Supplementary material

Appendix A: Data regarding stand growth and calculation of log

We used forest inventory data, forest maps, road network data for the study site, yield tables for sugar-planted forests from Yamagata Prefecture, and digital elevation model (DEM) data with a 10-m spatial resolution from the Geospatial Information Authority of Japan (GSI).

The names of A-, B-, and C-grade logs have no clear definition (Forestry Agency of Japan, 2015), and the boundary between A- and B-grade logs varies depending on the demand and time of the year. To avoid overestimating profitability, we treated A-grade logs of relatively high quality, which are always considered A-grade logs used for laminated lumber for sawmilling and laminated lumber for building construction. Other lumber, whose quality varied according to the demand and season, was classified as a B-grade log for laminated wood. The portion of wood that could not be bucked into logs was considered fuelwood.

Owing to the snow cover in this area, past interviews revealed many trees with root bends 50–60 cm above ground level. In this study, the A-grade log harvesting height, which represents the height at which A-grade logs can be bucked from ground level, was also set. The presence or absence of knots or *tobikusare* (decay and discoloration caused by *Anaglyptus subfasciatus* Pic.) rot in the wood has a significant role in determining whether A-grade logs can be bucked, and both the knots and *tobikusare* rot can be reduced by pruning. However, in the present study, we adopted the assumption of a 5.5 m A-grade logging height without pruning and a 60% bent ratio (a 6:4 ratio of straight trees to bent trees), considering the standard condition described by Suzuki et al. (2018). For straight and bent trees, the logging height was set at 0.3 m above the ground level, and the logging of straight trees began from this point. For the bent trees, the logs were bucked after removing 2 m of fuelwood, including the bent portion. The logs were bucked in the order of log type numbers, as shown in Table S1, starting with the smallest number.

The types of logs to be bucked are listed below: As there was no demand for large-diameter A-grade logs (logs exceeding 34 cm), the maximum top-end diameter class of log type 1 was recorded as B-grade logs of log type 3.

The prescriptions consisted of three components: rotation age, thinning age, and thinning rate (Table S2). The rotation age was set at 5-year intervals from 50 to 120 years. The

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thinning age and rate were set according to Suzuki et al. (2018). However, 70-year commercial thinning was conducted only when the rotation age was ≥ 75 years.

Profit was determined by subtracting logging and nursery costs from income and adding subsidies. All calculations were performed per hectare and determined by forest age and site class. In addition, the profit for each age group was divided by age to obtain the profit per hectare per year. Basic information on profit calculations is presented in Table S3.

Although the forests of site classes 1 to 5 existed at the study site, we excluded site classes 1 and 2 because of their extremely small areas and calculated the area for site classes 3 to 5.

The average height of the main forest trees, density of standing trees, and volume were calculated using the methods described by Moriya and Tatsuhara (2014). First, the tree height, forest age, and site class were obtained from a yield table (Yamagata Prefectural Government, 1980). The site index curve equation was estimated using the Mitscherlich equation to calculate the average height of the main forest trees as follows:

$$H = M\{1 - Lexp(-kt)\}, \qquad \text{(S1)}$$

where H is average height [m]; t is age; M is parameter based on site class; and L and k are parameters. The parameter values are shown in Table S4.

The density and volume of standing trees per hectare were calculated using the following equations from the Stand Density Control Diagram (Forestry Agency of Japan, 1979) with reference to Tadaki (1963) and Moriya et al. (2013):

$$\log_{10} N_{Rf} = c_1 - c_2 \log_{10} H, \qquad \text{(S2)}$$

where c_1, c_2 represent parameters; V_{Rf} is volume per hectare at maximum density; and N_{Rf} is the number of trees per hectare at maximum density. The values of these parameters are listed in Table S5.

Without timber thinning, the forest was assumed to grow along the natural mortality line as follows:

$$\frac{1}{N} = \frac{1}{N_0} + D\frac{V}{N}, \qquad \text{(S3)}$$

where N_0 is planting density, and D is parameter.

$$V = \left(b_1 H^{-b_2} + \frac{b_3 H^{-b_4}}{N}\right)^{-1}, \qquad \text{(S4)}$$

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where V is volume per ha [m³]; N is number of trees per ha; and b_1, b_2, b_3, b_4 represent parameters.

Equations (S2–S4) intersect at (N, V) = (N_{Rf}, V_{Rf}): H can be eliminated by solving Equation (S3) for H and substituting it into Equation (S2). As Equations (S3) and (S4) are tangential to each other at (N, V) = (N_{Rf}, V_{Rf}), the slopes of the tangent lines are equal. Under these conditions, by solving the simultaneous binary equations for N and V, the corresponding values of N and V were obtained once the value of H was determined from (S1). In the case of natural mortality line transfer during thinning, a new N_0 was obtained from N, V after thinning, using the same procedure.

Because the method of timber harvesting was determined by diameter class, the number of trees per diameter class in the stand was required. Therefore, we used the methods of Nagumo et al. (1981), Tatsuhara et al. (1992), and Moriya and Tatsuhara (2014) to create diameter distributions based on the Weibull distribution.

The Weibull distribution is expressed as follows:

$$f(d) = \frac{m}{\alpha}(d-\gamma)^{m-1}\exp\left\{-\frac{(d-\gamma)^m}{\alpha}\right\}, \tag{S5}$$

where d is diameter[cm], $f(d)$is diameter distribution and m, α, and γ represent parameters. The procedures for determining the three parameters m, α, and γ are described below.

First, the value of γ was determined using Equation (S6):

$$\gamma_S = g_S t^{0.25} N^{-0.85} \tag{S6}$$

g_S: parameter corresponding to site class S

g_1 = 1,390, g_3 = 0.85g_1, g_4 = 0.75g_1, g_5 = 0.70g_1

Next, d−γ in Equation (S5) was replaced with x, to obtain Equation (S7):

$$g(x) = \frac{m}{\alpha}x^{m-1}\exp\left(-\frac{x^m}{\alpha}\right), \tag{S7}$$

$g(x)$: Weibull distribution for x

The mean $E(x) = \overline{d}-\gamma$, variance $V(x)$, and the coefficient of variation CV_x of this distribution were expressed by Equations (S8)–(S10).

$$E(x) = \alpha^{\frac{1}{m}}\Gamma\left(1+\frac{1}{m}\right) \tag{S8}$$

where Γ represents the gamma function for complex numbers z, whose real part is positive.

$$\Gamma(z) = \int_0^\infty t^{z-1}e^{-t}\,dt$$

$$V(x) = \alpha^{\frac{2}{m}}\left\{\Gamma\left(1+\frac{2}{m}\right) - \Gamma^2\left(1+\frac{1}{m}\right)\right\} \tag{S9}$$

$$CV_x = \frac{\sqrt{V(x)}}{E(x)} \tag{S10}$$

From these equations, Equation (S11) was obtained:

$$CV_x^2 = \frac{\Gamma\left(1+\frac{2}{m}\right)}{\Gamma^2\left(1+\frac{1}{m}\right)} - 1 \tag{S11}$$

As the variance did not change before or after the replacement (parallel shift) of d−γ and x, the coefficient of variation CV_d before the replacement was expressed by Equation (S12):

$$CV_d = \frac{\sqrt{V(x)}}{\bar{d}} = \frac{\sqrt{V(x)}}{E(x)+\gamma} \tag{S12}$$

This was expressed by Equation (S13):

$$CV_x = \frac{CV_d}{1-\frac{\gamma}{\bar{d}}} \tag{S13}$$

Next, to obtain the coefficient of variation CV_d of the diameter distribution, the mean breast height diameter $\overline{d}$ and quadratic mean diameter $\overline{d_g}$, corresponding to the number of trees and mean tree height, respectively, were calculated using Equations (S14)–(S17) from the stand density control diagram (Forestry Agency of Japan, 1979).

$$HF = e_1 + e_2 H + \frac{e_3 H\sqrt{N}}{100} \tag{S14}$$

$e_1,\ e_2, e_3$: parameters, HF : stand form height

$$G = \frac{V}{HF} \tag{S15}$$

G : Total basal area

$$\bar{d}_g = 200\sqrt{\frac{G}{\pi N}}, \tag{S16}$$

$$\bar{d} = f_1 + f_2\bar{d}_g + \frac{f_3 H\sqrt{N}}{100} \tag{S17}$$

f_1, f_2, f_3 : *parameters*

The values of the parameters in Equations. (14) and (17) are listed in Table S6.

The diameter variance V_d was obtained using Equation (S18):

$$V_d = \overline{d_g}^{\,2} - \bar{d}^2 \tag{S18}$$

From the mean $\bar{d}$ and variance V_d of the diameter, the coefficient of variation CV_d was obtained using Equation (S19):

$$CV_d = \frac{\sqrt{V_d}}{\bar{d}} \tag{S19}$$

After obtaining CV_x, m satisfied Equation (S11), and α was further determined by Equation (S8). Thus, the three parameters m, α, and γ were known. The number of trees per diameter class was obtained using Equation (S20) as follows:

$$n_i = s_i f(d_i) N, \tag{S20}$$

where i is diameter class, n_i is the number of trees per hectare of diameter class i, s_i is the range of diameter classes, $f(d_i)$ represents the probability of the existence of diameter class d_i and N represents number of trees per hectare.

The number of trees was calculated as an integer value by rounding; if the sum of n_i did not equal N, the diameter class with the highest number of trees in the diameter class was adjusted. Diameter classes were treated as 2 cm brackets.

The height curves by diameter class for the established diameter distribution were determined using height curves relative to the mean diameter, following Shiraishi (1981), as represented by Equation (S21).

$$\frac{h_i}{H} = \left(\frac{d_i}{\bar{d}}\right)^{0.5594-0.00178t} \tag{S21}$$

h_i: height of diameter class d_i, t: age

During understory thinning, the diameter distribution of the trees to be thinned did not match the Weibull distribution and was biased toward relatively small diameters. The thinning rate was set for each diameter class using the method described by Shiraishi (1986). In this study, thinning refers to timber thinning from below.

$$R_i = \frac{d_i - d_{min}}{d_{max} - d_{min}}, \tag{S22}$$

where d_i: diameter class i, d_{min}: minimum diameter class, and d_{max}: maximum diameter class.

The thinning rate P_i based on diameter class is expressed by linear Equation (S23) for R_i:

$$P_i = 0.1481 R_i + C \tag{S23}$$

P_i: thinning rate of diameter class i; C: parameter.

Therefore, the thinning rate by diameter class for all diameter classes was established by determining C, which satisfied Equation (S24).

$$N_{thin} = \sum_{d_i=d_{min}}^{d_{max}} P_i n_i \qquad \text{(S24)}$$

N_{thin}: number of trees thinned; n_i: number of trees per diameter class

C can be calculated by substituting P_i in Equation (S23) with P_i in Equation (S24) and solving for *C*. The stem taper curve was determined using Equation (S25) as described by Tatsuhara et al. (1992).

$$y^2 = px^r \qquad \text{(S25)}$$

x: Relative height from the edge of the tree (0: edge of the tree; 1: edge of the ground) with height $h = 1$.

y: Diameter relative to reference diameter, *p*, *r*: parameters; *p* and *r* were determined as follows.

If the real diameter $d_{0.9}$ at a relative height of 0.9 was the reference diameter, and d_x is the real diameter of the trunk at relative height *x*, Equation (S25) passes through (0.9, 1); thus, Equations (S26) and (S27) hold.

$$1 = p \times 0.9^r \qquad \text{(S26)}$$

$$p = \left(\frac{10}{9}\right)^r \qquad \text{(S27)}$$

Let d_b be the diameter of the breast height, and let the relative height ϕ of the breast height h_b, as represented in Equation (S28):

$$\phi = 1 - \frac{h_b}{h} \qquad \text{(S28)}$$

Since Equation (S25) passes through (ϕ,$d_b/d_{0.9}$), Equation (29) holds:

$$\left(\frac{d_b}{d_{0.9}}\right)^2 = p\phi^r \qquad \text{(S29)}$$

Let *v* be the single-tree volume; then, and Equation (S30) holds.

$$v = \frac{\pi d_{0.9}^2 h}{4} \times \int_0^1 y^2\, dx = \frac{\pi d_{0.9}^2 h}{4} \times \frac{p}{r+1} = \frac{\pi d_{0.9}^2 hp}{4(r+1)} \qquad \text{(S30)}$$

Substituting Equation (S29) into (S30) yields Equation (S31):

$$v = \frac{\pi d_b^2 h}{4(r+1)\phi^r} \qquad \text{(S31)}$$

Let v_i be the single-tree volume for the diameter class d_i.

$$V = \sum_{i=1}^{I} n_i v_i = \sum_{i=1}^{I} \frac{\pi d_i^2 h_i n_i}{4(r+1)\phi_i^r} \quad \text{(S32)}$$

By determining the value of *r* that satisfies this condition, *p* can be determined using Equation (S26). Using this procedure, the trunk form can be set and the diameter for any height can be obtained.

A relative stem-taper curve was used to determine whether the timber bucked.

When harvesting timber from an arbitrary relative height *x* to length *L*[m], maximum diameter class D_{max}, and minimum diameter class D_{min}, the relative height *x*' at the end can be expressed by Equation (S33) as follows:

$$x' = x - (L + 0.1)/H, \quad \text{(S33)}$$

where *H*: height[m], and 0.1 is the extra length.

The first step was to determine whether the logs to be bucked qualify as A-grade logs, which depends on whether they meet the criteria for A-grade log harvest height. The relative tree height of the bucked A-grade log was calculated using Equation (S34).

$$H_{pru} = H_{cut}/H \quad \text{(S34)}$$

H_{pru}: Relative height of the bucked A-grade log; and H_{cut}: A-grade log harvest height [m]; therefore, if the following criteria are met, the log can be bucked:

$$H_{pru} \le x'. \quad \text{(S35)}$$

The relative top-end diameter is obtained by transforming Equation (S25) as follows:

$$y_{x'} = \sqrt{p \times x'^{\,r}} \quad \text{(S36)}$$

p, r: $parameters,$ $\quad y_{x'}$: $relative\ top\ end\ diameter\ at\ relative\ height\ x'$

The top-end diameter outside the bark was obtained by multiplying the relative end diameter by the diameter at a relative height of 0.9, the top-end diameter outside bark was obtained.

$$D_{x'} = y_{x'} \times d0.9 \quad \text{(S37)}$$

$D_{x'}$: $top\ end\ diameter\ outside\ bark\ at\ relative\ height\ x'$ $[cm]$,

$d0.9$: $diameter\ at\ relative\ height$ 0.9 [cm]

The minimum top end inside the bark was required to determine whether to buck a log and calculate its volume. The bark thickness ratio was set to the power of the diameter and the top-end diameter inside the bark was calculated from the top-end diameter outside the bark using Equation (S38):

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$$D_{bark} = \left(1 - 0.18047\, D_{x'}{}^{-0.2316}\right) D_x, \tag{S38}$$

D_{bark}: *top end diameter inside bark* [cm]

The top-end diameter inside the bark was used to calculate the minimum top-end diameter by considering the deviation rate.

$$D_{ellip} = \left(1 - \frac{0.045}{4}\right) D_{bark} \tag{S39}$$

D_{ellip}: *minimum top end diameter taking into account the deviation rate* [cm]

Therefore, if D_{ellip} satisfies the following inequality, the log is bucked; otherwise, it is not:

$$D_{min} \leq D_{ellip} \leq D_{max}. \tag{S40}$$

If this inequality is satisfied, D_{ellip} is the end diameter of the log that was bucked log. However, in this case, because the end diameter class was treated as a 2 cm bracket, the top-end diameter class was the largest even number that did not exceed D_{ellip}.

In this study, the bucking pattern that maximized the income per site class, age, and diameter class was determined. As the unit price of biomass wood is currently low and maximizing log income corresponds to maximizing revenue, income comparisons were made based on log income.

First, we created the bucking patterns that would satisfy the following two conditions: a bucking height of 5.5 m for A-grade logs, which were bucked as a butt log only, and all logs were bucked in the order of their log type number. However, for large-diameter logs (36 cm or larger), type 2 logs can buck even after type 3 logs have been bucked as butt logs.

Next, log income was calculated for all bucking patterns. Log volume was calculated based on the Japanese Agricultural Standard's squared diameter method, and log income was obtained by multiplying the log volume by the unit price for each type of log. The bucking pattern that yielded the highest log income was determined. The root and treetop volumes of the pattern were then obtained by integrating the stem taper curve, which was multiplied by the unit price of biomass wood to obtain biomass wood income. This determines the optimal bucking pattern for each diameter class and the corresponding income.

Income by diameter class was multiplied by the number of trees in that diameter class and summed to calculate income by forest age and site class.

The logging system consists of felling using a chainsaw, collecting grapples, crosscutting and delimbing using a processor, and removing grapples using a forwarder. In the present study, following Suzuki et al. (2018), the processor was assumed to operate at the landing site after yarding was conducted using a grapple mounted on a crawler. The harvesting system is thus designed to ensure that the processor operates on relatively stable and level ground, such as landings. Accordingly, it was assumed that timber harvesting was feasible across all FMUs included in the present study. The methods of Oka (2006) and Nakajima et al. (2017) were used for the standard work schedules. The assumed standard work schedule and assumptions are presented in the Appendix Table S2. Based on the survey, we assumed that the silvicultural cost of stands of the same age was the same within a site class, as shown in Tables S1–S9. The man-days and forestry cost information used to determine the cost of the nursery are shown in Tables S8 and S9.

Subsidies were assumed to be obtained by multiplying the standard unit price from the Forestry Promotion Division, Department of Agriculture, Forestry and Fisheries, Yamagata Prefecture government (Suzuki et al., 2018) by 0.51 (the afforestation subsidy assessment factor of 170 multiplied by the thinning subsidy rate of 0.3) (Table S9) for each operation performed.

Table S1. Classification of log types, dimensions, and unit prices for *Cryptomeria japonica* plantations in Japan.

Log type number	Log grade	Log length (m)	Top-end diameter class (cm)	Unit price
1	A-grade log		16–34	10,800 yen/m^3
2	A-grade log	3	16–34	10,800 yen/m^3
3	B-grade log	2	26–70	7,200 yen/m^3
4	B-grade log	2	18–24	6,550 yen/m_3
5	B-grade log	2	14–6	4,500 yen/m^3
Biomass wood			Weight conversion	5,000 yen/t

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Table S2. Operations performed in a forest management unit. **(a)** Thinning age and thinning rate. **(b)** Person-day values for nursery.

Table S2(a)

Age (years)	**Operation**	**Value of person-days (person-days ha^{-1})**
1	Site preparation	25
1	Planting	15
2	Weeding	7
3	Weeding	7
4	Weeding	7
5	Weeding	7
6	Weeding	7
7	Weeding	7
12	Clearing	12
Total		94

Table S2(b)

Thinning age (years)	**Thinning type**	**Thinning rate (%)**
20	Pre-commercial thinning	30
40	Pre-commercial thinning	30
70	Commercial thinning	25

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Table S3. Basic information on profit calculations.

Item	**Symbol**	**Unit**	**Value/ formula**	**Remarks**
Wage	*w*0	yen/person-day	16,000	Suzuki et al. (2018)
Miscellaneous expense ratio	*ex*		0.1	Ogura & Ogura (1997)
Labor cost	*w*	yen/person-day	*w*0(1 + *ex*)	

Suzuki K, Tatsuhara S, Nakajima T, Kanomata H, Oka M, 2018. Predicting effects of logging systems and bucking strategies for privately qwned sugi (*Cryptomeria japonica*) plantations in Atsumi District, Tsuruoka City, Yamagata Prefecture. J For Plann 24 (2): 15-27.

Ogura Y, Ogura Y, 1997. Valuation of forest land and standing timber – How to see and buy a mountain. Seibun-sya, Osaka, Japan. 430pp.

Table S4. Parameter values of the site index curve equation.

M	***L***	***k***
45.71–5.03*S*	1.004	0.020

S represents the site classes 3 to 5.

Table S5. Parameter values of the stand density control diagram.

b_1	b_2	b_3	b_4	c_1	c_2
0.06004657	1.35233688	3.743.30	2.82482815	5.29374	1.47249

Table S6. Parameter values of the stand density control diagram.

e_1	e_2	e_3	f_1	f_2	f_3
0.667196	0.387485	0.189979	–0.382224	0.986197	0.000000

Table S7. Cost information for the nursery.

Item	**Symbol**	**Unit**	**Value/ formula**	**Remarks**
Cost of seedling	*rfP*	yen	153	Zheng et al. (1995)
Cost of planting	*rfC*	yen ha^{-1}	*rfP* × *N*0	
Person-day value for reforestation	*rfPd*	person-day ha^{-1}	(Total of Table 7) × (0.95858 + 0.01523 × *sI* + 0.00008 × *Smin* + *sC* – 1)	Zheng et al. (1995)
Wages for reforestation and nursery	*rfW*	yen ha^{-1}	*W* × *rfPd*	
Cost of planting control	*rfCt*	yen	*rfW* + *rfC* × 1 + ex	

Zheng Y, Nagumo H, Tatsuhara S, 1995. A study on a forest management planning system - short-term plan. J Jpn For Soc 77: 28-34.

Table S8. Information regarding the subsidy amount for various forest operations.

Forest operation	**Subsidy amount (yen ha^{-1})**	
Artificial reforestation	680,850	
Weeding	107,610	
Clearing	98,940	
Pre-commercial thinning	85,680	
[1] Commercial thinning	10–20 m^3	132,090
	20–30 m^3	175,440
	30–40 m^3	218,790
	40–60 m^3	261,630
	60–80 m^3	348,330
	>80 m^3	435,030

[1] Subsidies are provided when thinned wood is used to obtain both non-commercial and commercial timber.

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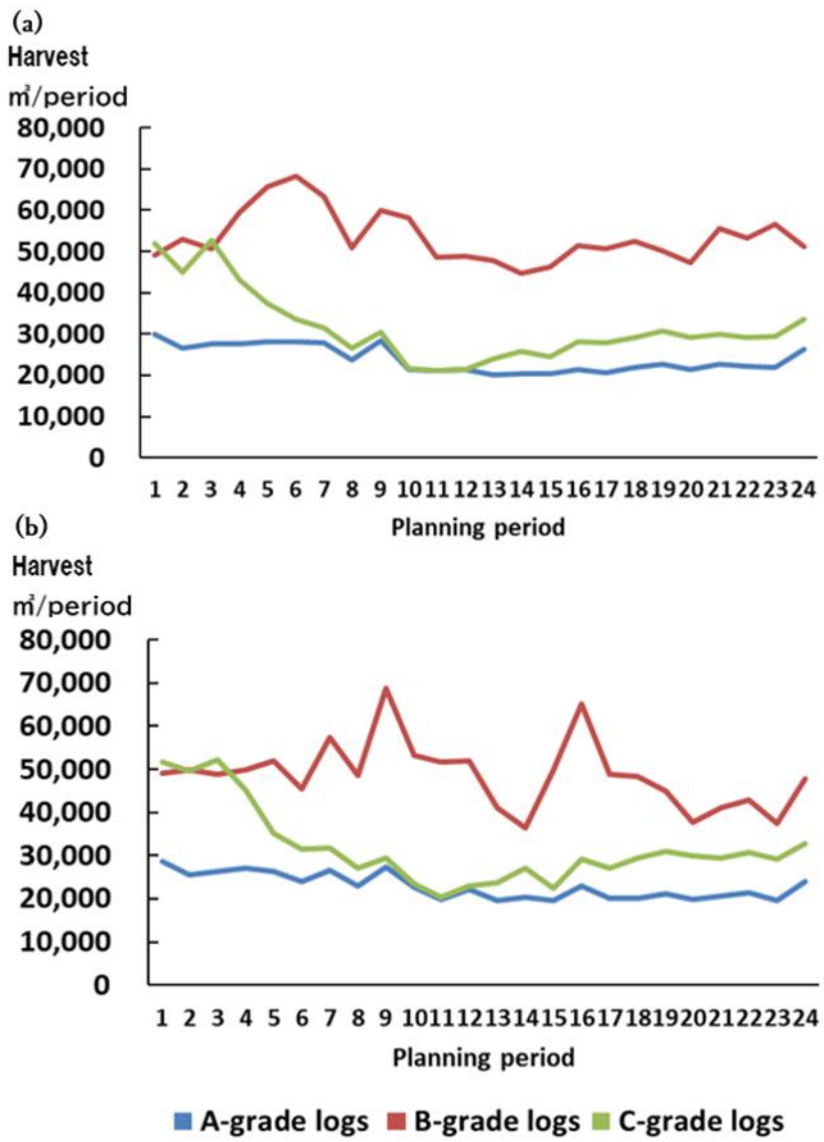

Figure S1. Changes in harvests based on the grades of logs when site classes (a) were considered and (b) were not considered.

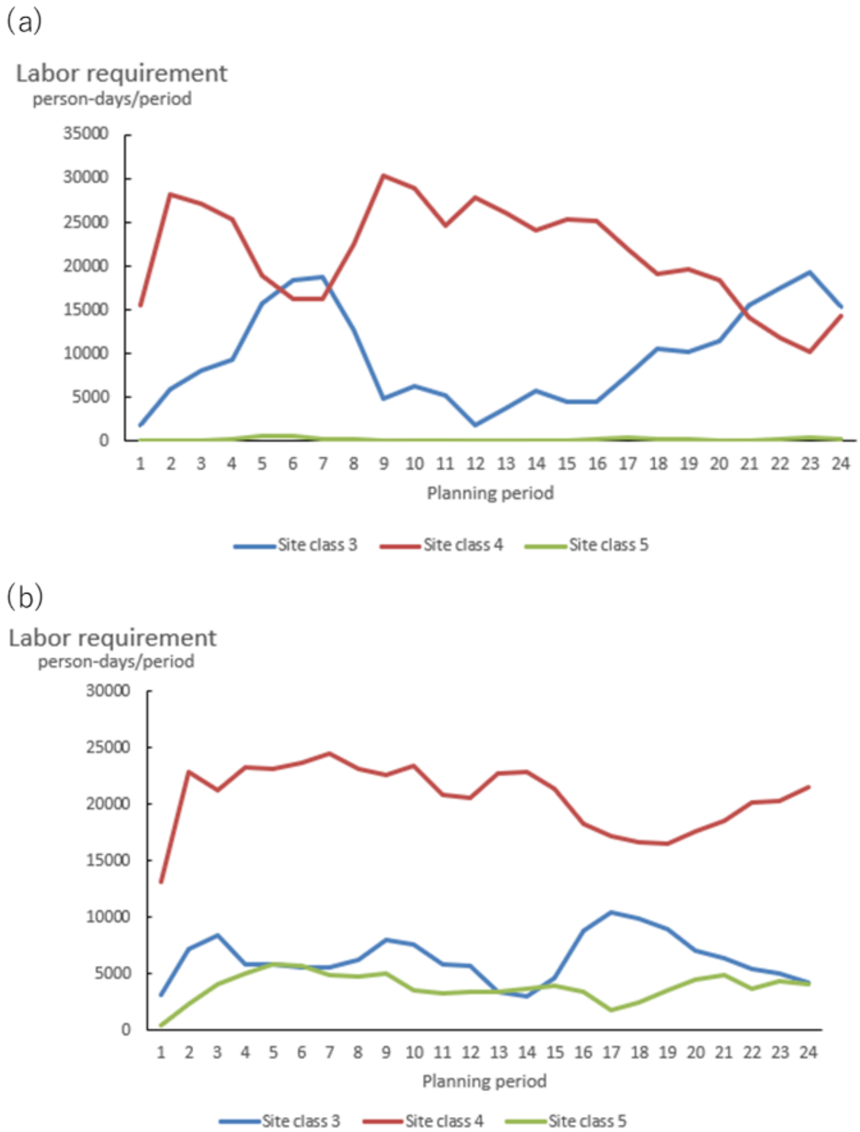

Figure S2. Changes in labor requirements based on the site classes in each period when the site classes (a) were considered and (b) were not considered.

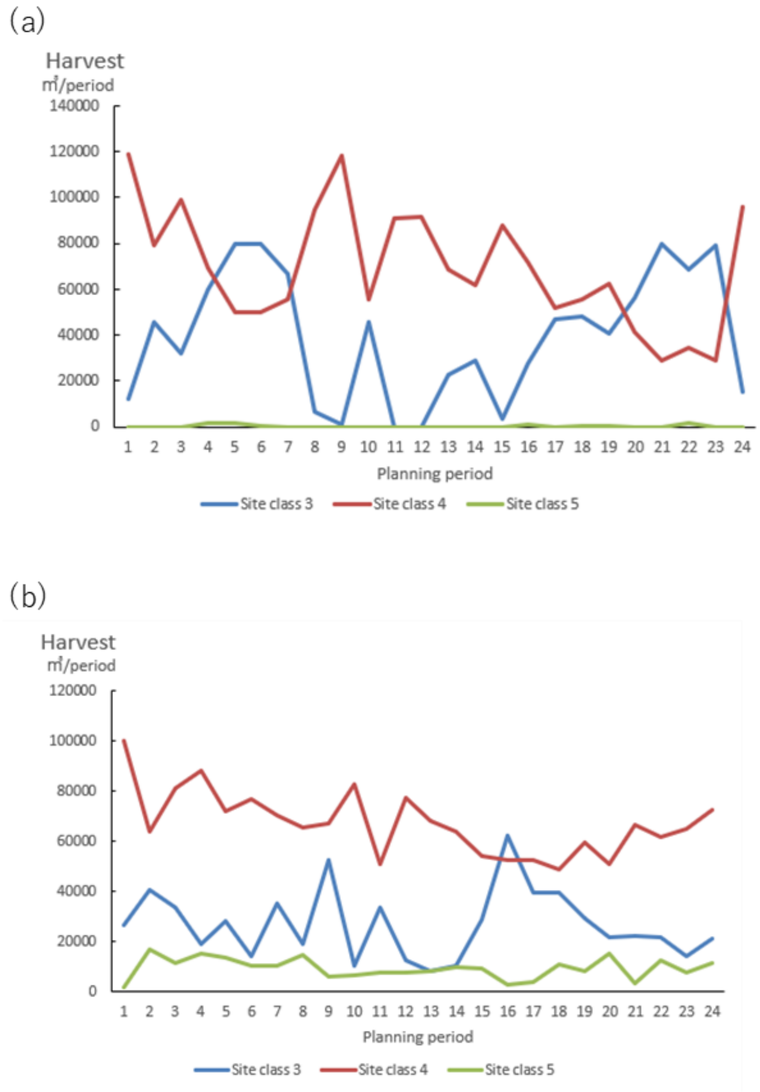

Figure S3. Changes in harvests based on the site classes in each planning period when the site classes (a) were considered and (b) were not considered.

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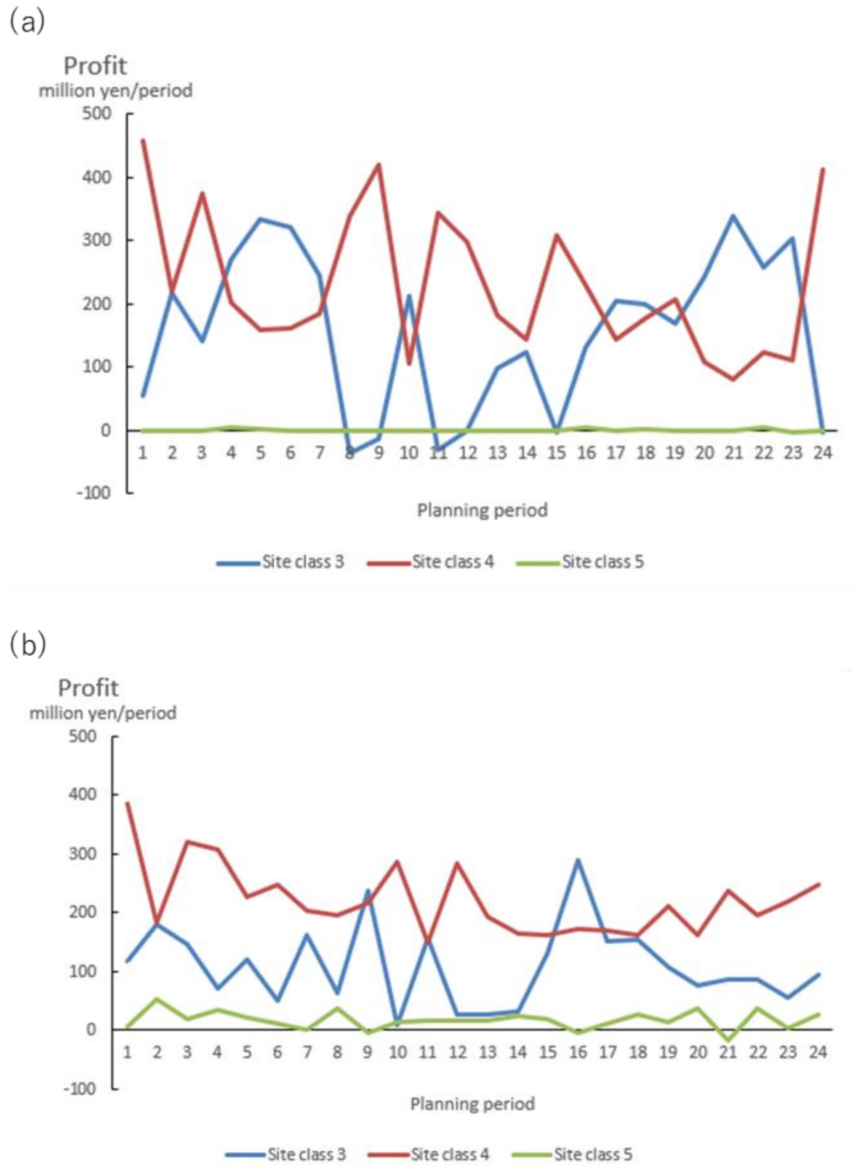
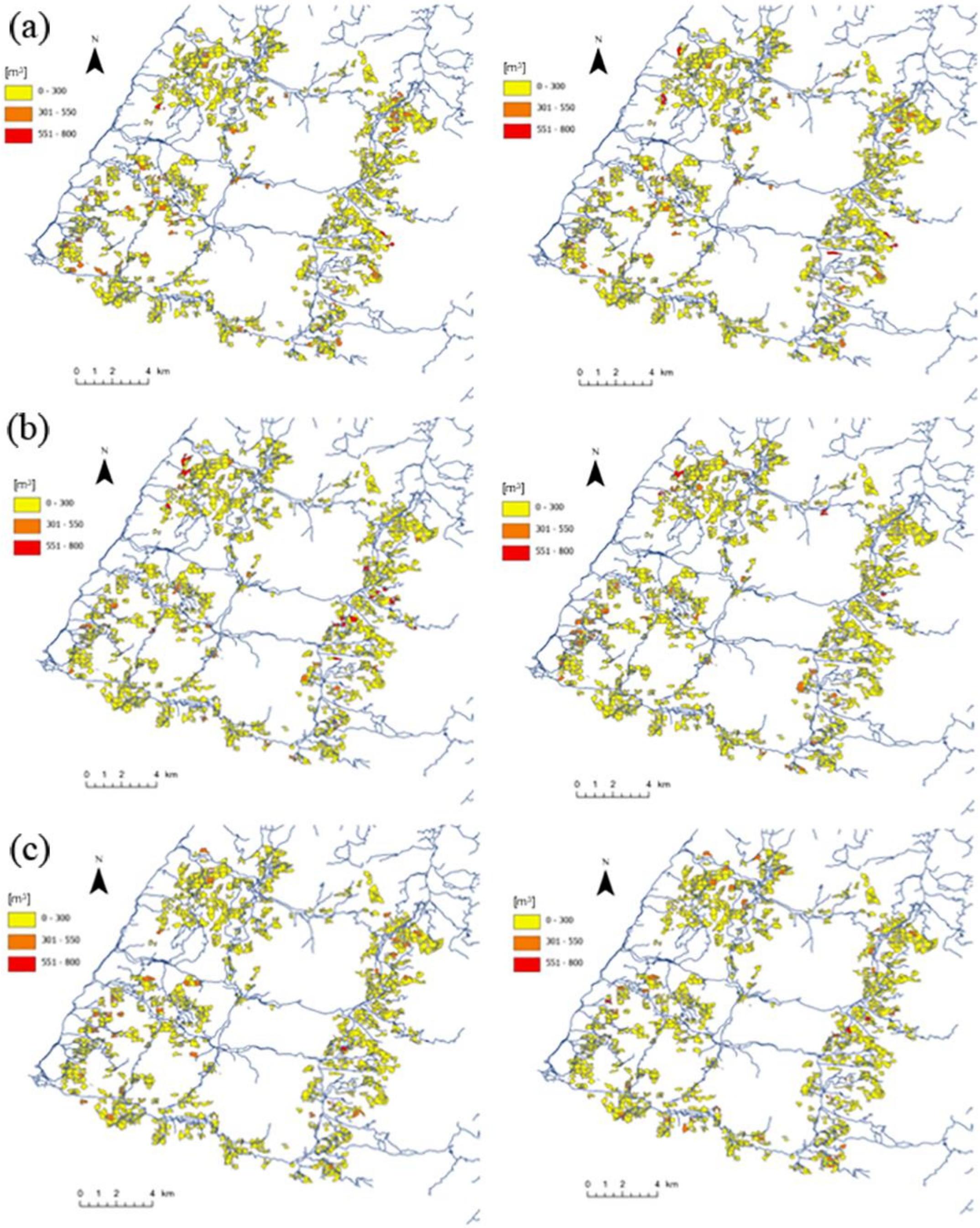


Figure S4. Changes in profits based on the site classes in each planning period when the site classes (a) were considered and (b) were not considered.



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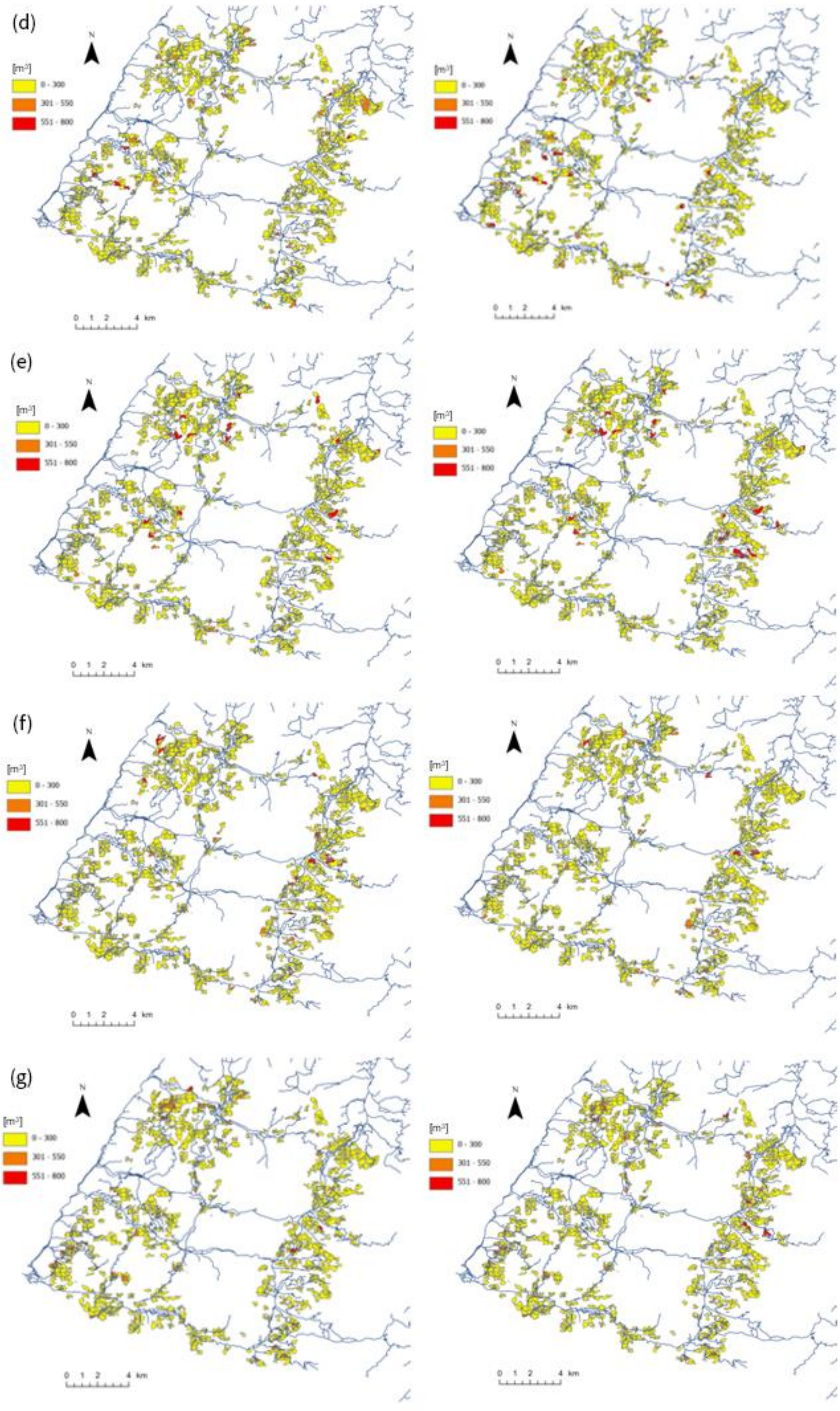
(d)
(e)
(f)
(g)
N
[m³]
0 - 300
301 - 550
551 - 800
0 1 2 4 km

Figure S5. Comparison of harvest volumes (m³/ha) with site classes considered (left) and not considered (right) for the (a) 1st, (b) 4th, (c) 8th, (d) 12th, (e) 16th, (f) 20th, and (g) 24th planning periods. Green lines represent forest road networks.

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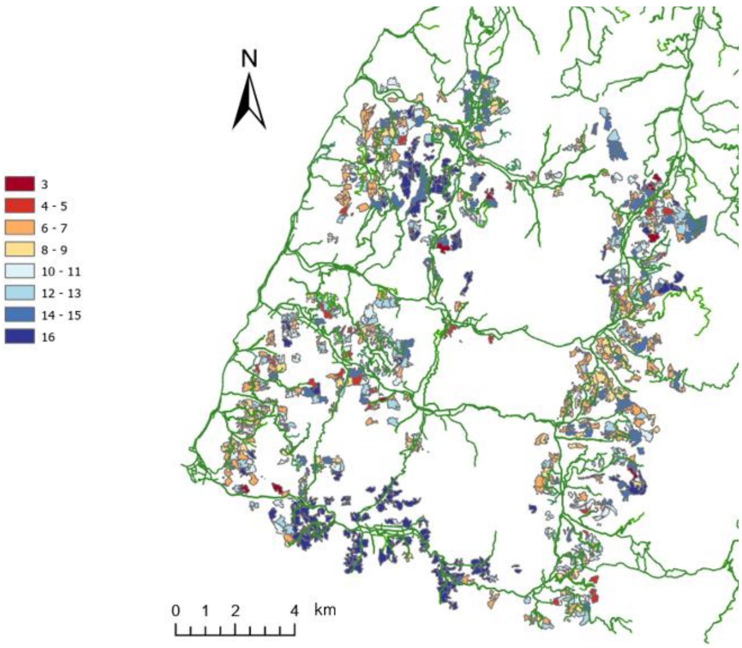
(a)



(b)

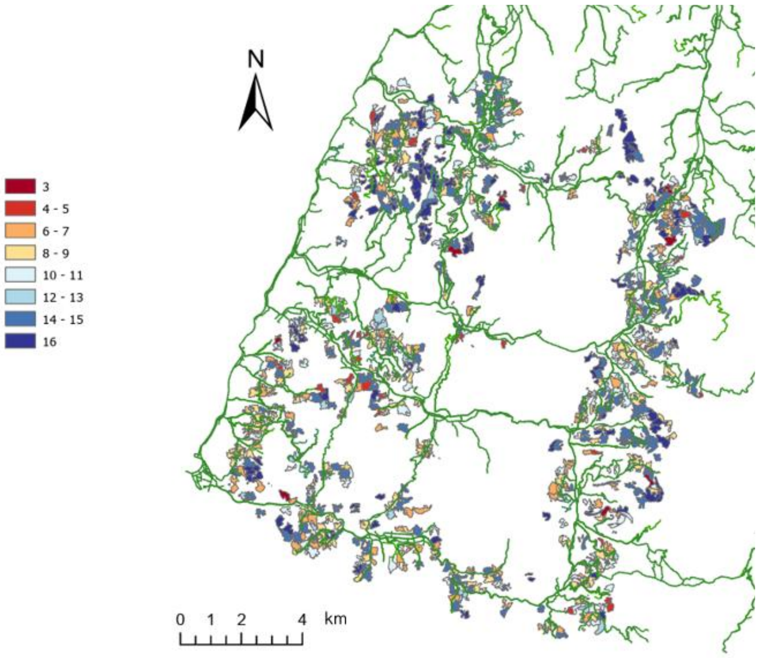


Figure S6. Selected prescriptions when site classes (a) were considered and (b) were not considered. Prescription 3: 60 years; prescription 4: 65 years; prescription 5: 70 years; prescription 6:7 5 years; prescription 7: 80 years; prescription 8: 85 years; prescription 9: 90 years; prescription 10: 95 years; prescription 11: 100 years; prescription 12: 105 years; prescription 13: 110 years; prescription 14: 115 years; prescription 15: 120 years; and prescription 16: no clear-cutting.

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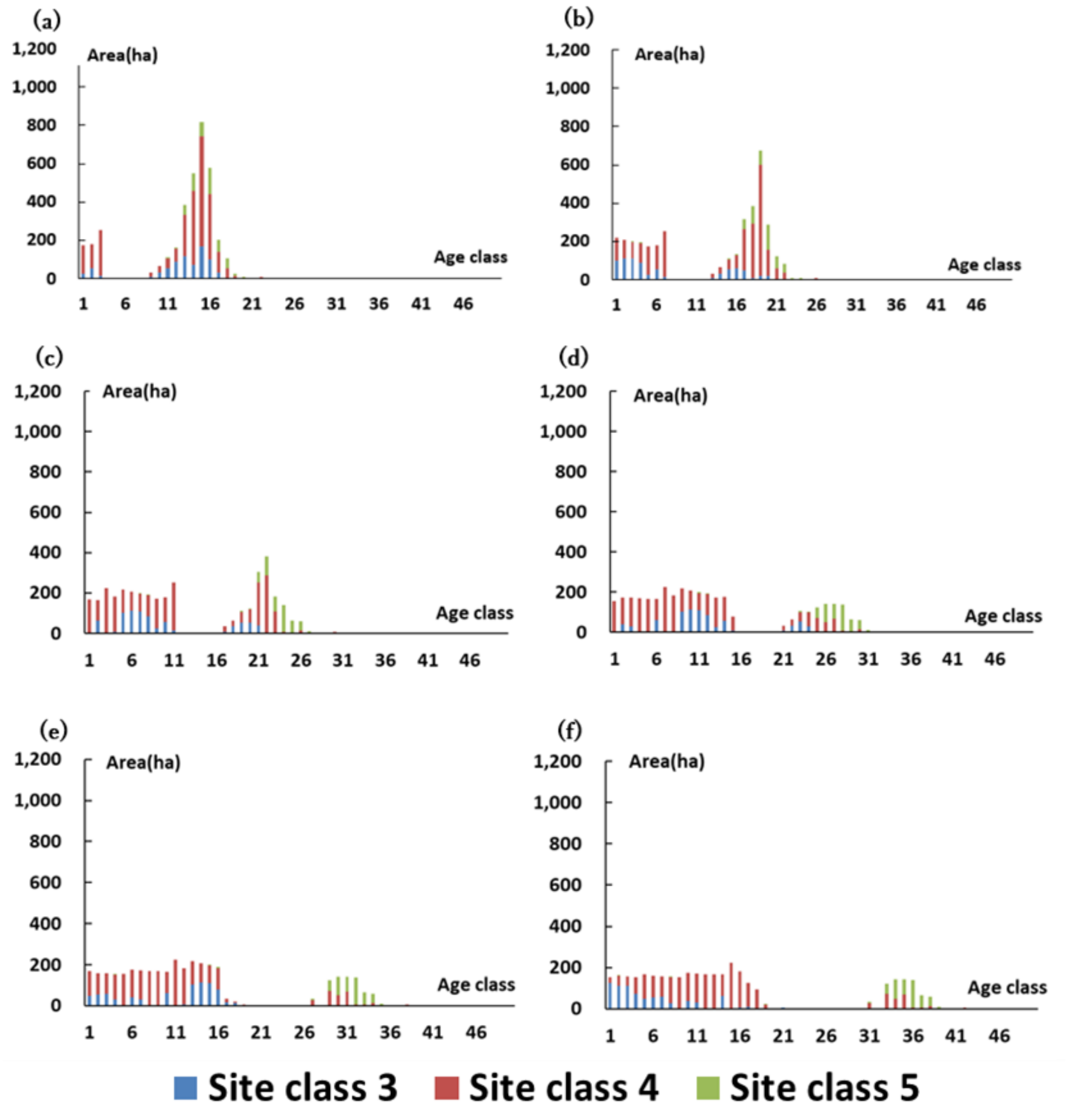

Figure S7. Changes in age-class distribution when site classes were considered in the (a) 4th, (b) 8th, (c) 12th, (d) 16th, (e) 20th, and (f) 24th (final age-class composition) planning periods.

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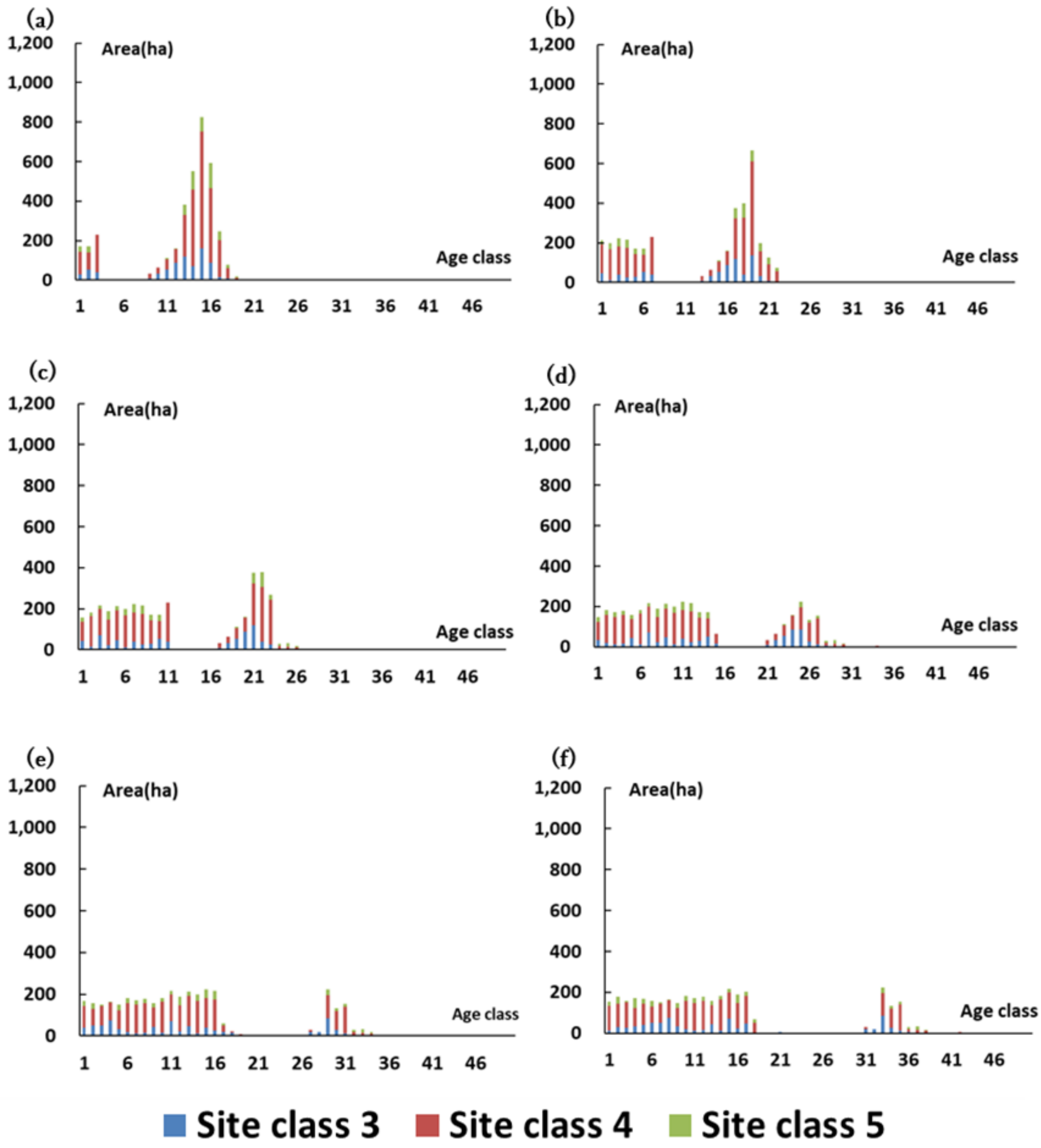

Figure S8. Changes in age-class distribution when site classes were not considered in the (a) 4th, (b) 8th, (c) 12th, (d) 16th, (e) 20th, and (f) 24th (final age-class composition) planning periods.