ZEIDE's model is valid because the mathematical expression of equations (4) and (13) are identical when equation (13) is expressed in logarithmic form. Therefore, according to these allometric models, the power function and ZEIDE's model of the D_q-N_u relationship implicitly assume that stand leaf mass changes following equations (10) and (12), respectively.

Comparing equation (2) with equation (11), the constant leaf mass (K) is estimated from the self-thinning coefficient of equation (2) and the allometric coefficient of equation (7), as follows:

$$K = a\exp(\beta) \tag{14}$$

Note that the validity of equation (14) requires that γ from equation (2) is equal to b from equation (7). Comparing equation (4) with equation (13), the coefficients related to the change in stand leaf mass during stand development (K, b_0, and γ) from equation (12) are estimated from the self-thinning coefficients of equation (4) and the allometric coefficients of equation (7), as follows:

$$K = a\exp(\beta)$$
$$b_0 = b - \gamma$$
$$\lambda = -\eta. \tag{15}$$

Thus, we can predict the D_q-W_L relationship using equations (10) or (12) with the coefficients estimated by equations (14) or (15) from self-thinning (equations (2) or (4)) and allometric (equation (7)) relationships.

We examined the effects of changes in stand leaf biomass during stand development on the form of the D_q-N_u and D_q-N_t relationships. For this analysis, we compared the D_q-W_L relationship in the experimental plots with those estimated using equations (10) or (12). When the power law was selected as the most reasonable model, we estimated the change in stand leaf biomass during stand development using equations (10) and (14). Here, we determined b of equation (7) as γ, which was obtained by fitting equation (2), because equation (14) requires the condition that γ is equal to b. Then, we determined a of equation (7) as $\overline{w}_L\overline{D}_q^{-\gamma}$, where $\overline{w}_L$ and $\overline{D}_q$ are the mean values of w_L and D_q, respectively, obtained at each measurement time in all plots. When ZEIDE's model was selected as the most reasonable model, we estimated the change in stand leaf biomass during stand development using equations (12) and (15). Here, we determined a and b as regression coefficients obtained by fitting equation (7) to the data using a linear mixed-effects model similarly to the method used for equation (5).

RESULTS

D_q-N_u Relationship in Unthinned Stands

For the whole period between the first and last measurements in the unthinned stands, the AIC value for the D_q-N_u relationship using REINEKE's power function was greater (less negative) than that obtained using ZEIDE's model, and the difference was greater than 2 (Table 2). These results indicate that ZEIDE's model is a more reasonable model than REINEKE's power function. Thus, nonlinearity on a log-log scale was found using data for the whole period (Fig. 2a).

Stem densities at the time of the first measurement (31 years old) in the three unthinned plots varied greatly among the plots (Fig. 3, Table 1). However, stem density decreased with age in all three plots, and the decrease in the plot with the highest density at this first measurement (plot 3) was larger than that in the plots with a lower density (plots 1 and 2). The decrease in plot 3 began earlier (about age 36) than in the other plots. We selected the period from 41 years to the age at the last measurement (96 years) for plot 3 and from 56 to 96 years for plots 1 and 2 as the self-thinning period, during which time sufficient mortality occurred to meet the criteria for the self-thinning period. We only used data during this self-thinning period for the following analyses of the D_q-N_u relationship in the unthinned stands.

During the self-thinning period, AIC values for the D_q-N_u relationship in unthinned stands using REINEKE's power function were greater (less negative) than those using ZEIDE's model, but the difference was smaller than 2 (Table 2). The AIC values therefore indicate that neither model appears to be significantly superior. However, examining the other statistics in Table 2 reveals that one of the coefficients of ZEIDE's model (η_0) was not statistically significant (p = 0.076), whereas the coefficients of REINEKE's model were all statistically significant (p < 0.001). From these results, we judged that REINEKE's power function was a more reasonable model than ZEIDE's model. Thus, nonlinearity on a log-log scale was not found for the self-thinning period in the unthinned stands (Fig. 2a).

Total leaf mass in the unthinned stands increased with age during the early period, reaching almost steady values by around 60 years (Fig. 4a). The period for which mortality was judged to be sufficiently high to meet the criteria for self-thinning (Fig. 3) nearly overlapped with the period experiencing a steady state for total leaf mass (Fig. 4a).

The change in total leaf mass with increasing D_q in the unthinned plots was close to the values estimated using equations (12) for the whole period, and (10) for the self-thinning period (Fig. 5a). This result indicated that the allometric models in equations (13) and (11) are valid for the whole period and the self-thinning period, respectively.

D_q-N_t Relationship in Thinned Stands

The AIC value for the D_q-N_t relationship in thinned stands was smaller (more negative) using Zeide's model than using Reineke's power function, and the difference was greater than 2 (Table 2). These results indicate that Zeide's model was a more reasonable model than the power function (Fig. 2b).

The total leaf mass in the thinned stands fluctuated widely with age due to the sudden and discontinuous decreases caused by thinning (Fig. 4b). However, on average, the total leaf mass increased with age during the early period, reaching nearly steady values by around 80 years.

The change in total leaf mass with increasing D_q in thinned forests was estimated reasonably well using equation (12) (Fig. 5b). This result indicated that the allometric model of equation (13) is valid.

DISCUSSION

In Old, Overcrowded Stands, Does the D_q-N_u Relationship Deviate from the Power Function Due to the Effects of Aging?

During the self-thinning period, the D_q-N_u relationship in the unthinned stands was linear in the log-log graph (Fig. 2a) and was thus approximated by the power function (Table 2). Thus, the D_q-N_u relationship in old overcrowded stands did not deviate from the power function due to the effects of aging. The total leaf mass in unthinned stands remained relatively steady during the self-thinning period (Fig. 4a). The change in stand leaf mass as a function of D_q was predicted reasonably well based on the allometric model (Fig. 5a), which related the change in total leaf mass during stand development to the D_q-N_u relationship. Thus, the allometric model is valid, and the constancy of stand leaf mass supports the validity of Reineke's power function.

Our finding of linearity in the long-term trajectory of the D_q-N_u relationship is inconsistent with the results of several previous studies that reported nonlinearity in this relationship (e.g. Meyer, 1938; Laasasenaho and Koivuniemi, 1990; Zeide, 1995, 2005). One possible reason for this discrepancy is that the age at which forests reach the transition from Phase C to Phase D in Figure 1 may differ among species; specifically, the age for Japanese cedar may be older than those of other species. Japanese cedar forests in Akita District, where our study site is located, are well known to grow more slowly at early ages and to exhibit less of a decline at older ages than is the case in other regions of Japan (e.g. Terazaki *et al*., 1964). Thus, our Japanese cedar forests may proceed more slowly along the trajectory of stand development than is the case for other species or for the same species in other regions. Therefore, the stands we used in our analysis may still be too young for us to observe nonlinearity.

Another possible reason for the discrepancy is that we excluded data during periods when mortality was not sufficiently high to indicate the occurrence of the self-thinning phase (i.e., phases A and B in Fig. 1). If we used all data for the whole period between the first and last measurements in the unthinned stands, nonlinearity occurred (Fig. 2a, Table 2). This nonlinearity was attributed to a change in stand leaf mass during stand development for the study period as a whole (Figs. 4a, 5a). However, in this case, the factor responsible for the nonlinearity is an increase in leaf mass at a younger age, but not the decline at an older age that Zeide (2005) assumed. Similarly, some of previous studies that used data from young stands may have wrongly argued for nonlinearity during the

Table 2 Comparisons of model performance for the D_q-N_u and D_q-N_t relationships in unthinned and thinned stands

Relationship	Treatment	Range of data	Equation	Fixed effects			Random effects†			AIC‡
				β_0	γ_0	η_0	β_i	γ_i	η_i	
D_q-N_u	Unthinned	All measurements	Power	10.738	1.074		+**	+		–69.12
				(p < 0.001)	(p < 0.001)					
			Zeide	5.001	–1.404	0.088	+	+		–116.77
				(p < 0.001)	(p < 0.001)	(p < 0.001)				
		Self-thinning period only*	Power	12.186	1.486		+			–122.54
				(p < 0.001)	(p < 0.001)					
			Zeide	13.132	1.868	–0.012	+			–123.17
				(p < 0.001)	(p < 0.001)	(p = 0.076)				
D_q-N_t	Thinned	All	Power	10.765	1.223		+	+		–386.81
				(p < 0.001)	(p < 0.001)					
			Zeide	8.911	0.465	0.023	+	+		–421.77
				(p < 0.001)	(p = 0.001)	(p < 0.001)				

* Self-thinning period means the period during which sufficient natural mortality occurred.
† + indicates that the random-effects parameter is present in the model.
‡ Akaike's information criterion (AIC) for another model with a combination of random effects was larger (less negative) than that of the model represented in this table for each equation.

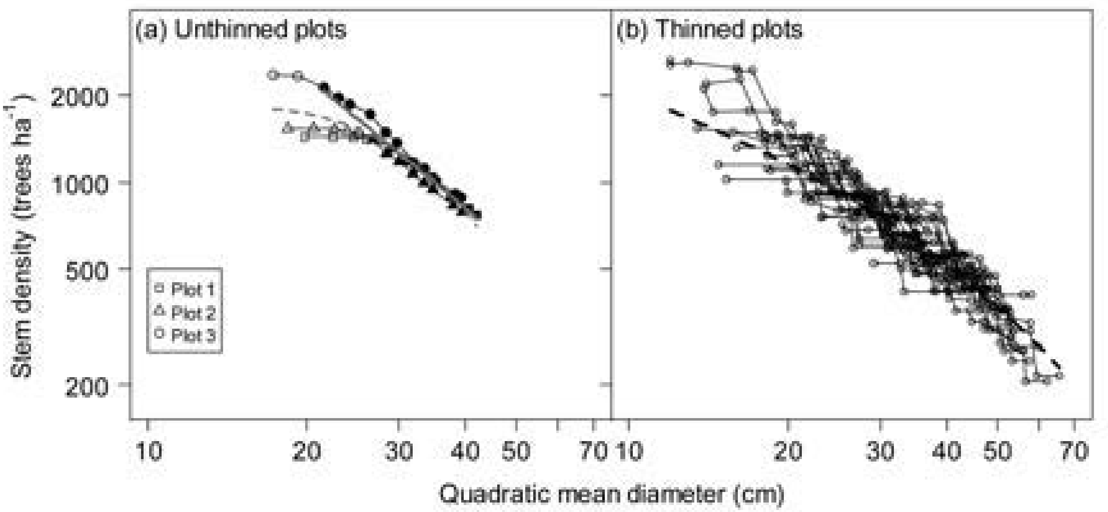

Fig. 2 Relationship between the quadratic mean diameter (D_q) and the stem density in (a) unthinned (N_u) and (b) thinned (N_t) stands. The black symbols in (a) indicate that the plot is experiencing the self-thinning. Gray dashed and solid lines in (a) show the values estimated using the fixed effects of the selected models for unthinned stands during the whole period between the first and last measurements and during the self-thinning period, respectively. The black dashed line in (b) represents the values estimated using the fixed effects of the selected models for thinned stands.

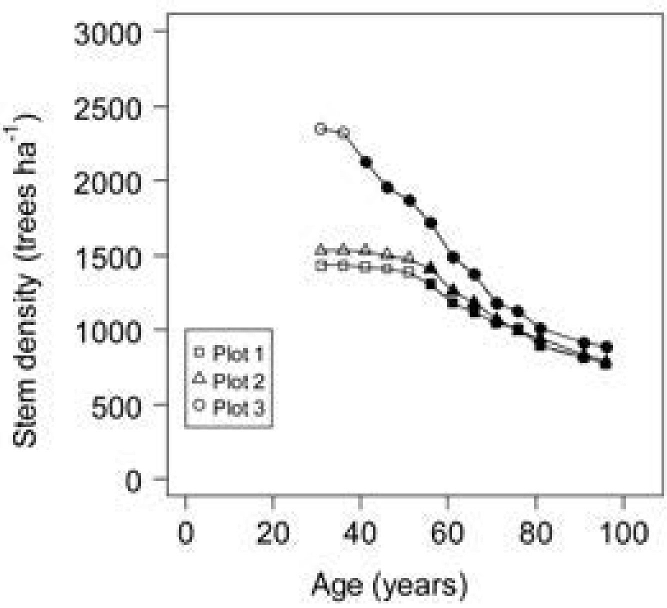

Fig. 3 Change in stem density in the unthinned stands. The black symbols indicate that the plot is experiencing the self-thinning period.

transition from phases C to D because they inadvertently used data from phases B to C.

Our results indicated that REINEKE's power function will be useful for unthinned forests in our study area to an age of around 100 years. The rotations of Japanese cedar plantations in Japan are generally becoming longer from 30 to 60 years to 100 to 150 years, and scientific information on these old plantations is needed to support their management. REINEKE's power equation can potentially be used to develop guidelines for managing these plantations with an extended rotation period; for example, the stand density index *SDI* (REINEKE, 1933) calculated by using REINEKE's equation can be used to describe the degree of crowding. In Japan, diameter-based indicators for stand density, such as *SDI*, have not previously been used for forest management, although *SDI* has been widely applied in forestry in several other countries (Avery and Burkhart, 1994). Instead, in Japan, height-based indicators for stand density, such as the relative yield index (ANDO,

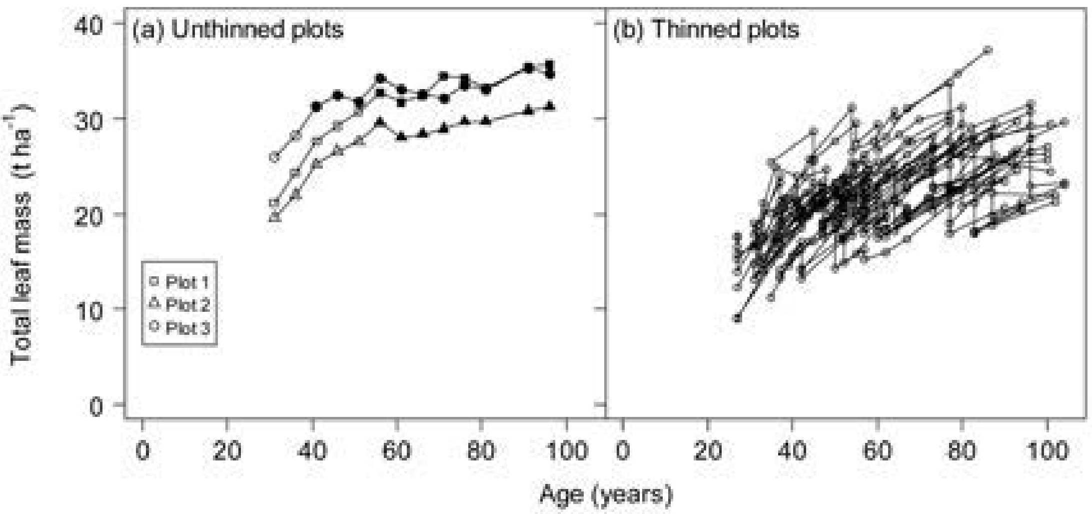

Fig. 4 Change in total leaf biomass in (a) unthinned and (b) thinned stands. The black symbols in (a) indicate that the plot was experiencing the self-thinning period.

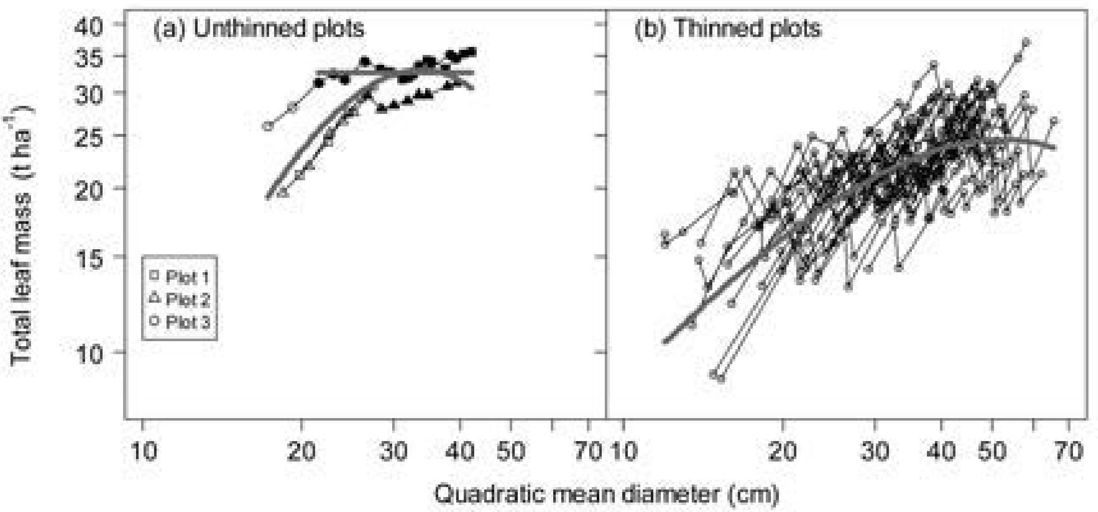

Fig. 5 Changes in total leaf biomass as a function of the quadratic mean diameter (D_q) in (a) unthinned and (b) thinned stands. The black symbols in (a) indicate that the plot is experiencing the self-thinning period. The gray straight line in (a) shows the values estimated using equations (10) and (14) for REINEKE's power function. The gray curved lines in (a) and (b) show the values estimated using equations (12) and (15) for ZEIDE's model. Here, we used $\ln w_L = -8.962453 + 1.557248 \ln D_q$ for the unthinned plots and $\ln w_L = -9.322756 + 1.688687 \ln D_q$ for the thinned plots as the regression results for equation (7) expressed in logarithmic form to determine coefficients *a* and *b* for use in equation (15).

1968) based on the self-thinning law and other ecological laws, are commonly used. However, diameter measurements are more accurate and less time-consuming than tree height measurements (Miyake *et al.*, 2003). According to Avery and Burkhart (1994), the measurement consideration is a key reason for the wide application of *SDI* in forestry. Therefore, in the future, REINEKE's power function should be used to support management of old Japanese cedar forests in Japan

In Old Thinned Forests, Does the D_q-N_t Relationship Deviate from the Power Function Due to the Effects of Aging?

The D_q-N_t relationship in thinned stands was nonlinear in a log-log graph (Fig. 2b) and was therefore approximated by ZEIDE's function (Table 2). Thus, the D_q-N_t relationship in old thinned stands deviates from the values predicted using the power function. However, the deviation was not due to the effects of aging, but was instead a consequence of temporal variability in the total stand leaf mass. Total leaf mass increased with age during the early period, reaching nearly steady values (Fig. 4b). The allometric model predicted the changes in stand leaf mass as a function of D_q reasonably well

(Fig. 5b). Thus, the allometric model is valid, indicating that the increase in stand leaf mass accounted for the validity of ZEIDE's model and that the deviation was due to an increase in stand leaf mass at a younger age, but not due to the decline at older ages, as ZEIDE (2005) assumed.

The factor responsible for the deviation was different from that in ZEIDE's original assumption. However, ZEIDE's function can still approximate the D_q-N_t relationship in old thinned stands because it can implicitly describe the increase in stand leaf mass at an earlier age (Phase B in Fig. 1), as well as the decrease at an older age (Phase D in Fig. 1). In managed forest stands, the power law has typically been used to develop simple stand yield tables or more complicated stand growth simulators (e.g., SHIRAISHI, 1986; SCHÜTZ and ZINGG, 2010). Taking a more long-term perspective, we recommend that in addition to the power function, ZEIDE's model should be considered as a candidate for developing stand yield tables or stand growth simulators.

Comparison of Stand Development in the Unthinned and Thinned Forests

Figures 4 and 5 indicate two important changes in stand leaf mass with increasing stand age and tree size: (1) Both forms of the curve for the changes in unthinned and thinned forests were convex upward. (2) Although the stand leaf mass had reached a nearly constant value in unthinned forests at an early age and small tree size, stand leaf mass appeared to have not yet reached a completely constant stage in the thinned forests, or reached this constant stage at an older age and greater tree size than in the unthinned forest. These two results indicated that thinning shifts the curve for changes in stand leaf mass with increasing age and tree size to the right. In other words, thinning increases the tree size and delays the age at which the stand leaf mass reaches its peak.

Applying these results to the model shown in Figure 1, in which the trajectory in unthinned forests appears to pass through Phase B and to be proceeding through Phase C, the trajectory in thinned forests appears to be proceeding through Phase B. This result appears to disagree with the inference in the Introduction that stand development proceeds more rapidly in thinned stands than in unthinned stands. If we instead superimpose Figure 2a on Figure 2b (thereby creating Fig. 6) and compare the results with Figure 1, it appears that the trajectory in thinned forests, which is proceeding through Phase B, will eventually reach Phase D without having passed through Phase C. Thus, thinning prevents forests from entering Phase C (i.e., from entering the self-thinning period). This description may be no surprise, but it nonetheless has useful implications for understanding the effects of thinning on stand volume growth, as reported by NISHIZONO *et al.* (2008b) and NISHIZONO (2010).

NISHIZONO *et al.* (2008b) and NISHIZONO (2010) analyzed the effects of thinning on stand volume growth using the same dataset used in the present study. They reported that the growth stage appears to become younger after thinning and that this apparent "rejuvenation" effect delays the onset of the age-related decline in stand volume growth when the thinning intensity is not excessive. Thus, the net yield and net increment in thinned stands surpass those in unthinned stands at older stand ages. In addition, one of the probable explanations of the delay in the age-related decline caused by thinning is a decrease in mortality. Unifying the findings of our previous studies with those of the present study, we propose the following hypothesis for interpreting the effects of thinning on stand volume growth when the thinning intensity is not excessive: (1) Moderate thinning prevents forests from entering the self-thinning phase, because it delays the stand leaf mass from reaching the maximum, leading to an apparent "rejuvenation" effect. (2) The absence of a self-thinning period leads to less mortality. The decreased mortality delays the onset of the age-related decline in stand volume growth. (3) Therefore, the net yield and net increment in thinned stands surpass those in unthinned stands at older stand ages.

In our previous research (NISHIZONO *et al.*, 2008; NISHIZONO, 2010), we did not note how the effects of thinning on stand volume growth resulted from the change in stand development associated with self-thinning. Our present results appear to indicate that the effects of thinning on stand volume growth is strongly related to the effects on stand development associated with self-thinning and changes in stand leaf mass. In addition, NISHIZONO's (2010) findings should be strictly limited to the stages of stand development before Phase D, because the dataset used in that earlier study did not include any data from Phase D, and the existence of self-thinning during Phase D was unclear. The hypothesis we have proposed in this section has not been substantiated by an adequate test, and therefore requires further analyses. To test this hypothesis, we will analyze the effects of thinning on mortality and stand structure in more detail in our future research.

CONCLUSIONS

In the present study, we studied the ability of REINEKE's power function to describe the long-term trajectory of the relationships between D_q and stem density in thinned (N_t) and unthinned (N_u) forests. We found that in old thinned stands, the D_q-N_t relationship deviated from the power function, whereas the D_q-N_u relationship in unthinned stands did not deviate from this function during the self-thinning period. These results were strongly related to the changes in stand leaf mass that occurred during stand development. Furthermore, we proposed the hypothesis that the effects of thinning on stand volume growth are strongly related to the changes in stand development associated with self-thinning and changes in stand leaf mass. In future research, this hypothesis must be tested. For both the thinned and the unthinned stands, our experimental forests appear to have not yet reached Phase D in Figure 1. Therefore, the age at which forests reach the transition to Phase D remains uncertain. To answer this question and gain a deeper understanding of the relationships between self-thinning and stand growth, continual long-term monitoring will be needed in our experimental forests.

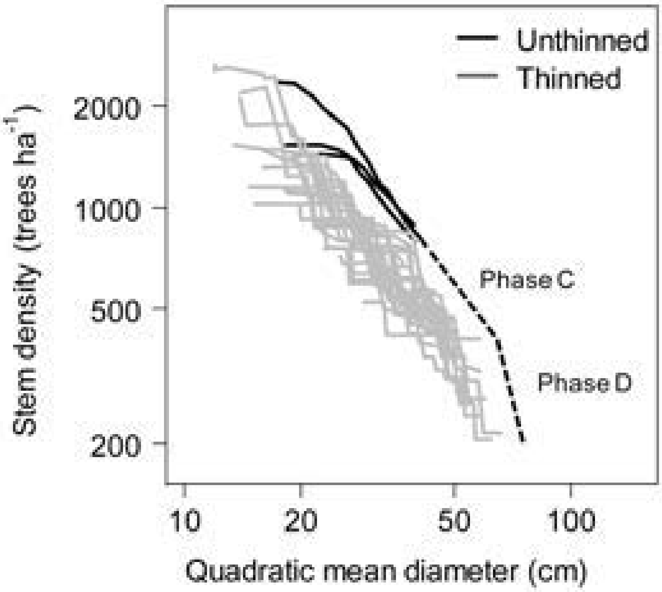

Fig. 6 Comparison of the relationships between the quadratic mean diameter (D_q) and stem density in unthinned (N_u) and thinned (N_t) stands. The dashed line indicates the hypothetical trajectory for an unthinned stand, assuming that the schematic model in Figure 1 is valid.

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APPENDIX A

First, the data on leaf mass, DBH, tree height, and age of *C. japanica* individual trees was collected from ten research reports. Second, we selected the data only on trees included within the range of DBH and age in our data used for this study (i.e., 6.1-84.5 cm in DBH, 27-104 years in age). Thereby, the data selected was derived from five research reports (HARADA *et al.*, 1972, NISHIMURA *et al.*, 1992a, b; WATANABE and MOTEKI, 2007; TANGE and KOJIMA, 2010). The ranges of DBH and age in the final dataset (covering 148 trees) were 7.5 to 58.1 cm and 28 to 92 years, respectively. The individual leaf mass was estimated from d_i and h_i using equation (3).

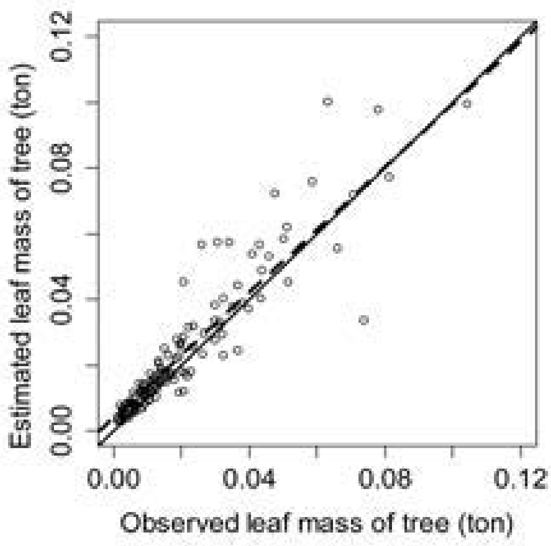

Fig. A1 Relationship between observed and estimated leaf mass by equation (3). The solid line represents 1:1; the dashed line represents linear regression.

Linear regression analysis was performed for the relationship between the observed leaf mass (x) and estimated leaf mass (y) by using equation (3) (Fig. A1). The equation of the regression line was y=0.9508x+0.0041 (p < 0.001 for slope and intercept, and r^2=0.8452), and 95% confidence intervals were 0.8797 and 1.0220 for slope, and 0.0020 and 0.0062 for intercept. These results indicated that the regression line was close to y=x, and that equation (3) has sufficient predictive capacity. Therefore, equation (3) is valid for the data derives from literature, independent of the data used by HOSODA and IEHARA (2010). It should also be noted that there were ten sample trees with DBH $\geq$ 45 cm in our dataset, but only four in the dataset used for determining equation (3) (HOSODA, personal communication), and that there were 21 sample trees with age $\geq$ 80 years in our dataset, but only four in the dataset used for determining equation (3) (HOSODA, personal communication). Thus, our dataset contained a larger number of large and old trees than in the dataset of HOSODA and IEHARA (2010).

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Article

Simple Method for Land-Cover Mapping by Combining Multi-Temporal Landsat ETM+ Images and Systematically Sampled Ground Truth Data：A Case Study in Japan

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ABSTRACT

This study aimed to propose a simple and practical method for land-cover mapping by multi-temporal Landsat Enhanced Thematic Mapper Plus (ETM+) images in combination with systematically sampled ground truth data. The land-cover mapping was attempted and evaluated in two study areas located in northern and southwestern Japan, using two-seasonal and three-seasonal images. The results of this study indicated that the accuracy of land-cover map can be improved by addition of autumn image to two-seasonal images of spring and summer images. The user's accuracy was greatly improved in the land-cover which shows clear seasonal changes of spectral characteristics such as deciduous forests. The final land-cover maps of entire study areas were created using two-seasonal images and three-seasonal images (the overall accuracy and overall Kappa coefficient were 81.4% and 0.746 for Study Area 1, and 87.6% and 0.779 for Study Area 2, respectively). In recent years, access to ETM+ images of many different seasons is becoming easier. This study indicated that the approach using multi-temporal ETM+ images from many different seasons would be one of the possible choices in order to create nationwide land-cover map with higher accuracy.

Keywords: forest type, Landsat ETM+, unsupervised classification, wall-to-wall map

INTRODUCTION

Land-cover maps derived from remotely-sensed data provide fundamental information on land entities at a regional and national scale. In particular, land-cover maps including forest types can be used for forest management and various ecological applications (Franklin, 2001; Cohen and Goward, 2004; Kerr and Ostrovsky, 2003; Riitters *et al.*, 2002; Turner *et al.*, 2003; Wulder *et al.*, 2008). In addition, the land-cover maps are used as essential data in process-based models to simulate carbon cycles in relation to global warming (Ito and Oikawa, 2002; Sasai *et al.*, 2005). To elicit the appropriate result in related studies, the use of accurate land-cover map is extremely important.

One of the serious problems encountered in remote sensing data analysis is changes of spectral characteristics caused by seasonal changes of vegetation (Awaya and Tanaka, 1996; Awaya and Tanaka, 1999). The seasonal changes of spectral characteristics cause the variation in the classification results (Murakami, 2004). In addition, the difference of the phenology within the single-date image also influences classification result, in a large geographical extent especially. Therefore, these factors should take into consideration in the analysis of remotely-sensed data to avoid spectral confusion (Gofc-Gold, 2011).

On the other hand, because the pattern of seasonal changes are different among the land-cover, the approach using multi-temporal satellite images is a simple and effective approach to improve the accuracy of land-cover map. The multi-temporal images from coarse-resolution satellite sensors such as NOAA/AVHRR (Advanced Very High Resolution Radiometer), SPOT/VEGETATION, and Terra/MODIS (MODerate-resolution Imaging Spectroradiometer) have been widely used for land-cover mapping (e.g., Saito *et al.*, 2007; Xiao *et al.*, 2002), because these sensors can be observed the Earth at less than one day intervals and these coarse-spatial-resolution images are usually freely available. In recent years, images recorded by the Enhanced Thematic Mapper Plus (ETM+) sensor installed on Landsat satellite also became freely available, thus this enabled us to use the images from many different seasons for the land-cover mapping at a nationwide scale with fine spatial resolution.

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Many studies already have shown the utility of multi-temporal medium-resolution satellite images for land-cover mapping (BROWN DE COLSTOUN *et al.*, 2003; MCCLEARY *et al.*, 2008; VOGELMANN *et al.*, 1998; WOLTER *et al.*, 1995; YAMAGATA *et al.*, 1996; YUAN *et al.*, 2005), especially using images from two different seasons. SAKAI *et al.* (2009) showed that the use of the multi-temporal ETM+ images was effective to increase classification accuracy in the mountainous area of northern Japan, and concluded that the use of the ETM+ images from two or three different seasons was suitable in terms of classification accuracy and efficiency. They also reported that the differences of classification accuracy between images which applied atmospheric and topographic effect correction and the un-corrected images would become small when using many images from different seasons (SAKAI *et al.*, 2009). From these findings, it seems that the approach using multi-temporal ETM+ images would have a possibility as a simple and practical method for land-cover mapping at areas influenced by seasonal change, although this approach should be verified its availability in other regions and may need to be slightly modified for practical operation.

This study aimed to propose a simple and practical method for land-cover mapping which includes forest types by combining multi-temporal ETM+ images and systematically sampled ground truth data. As mentioned above, in recent years, access to ETM+ images of many different seasons is becoming easier; we therefore especially focused on the utility of images from three different seasons for accuracy improvement. In this study, we evaluated an availability of the method in two study areas located at different geographical and ecological areas of Japan.

MATERIALS AND METHODS

Study Areas

Location of the two study areas are shown in Fig. 1. Study Area 1 is located in eastern part of Hokkaido, Japan (path106-row030 on the world reference system-2), and belongs to the cool temperate zone. This study area contains evergreen coniferous, deciduous coniferous and deciduous broadleaved forests. Study Area 2 is located in southern part of Kyushu, Japan (path112-row038 on the world reference system-2), and belongs to the warm temperate zone. This study area contains evergreen coniferous, evergreen broadleaved and deciduous broadleaved forests. The climatic conditions differ considerably between two study areas because they are more than 1,000 km apart in latitudinal direction.

In Study Area 1, the annual average temperature is 5.9°C and the annual rainfall is 1,045.2 mm at Kushiro Meteorological Observatory (latitude 42° 59.11′N , longitude 144° 22.6′E) between 1971 and 2000 (JAPAN METEOROLOGICAL AGENCY, 2001). Most of the area is covered by snow between October and April. In contrast, Study Area 2, the annual average temperature is 18.3°C and the annual rainfall is 2,279.0 mm at Kagoshima Meteorological Observatory (latitude 31° 33.2′N , longitude 130° 32.8′E) between 1971 and 2000 (JAPAN METEOROLOGICAL AGENCY, 2001).

In Study Area 1, plantation forests are mainly composed of Japanese larch (*Larix kaempferi*), Saghalien fir (*Abies sachalinensis*) and Ezo spruce (*Picea jezoensis*) (MIYAWAKI, 1988). Natural regeneration forests are classified to a deciduous broadleaved forest and a mixed forest of evergreen

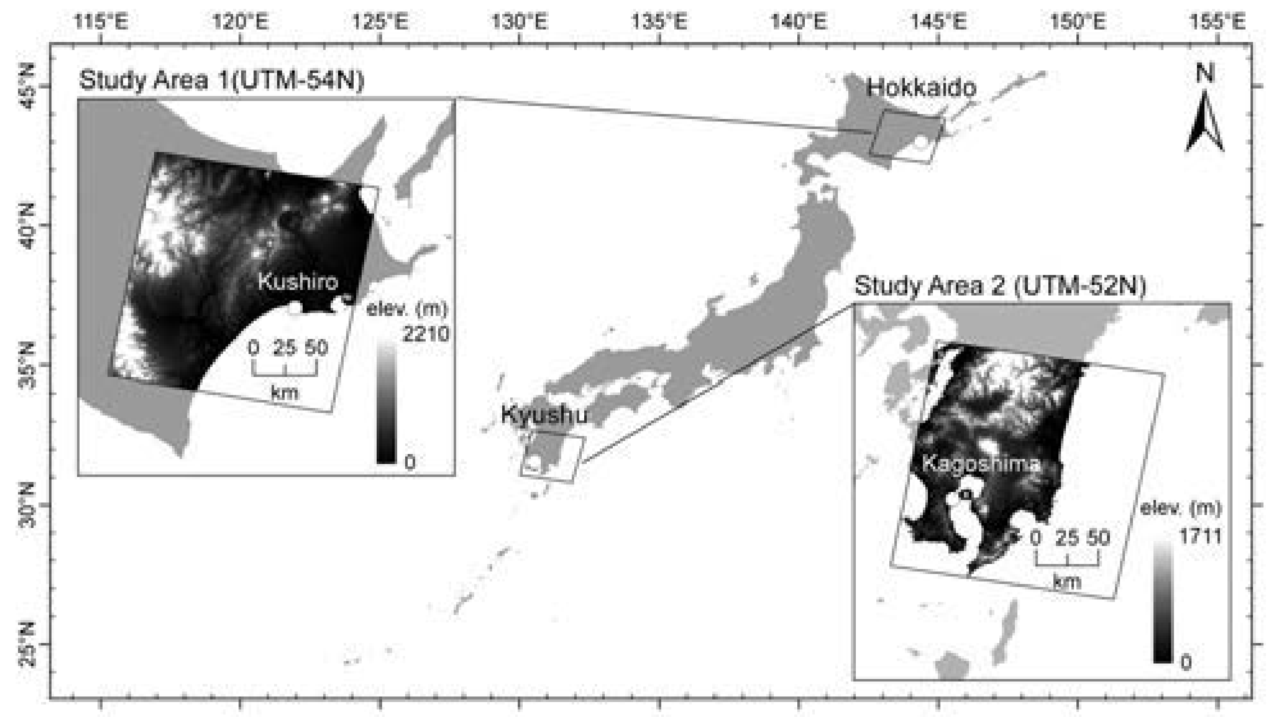

Fig. 1 Location of study areas.
The black and white background shows the digital elevation model published by the Geospatial Information Authority of Japan. The circles represent the locations of the Kushiro and Kagoshima Meteorological Observatories.

coniferous and deciduous broadleaved trees. Generally, evergreen broadleaved forest does not exist due to climatic limitation. The forest floor is often covered by dwarf bamboo (*Sasa* sp.). Large-scale agricultural fields, grasslands, wetlands are widely distributed on the plains of Study Area 1. On the other hand, in Study Area 2, the plantations are composed of Japanese cedar (*Cryptomeria japonica*) and Japanese cypress (*Chamaecyparis obtusa*) which are main commercial timber trees in Japan. Deciduous coniferous species are rarely planted. In natural regeneration forest, evergreen broadleaved trees are dominated in warmer temperatures or at relatively low altitudes; in contrast, deciduous broadleaved trees dominated in low temperatures or at high altitudes. Forest floor in this region at high altitude is often covered by dwarf bamboo. Agricultural field are widely spread; however, range of grasslands and non-forest natural vegetation is limited in this area (Miyawaki, 1981).

Satellite Images and Pre-Processing

ETM+ images acquired between 1999 and 2002 were used in this study. These images were provided by the Earth Resources Observation and Science (EROS) Center, the United States Geological Survey (USGS). The product type of all images was level 1T (standard terrain correction; L1T). The L1T products were orthorectified using the digital elevation model (DEM) derived from the Shuttle Radar Topography Mission (SRTM), and resampled using the cubic convolution method. We used digital numbers (DN) from channel 3 (Red), 4 (Near Infrared) and 5 (Shortwave Infrared), because the combination of these three channels has a similar performance to the use of the six channels image (i.e. channel 1, 2, 3, 4, 5, and 7) for the image classification (e.g., Sheffield, 1985; Yamagata *et al*., 1996).

ETM+ images recorded before foliation of deciduous trees with high sun elevation (i.e. spring) were selected as the images of leaf-off period (H1 and K2). Only small areas along the shoreline were covered by clouds in H1, thus we assumed that these clouds can be negligible. More than two images were selected to cover the entire study area at leaf-on period to remove cloud cover area because there were many clouds in this period. The ETM+ images recorded at autumn (H6 and K4) were used as additional images. Table 1 shows acquired date, season, status of the forest canopy, sun elevation angle, and cloud coverage (original image including coastal water body) of each ETM+ image.

Multi-temporal ETM+ images from two different seasons and three different seasons (hereafter we referred as two-seasonal image and three-seasonal image, respectively) were used for the image classification. Thus, the multi-temporal images used for the classification have $3n$-dimensional feature space (i.e. explanatory variable spaces; 3 channels × n seasons). For example, if we used two-seasonal image, the image have six-dimensional feature space. The combination of images from leaf-on and leaf-off periods of deciduous trees is considerably reasonable for classifying forest type since the spectral differences between these two periods are crucial to distinguish evergreen forest from deciduous forest. Therefore, we used at least two images from leaf-on and leaf-off periods for the classification. Table 2 and Table 3 show the list of two-seasonal and three-seasonal images used for the classification, respectively.

Areas of coastal water body were masked out using the Japanese shoreline data of the Digital National Land Information, which was published by the National and Regional Planning Bureau, the Ministry of Land, Infrastructure, Transport and Tourism, Japan. Clouds, hazes and their shadows on all single-date images that were included

Table 1 Overview of original ETM+ images used in this study

(*a*) Study Area 1

ID	Date	Season	Status of the forest canopy	Sun elevation angle (°)[a]	Cloud coverage (%)[b]
H1	29 Apr. 2002	Spring	Leaf-off	55.83	14
H2	26 June 2000	Summer	Leaf-on[c]	63.11	29
H3	11 Aug. 1999	Summer	Leaf-on	56.35	23
H4	13 Aug. 2000	Summer	Leaf-on	55.46	9
H5	16 Aug. 2001	Summer	Leaf-on	54.51	65
H6	28 Sep. 1999	Autumn	Leaf-on/Leaf-off	41.99	1

(*b*) Study Area 2

ID	Date	Season	Status of the forest canopy	Sun elevation angle (°)[a]	Cloud coverage (%)[b]
K1	17 Apr. 2000	Spring	Leaf-off	59.53	0
K2	25 May 2002	Summer	Leaf-on	66.03	0
K3	6 July 2000	Summer	Leaf-on	65.92	8
K4	16 Oct. 2002	Autumn	Leaf-on/Leaf-off	44.62	0

[a] obtained from image header file
[b] obtained from scene information provided by the USGS Global Visualization Viewer. These values denote the cloud coverage that contains errors and the clouds on the sea.
[c] deciduous trees in most study area seemed to after leaf expansion. However, leafless trees were found in some areas in high elevation.

in each multi-temporal image were identified by visual interpretation, and masked out manually from each multi-temporal image. Correction of topographic effects was not performed because we focused on the use of multi-temporal images in this study.

Ground Truth Data

Systematically sampled ground truth data derived from first term (1999-2003) of the Forest Resources Monitoring Survey (FRMS) (Hirata *et al.*, 2010; Iehara, 1999) was used for assignment of the land-cover class and validation of the land-cover maps. The FRMS plots were set up at systematic 4-km grid intervals. Using FRMS plot data, we defined the following seven land-cover classes: evergreen coniferous forests (ECF), deciduous coniferous forests (DCF), evergreen broadleaved forests (EBF), deciduous broadleaved forests (DBF), non-forest vegetation and agricultural fields (including bare soil lands) (V&A), urban and built-up lands (URB), and water (WAT). The procedure of the development of the ground truth data is described in the following steps:

(a) For the sampled circular plots in forest area, land-cover class (i.e. forest type) was determined by the stand volume data based on the field survey (medium and small circular area; 0.04ha). If the stand volume of one specific forest type (i.e. ECF, DCF, EBF and DBF) exceeded 75% of the total volume of the plot, the forest type of the plot was defined as that forest type. Mixed forests were excluded from the analysis in this study.

(b) For the sampled plots in non-forest area, the land-cover type was determined by our interpretation of the black and white aerial photograph (1-m ground resolution; taken around 1990) and the ETM+ images.

(c) Homogeneity in a circular area with a radius of 50 m (i.e. over 3×3 pixels of ETM+) surrounding each plot was checked by visual interpretation of the aerial photographs to avoid misclassification due to geometric errors between ETM+ images and sampled circular plot. Plot in heterogeneous area (e.g., edge of forest stand) were excluded from the analysis.

(d) Sampled plots which were dramatically changed by clear-cutting or other disturbances were excluded from the analysis. In addition, five plots were excluded from the analysis because these plots were located on snow cover area in H1.

In total, 631 and 338 ground truth data were used in this study for Study Area 1 and Study Area 2, respectively. The ground truth data were randomly divided into two data sets, i.e. an assignment data and a validation data, for each study area. As a result, 300 and 331 ground truth data were used for the assignment and validation in Study Area 1, respectively, and 161 and 177 ground truth data were used for the assignment and validation in Study Area 2, respectively.

Land-Cover Mapping

We chose the unsupervised classification approach to produce land-cover map. The Iterative Self-Organizing Data Analysis Technique A (ISODATA) (Ball and Hall, 1965), which is a widely used clustering technique, was applied for above mentioned multi-temporal images. Initial clusters of 50 and a convergence threshold of 95% were employed for the clustering. For assignments of the corresponding land-cover type to clusters, the assignment data was used together with the aerial photographs in order to ensure the accurate assignments. We assigned temporary land-cover class at first, and then modified it repeatedly until no further improvement appeared by visual assessment.

In both study areas, to remove the unclassified areas due to clouds, hazes, and their shadows, we overlaid classification results. We created overlaid land-cover maps from two-seasonal images and three-seasonal images separately. Overlaying of the classification results according to a priority order based on the map accuracy (Sakai *et al.*, 2008) is

Table 2 Combination and priority order for two-seasonal images

	Image combination	
Priority order	Study Area 1	Study Area 2
1	H1-H3	K1-K2
2	H1-H4	K1-K3
3	H1-H5	K1-K4
4	H1-H2	K4-K2
5	H1-H6	

Each ID (e.g. H1) is shown in Table 1.

Table 3 Combination and priority order for three-seasonal images

	Image combination	
Priority order	Study Area 1	Study Area 2
1	H1-H3-H6	K1-K2-K3
2	H1-H4-H6	K1-K2-K4
3	H1-H5-H6	
4	H1-H2-H6	

Each ID (e.g. H1) is shown in Table 1.

one possible method. However, the map accuracy would be changed depending on the validation data used for the accuracy assessment. Moreover, when we assess the mapping accuracy in the cloudless area on all images, it means the range of the target area become small and the number of validation data decreases. Therefore, it is difficult to guarantee the propriety of accuracy against the remains of study area. In undulating mountainous, topographical shadow is one of main factors in misclassification. To reduce topographic effects, and to overlay the classification results systematically, the priority order was determined based on the following rules:

(1) Classification result from multi-temporal image which contain image recorded with higher solar elevation is put in upper layer of overlaid land-cover map.
(2) A lower priority is given for the classification result from the multi-temporal images that contain phenological differences within a single-date image. For example, the classification results from the multi-temporal images combined with H2 are placed to lower layer.

The priority order of two-seasonal and three-seasonal images for each overlaid land-cover map was shown in Table 2 and Table 3, respectively. The coverage of land-cover map from three-seasonal images was 85.4% of whole study area in Study Area 1 and 94.5% in Study Area 2, respectively. In Study Area 2, K4 was used as both leaf-on and leaf-off image to cover the entire study area with two-seasonal images.

Final land-cover maps of two study areas were created by combining above mentioned land-cover maps derived from two-seasonal images and three-seasonal images. The land-cover map derived from three-seasonal images will be more accurate than that from two-seasonal images (Sakai *et al*, 2009). Thus, the land-cover maps derived from three-seasonal images were placed to upper layer than that from two-seasonal images.

Accuracy Assessments

Accuracy of land-cover maps were assessed using some accuracy measures derived from error matrix (Congalton and Green, 1999). We used overall accuracy and overall Kappa coefficient for map-level accuracy assessments, and user's accuracy for the class-level accuracy assessments.

In order to confirm that the accuracy of land-cover maps from the three-seasonal images is higher than those from two-seasonal images, we compared the accuracy between land-cover maps. To compare the accuracy by the same data, subset of validation data in the range of land-cover maps derived from three-seasonal images were used for the accuracy assessments. The statistical significance of the difference between land-cover maps was investigated using McNemar's test (Foody, 2004; Rozenstein and Karnieli, 2011). We also evaluated the accuracy of the final land-cover maps, using all validation data.

RESULTS

Table 4 shows the accuracy of land-cover maps derived from two-seasonal images and three-seasonal images in two study areas. The overall accuracy and overall Kappa coefficient of land-cover maps derived from three-seasonal images was higher than those of two-seasonal images in both study areas.

In Study Area 1, the overall accuracy was improved to 78.2% from 73.0%, and the overall Kappa coefficient was improved to 0.701 from 0.628. The McNemer's test confirmed that the accuracy improvement was statistically significant (χ^2 = 5.03, $p < 0.05$). The user's accuracy was mainly improved in DCF and DBF. The user's accuracy was almost unchanged in the other land-cover classes.

In Study Area 2, the overall accuracy was improved to 83.8% from 80.2%, and the overall Kappa coefficient was improved to 0.726 from 0.674; but not statistically significant (χ^2 = 1.25, not significant (NS)). The user's accuracy was mainly improved in DBF and V&A. However, the user's accuracy was decreased in the URB. The user's accuracy in other land-cover classes was almost unchanged, same as Study Area 1. The user's accuracy of EBF was lowest at 50%; therefore the reliability of the mapped distribution of EBF was insufficient by user's perspective at pixel-level.

The final land-cover maps are presented in Fig. 2. Table 5 shows the error matrices and accuracy measures of final land-cover maps. The overall accuracy and overall Kappa coefficient were 77.0% and 0.687, respectively, in Study Area 1. Those in Study Area 2 were 84.2% and 0.734, respectively. As mentioned earlier, the coverage of land-cover map from three-seasonal images was 85.4% of whole study area in Study Area 1. The final land cover maps contain the result of two-seasonal images. Therefore, the accuracy of final land-cover maps was slightly lower than that of land-cover maps derived from three-seasonal images in Study Area 1 (see right column of Table 4(a)), though a simple comparison is not appropriate because the number of validation data is different.

The land-cover maps indicated that the ECF are widely distributed in both study areas. DCF are distributed aggregatively in Study Area 1, while EBF are distributed fragmentary in Study Area 2. From the aerial photographic interpretation and field checking, we confirmed that the distributions of the land-cover in the maps are in good agreement with actual distribution at broad-scale.

DISCUSSION

In many previous studies, two-seasonal images were used for land-cover mapping (Brown de Colstoun *et al*., 2003; Tottrup, 2004; Vogelmann *et al*., 1998; Yuan *et al*., 2005). Although the accuracy improvement in Study Area 2 was not statistically significant, the present study indicated that the land-cover map could be produced more accurately using three-seasonal images than those from two-seasonal images. In class-level accuracy assessments, the user's accuracy was improved greatly in the classes that show clear seasonal changes of spectral characteristics (i.e., DCF and DBF) in both study areas. Therefore, the use of three-seasonal images would improve the accuracy of land-cover map, especially in the areas which contains many deciduous forests. As mentioned earlier, the ETM+ images can be used free of charge in recent years. Therefore, even if three-seasonal images from spring, summer, and autumn are used for the land-cover mapping, there is no problem concerning the cost

Table 4 Comparison of accuracy measures and result of McNemer's test.

(*a*) Study Area 1

Accuracy measure	Land-cover map derived from two- seasonal images	Land-cover map derived from three- seasonal images
User's accuracy (%)		
ECF	77.6	77.1
EBF	-	-
DCF	51.7	69.2
DBF	65.2	76.9
V&A	77.9	79.5
URB	100.0	100.0
WAT	100.0	100.0
Overall accuracy (%)	73.0	78.2
Overall Kappa coefficient	0.628	0.701

McNemer's test: $\chi^2 = 5.03$, $p < 0.05$, n=289

(*b*) Study Area 2

Accuracy measure	Land-cover map derived from two- seasonal images	Land-cover map derived from three- seasonal images
User's accuracy (%)		
ECF	95.6	94.8
EBF	46.2	44.8
DCF	-	-
DBF	60.0	75.0
V&A	66.7	94.1
URB	100.0	80.0
WAT	100.0	100.0
Overall accuracy (%)	80.2	83.8
Overall Kappa coefficient	0.674	0.726

McNemer's test: $\chi^2 = 1.25$, not significant (NS), n=167

ECF, evergreen coniferous forest; EBF, evergreen broadleaved forest; DCF, deciduous coniferous forest; DBF, deciduous broadleaved forest; V&A, non-forest vegetation and agricultural field; URB, urban and built-up land; WAT, water.

of image data. On the other hand, generally, the use of the image from many different seasons increase the analysis time. The approach of present study is simple; therefore use of this approach would be effective from the viewpoint of suppressing an increase in analysis time.

In Study Area 1, one of the major misclassifications occurred between DBF and V&A classes (After merging the seven classes into forest and non-forest, the overall accuracy was 88.2%; Table 5(a)) while misclassification between DBF and V&A did not occur in Study Area 2 (Table 5(b)). Although the spectral characteristics in a single-date image may be similar between non-forest vegetation and DBF, the seasonal change pattern in spectral characteristics for crops and DBF differ greatly because the DN of crops changes significantly before and after sowing or harvesting operation. On the other hand, the spectral pattern in grasslands and wildernesses, which exist widely in Study Area 1, is similar to that of DBF due to similar phenological changes. Therefore, it is necessary to develop more sophisticated approaches in order to correctly classify those misclassified land-cover classes. The support vector machine classifier that is an effective machine learning technique has been used for forest/non-forest classification in recent years (Knorn *et al.*, 2009). Our previous study also showed that the land-cover of forest and non-forest could be classified accurately in Study Area 1 (Tanaka *et al.*, 2011). Although supervised classification approach including support vector machine usually require large number of training data, a prior-classification of forest and non-forest by support vector machine might be effective to improve the classification accuracy.

For the other misclassification of the present study (e.g., misclassification between ECF and EBF), the optimal iterative unsupervised classification (OIUC) method (Jiang *et al.*, 2004), which repeats ISODATA clustering against indistinguishable clusters until homogeneous clusters are obtained, may be useful in order to improve the accuracy. The combination of our approach and OIUC method also should be investigated in the future.

In conclusion, the use of the three-seasonal ETM+ images was easy and effective approach in order to improve the accuracy of land-cover map. The approach of present study can be applied to other areas, and would improve the map accuracy. The use of multi-temporal ETM+ images from many different seasons would be one of the possible choices in order

Table 5 Error matrices of the final land-cover maps: (*a*) Study Area 1, and (*b*) Study Area 2.

(*a*) Study Area 1

	Validation data							User's
Land-cover map	ECF	EBF	DCF	DBF	V&A	URB	WAT	accuracy (%)
ECF	69		3	18				75.8
EBF								
DCF	2		19	5	5			63.3
DBF	3		5	55	7			78.6
V&A	2		3	22	100	1		78.2
URB						2		100.0
WAT							10	100.0

Overall accuracy=77.0%, Overall Kappa coefficient=0.687, *n*=331

(*b*) Study Area 2

	Validation data							User's
Land-cover map	ECF	EBF	DCF	DBF	V&A	URB	WAT	accuracy (%)
ECF	96	4		1				95.0
EBF	15	16		1				50.0
DCF								
DBF	2	1		9				75.0
V&A					17	2		89.5
URB					2	8		80.0
WAT							3	100.0

Overall accuracy=84.2%, Overall Kappa coefficient=0.734, *n*=177

ECF, evergreen coniferous forest; EBF, evergreen broadleaved forest; DCF, deciduous coniferous forest; DBF, deciduous broadleaved forest; V&A, non-forest vegetation and agricultural field; URB, urban and built-up land; WAT, water.

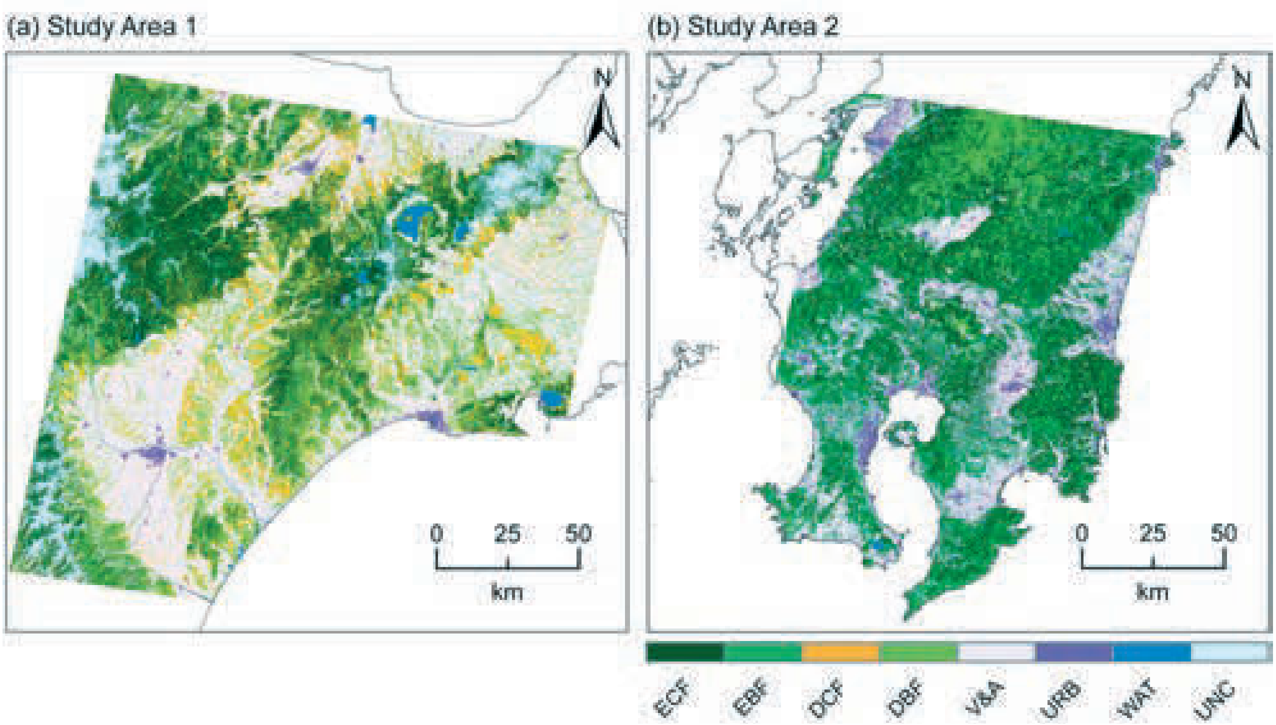

Fig. 2 Land-cover maps for (*a*) Study Area 1 and (*b*) Study Area 2.
ECF, evergreen coniferous forest; EBF, evergreen broadleaved forest; DCF, deciduous coniferous forest; DBF, deciduous broadleaved forest; V&A, non-forest vegetation and agricultural field; URB, urban and built-up land; WAT, water; UNC, unclassified.

to create nationwide land-cover map with higher accuracy.

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