Article

Examination of Maximum Sustainable Timber Yield Based on a Profitability Simulation

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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 m³, which is sufficient to supply the annual timber demand in Japan (78 million m³ 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

Fig. 1 Study area location

active forestry areas in Niigata Prefecture. In total, 23,175 ha of forest are individually owned, which occupy 82% of the total area.

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 m³, 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):

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

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	<i>SQ</i>			*1
Area	<i>A</i>	ha		*1
Initial age	<i>age</i>			*1
Forest zone	<i>Z</i>			*1, 4
Average slope	<i>s</i>			*1
Distance from road	<i>Smin</i>	m		*2
Maximum yarding distance	<i>Smax</i>	m		*2
Average yarding distance	<i>Save</i>	m		*2
Average lateral yarding distance	<i>ly</i>	m	$A/(Smax-Smin)$	
Lateral yardable distance		m	60	*3
Cable re-stretching frequency	<i>n</i>		$ly/60$ (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/m³. 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:

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

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

*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	$chH \times chLh$	
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	$lmP \times lmR$	
Depreciation of yarding machine	lmC	yen/day	$lmH \times lmCh$	
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	$12.295 \times v^{0.5} - 0.564$	*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	$(chL + cLF + sC) \times (1 + ex)$	
Productivity for yarding	lP	m ³ /day	$(Save^{(-0.2896)}) \times (v^{0.5337}) \times (ly^{(-0.04891)}) \times 10^{2.611}$	*3
Yarding wage	lW	yen/m ³	$w \times lPe / lP$	
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	$(lW + lmF + lmL + aC) \times (1 + ex)$	
Cost for installing and removing log deck	bC	yen	$w \times bP$ (when $V > 700$)	*1
Amount of labor for installing and removing yarder	wPe	person day	$(0.0763 \times Smax + 2.4) \times (1 + 0.35 + 0.7 \times n)$	*4
Cost for installing and removing yarder	wC	yen	$w \times wPe$	
Total cost at a logging site	oC	yen	$(cW / (1 + ex + i) + (cLF + lC) / (1 + ex) + fW) \times V + (wC + bC) / (1 + ex + i)$	
Cost of transporting workers	pT	yen	$oC \times (8.1 - 3.4 \times \log_{10}(oC / 1000000)) / 100$	*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	$Tv \times V$	
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

Site quality	Standard amount of labor (person days/ha)				Standard unit cost (yen/ha)
	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× ^{*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	<i>sa</i>	yen	150	*1
Seedling cost per ha	<i>saC</i>	yen/ha	$sa \times d$	
Slope index	<i>sI</i>		[s]	
Slope coefficient	<i>sC</i>		$1 + 0.1 \times (sI - 1)$	*2
Amount of regeneration labor	<i>l</i>	person · day	Table 4	
Actual amount of regeneration labor	<i>l'</i>	person · day	$L \times (0.95858 + 0.01523 \times sI + 0.00008 \times Smin + sC - 1)$	*2
Wage for regeneration	<i>aW</i>	yen/ha	$w \times l'$	
Planting and management cost	<i>aC</i>	yen/ha	$(aW + saC + ssC) \times (1 + ex)$	
Standard unit cost for regeneration	<i>aS</i>	yen/ha	Table 4	
Subsidies for regeneration	<i>aSub</i>	yen/ha	[aS]	
Regeneration cost per ha	<i>pC</i>	yen/ha	$aC - aSub$	
Regeneration cost	<i>pCt</i>	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:

$$\text{Subsidy per hectare} = \text{Standard unit cost} \\ \times \text{Assessment coefficient} \times \text{Subsidy rate.}$$

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:

$$\text{Profits} = \text{Gross income} - \\ (\text{Logging cost} + \text{Regeneration cost}).$$

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										
Volume of thinning logs (m³)												
0-20												
>20												
With logging	Under 46 years	267,430										
	At 46 years	343,510										
Volume of thinning logs (m³)												
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 m³, 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	$tV \times P$	
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	$toC \times (8.1 - 3.4 \times \log_{10}(toC / 1000000)) / 100$	*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	$1 / (22.817 \times v^{0.2903})$	*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 (m³/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	※

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 m³ 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 m³, which was about 1,000m³ 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

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

Table 10 Maximum sustainable yields for each scenario including thinned logs (m³/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	※

(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.

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.

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

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.

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 m³ to 25,400 m³, 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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