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Journal of Forest Planning is a peer-reviewed periodical that publishes articles, reviews, and short communications. It covers all aspects of forest management, modeling, and assessment such as forest inventory, growth and yield modeling, remote sensing and geospatial information technologies for forest management, forest management planning, forest zoning, evaluation of ecosystem services, managerial economics, and silvicultural systems. Manuscripts regarding forest policy, forest economics, forest environmental education, landscape management, climate change mitigation and adaptation strategies, and drone applications for forest management are welcome. The Journal aims to provide a forum for international communication among forest researchers and forestry practitioners who are interested in the above-mentioned fields.

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Predicting Effects of Logging Systems and Bucking Strategies for Privately Owned Sugi (*Cryptomeria japonica*) Plantations in Atsumi District, Tsuruoka City, Yamagata Prefecture

Komei Suzuki[1,2], Satoshi Tatsuhara[1,*],Tohru Nakajima[1], Hidesato Kanomata[3]
and Masaru Oka[4]

ABSTRACT

We simulate two forest management strategies applied to privately owned sugi (*Cryptomeria japonica*) plantations in Atsumi District, Tsuruoka City, Yamagata Prefecture, Japan, in order to assess potential improvements in profitability, labour requirements and harvests. The first strategy uses a traditional logging system with cable yarders yielding high-value logs; the second, 'efficient' strategy uses vehicle-based forestry machines to mass-produce regular logs. We create forest management units with areas greater than three hectares by merging stands and defining topographic conditions using a geographic information system. We consider sixteen variants of each strategy: 15 with candidate rotation ages ranging from 50 to 120 years and one with no clearcutting within the planning horizon. Harvests, labour requirements, and profits for these rotation ages are predicted for each forest management unit. We simulate harvest scheduling using 0-1 integer programming to show the proportions of chosen rotation ages and the changes in periodic harvests, labour requirements, and profits. The two strategies yield similar harvests, although the efficient strategy requires fewer person-days and generates greater profits than the traditional strategy. However, the efficient strategy is not suitable for some topographical conditions.

Keywords: forest valuation, plantation forest, private forest, rotation age, simulation

INTRODUCTION

The profitability of a forestry operation depends on a number of factors. Introducing high-performance forestry machines and constructing a high density forest road network, for example, may reduce the size of the workforce required but is costly to implement. In addition, most modern sawmills, the largest consumers of regular logs, are not designed to process large logs. Large logs fetch lower prices than regular-size logs and the size of logs increases the longer a forest is allowed to develop (Ijichi and Endo, 2010). Thus, it may be preferable to harvest logs more frequently, even if this increases the number of person-days required. So, it is difficult, given these competing factors, to identify the most profitable forest management strategy.

Forestry organizations, such as forest owners' cooperatives, are expected to play a key role in regional forest management in the present forest planning system in Japan (Forestry Agency of Japan, 2016). Forestry organizations have to identify a suitable forest management strategy, including (*inter alia*) a bucking strategy, logging system, and silvicultural regime. An important requirement in forest management is robust forecasting to support decision-making, due to the long regeneration times after final cutting. However, evaluating the profitability of forestry operations is complex, and must take into account numerous factors, including stability of employment and the sustainability of timber supplies. It is difficult to forecast intuitively future forest management including all these elements. Therefore, computer simulations that can predict the outcomes of different forest management strategies may thus provide important decision-support for organizations responsible for the long-term

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management of forests.

A number of studies have used mathematical techniques to predict harvests at a regional scale, including linear programming (Nagumo and Minowa, 1967; Nagumo and Koike, 1981) and dynamic programming (Yoshimoto, 2003). Linear programming has also been used to find trade-offs between forestry management and environmental objectives (Hiroshima, 1999). The computational complexity of the integer programming problems involved meant that, until recently, it was only possible to consider problems concerning small numbers of stands (Tanaka, 1996). However, significant improvements in computer hardware and software have enabled us to solve problems involving many more stands with integer programming.

In this study, we use integer programming to identify a management strategy for a 120-year period. A number of recent studies have applied integer programming to problems in forestry management. Toyama et al. (2012), for example, examined regional forest management incorporating integration of various aspects of adjacent forest areas, while Moriya and Tatsuhara (2014) predicted regional potential timber supplies, considering profitability. These studies focused on the prediction of supply and demand of timber in a region and formation of policies by local governments, rather than actual regional forest management by forestry organizations, as we do in this study.

Suzuki et al. (2018) assessed the effect of two strategies on the profitability of forest management. One was a 'traditional' strategy that used a logging system with cable yarders and was intended to produce high-value logs; the other was an 'efficient' strategy that used a logging system with vehicle-based forestry machines to mass-produce regular logs. However, Suzuki et al. (2018) considered an assumed model forest with a unit area. Instead, we assessed effects of logging systems and bucking systems on potential improvements in profitability, labor requirements and harvests at a regional scale. To do so, we modelled real forests containing stands differing in a number of variables, such as age, site quality, logging accessibility, and topography, thus enabling forestry organizations to make more informed decisions covering more diverse forests and areas when choosing management strategies.

Previous studies simulating forest management at a regional scale have used the subcompartment as the basic unit of management (Watanabe and Tatsuhara, 2013; Moriya and Tatsuhara, 2017). However, operations in an area of less than 1 ha are much less cost-effective than operations in larger areas (Toyama, 2011). Thus it makes little sense to carry out operations on each subcompartment separately; rather, it is desirable to carry out operations on several subcompartments that have been unified in some way. In this study, we address this issue by unifying subcompartments to form new, and more relevant, forest management units (FMUs).

MATERIALS AND METHODS

Study Site

In our simulations we consider privately owned sugi (*Cryptomeria japonica* D. Don) plantations in the Atsumi district of Tsuruoka City, in the southwestern part of Yamagata Prefecture, the area where forest owners are eligible for membership of the Atsumi Forest Owners' Cooperative (Fig. 1). According to forest inventory data, the total area of sugi plantations in the district is 7830.11 ha. The plantations are classified using a number between 1 and 6, based on the average height of trees, where 1 represents a site having the tallest trees on average and 6 the lowest. The total areas of sites of each site class, from 1 to 6, are 39.68, 52.10, 1829.46, 4875.14, 1033.24, and 0.49 ha, respectively. A logging system and bucking strategy designated 'efficient' is applied in these plantations. Effects of this strategy are compared to those of another strategy, designated 'traditional', applied in privately owned plantations located in the Sampoku district of Murakami City, in Niigata Prefecture (which borders Yamagata Prefecture), the area where forest owners are eligible for membership of the Murakami City Forest Owners' Cooperative (Fig. 1). The two logging systems and bucking strategies differ substantially, although site conditions in the two districts (which are both on the Japan Sea side of Honshu Island) are similar.

Designated erosion control forests and other lands with protected status under the Japanese Erosion Control Act were excluded from our simulations because they are not suitable for timber production. Stands with site classes 1, 2, and 6 were also excluded because they cover very small areas and stands older than 150 years were excluded because it is difficult to predict their growth. We considered the remaining areas of forests, covering 6,445 ha in total (Fig. 2). We refer to the minimal unit of forest sections in Atsumi district as a stand in this paper.

Setting Logging Systems and Bucking Strategies

The traditional strategy applied in our simulations (based on current practices in Sampoku district) consisted of felling and limbing with a chain saw, full tree cable yarding, and bucking with a chain saw at landings on forest roads. Bucking was simulated according to the strategy shown in Table 1, which is intended to produce high-value logs, such as long and large A-grade logs, as well as regular logs.

In contrast, the 'efficient' strategy applied in the simulations (based on current practices in Atsumi district, involving use of high-performance forestry machines) consisted of felling with a chain saw, limbing and bunching with a grapple loader with winch, bucking with a processor, and forwarding logs with a forwarder. Forest road density was set at 100 m/ha, the target density for vehicle-based logging of forests on gentle slopes (Forestry Agency of Japan, 2016). Bucking was simulated according to the strategy shown in Table 2, which is intended to mass-produce regular A-grade logs for a sawmill and laminated wood manufacture in Sampoku district, B-grade logs for another sawmill owned by the forest owners' cooperative to produce 2 m long laminas, and wood biomass for use in biomass power stations.

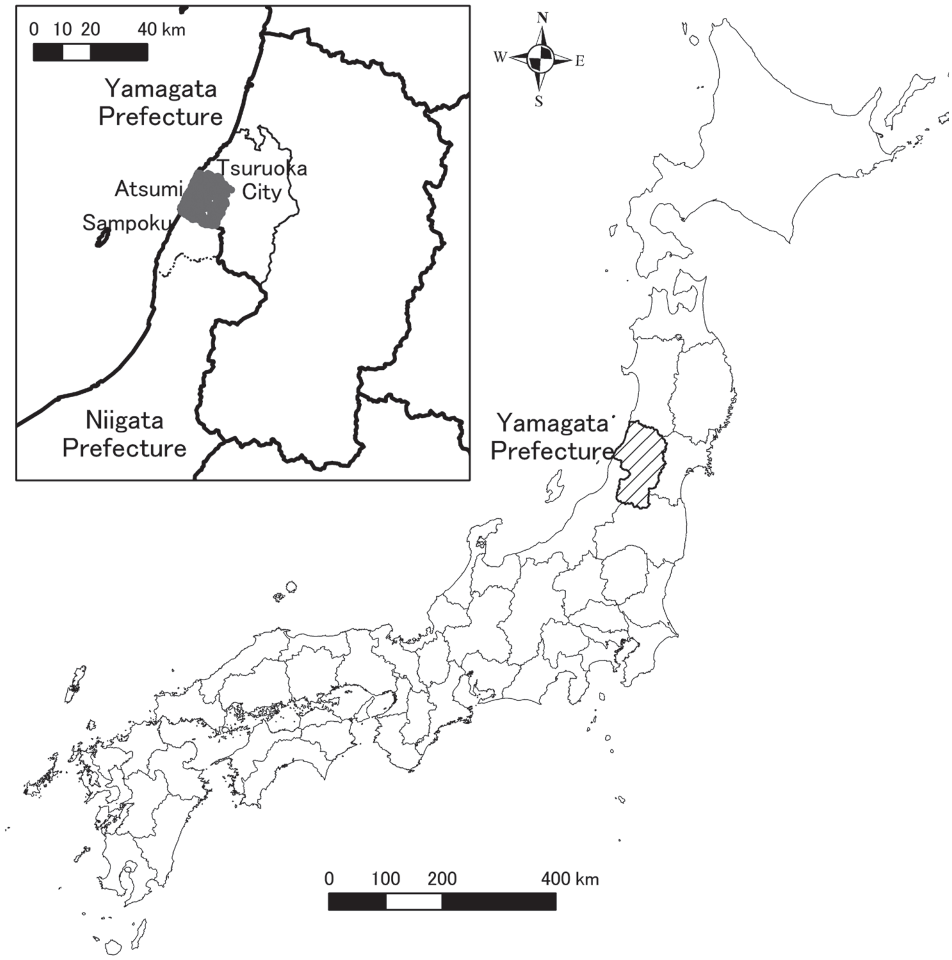

Fig. 1 Location of the study site.

Under both strategies, the percentage of bent trees was set at 60% and the maximal height of trees from which A-grade logs could be cross-cut was set at 5.5 m. In the bucking simulations, trees were cut at 0.3 m height above the ground. Logs were cut from straight trees starting from this height, and from bent trees after cross-cutting a 2 m long section including the bent part, following the orders of priorities in Tables 1 and 2. All combinations of log cross-cutting were tried and the total prices of the resulting logs were calculated, by summing products of multiplying the volume of each log by its unit price in these tables. The combination with the highest total price was chosen for each DBH class of tree.

Modelling Forest Management Units

We used forest inventory and map data and road data for 2015 provided by the Yamagata prefectural government, and digital elevation model (DEM) data provided by the Geospatial Information Authority of Japan (2016). We used ESRI ArcGIS 10.4 as our geographic information system (GIS).

First, the centroid of each stand was calculated using the 'add geometry attributes' command with the 'CENTROID_INSIDE' parameter to ensure the centroids calculated were within the stand. Then 8-ha square tiles were overlaid, and stands whose centroids were within the borders of a tile were merged. Merged stands with an area of at least 3 ha were selected as candidate forest management units (FMUs).

A traditional logging system using cable yarders is less affected than one using vehicle-based machinery by slope angle, but it is difficult to yard trees over a large ridge. For this reason, we added another condition: that the traditional strategy could not be assigned to any FMU including a compartment boundary, because compartments are usually divided by topographic features such as large ridges. Accordingly, we overlaid the merged stand and compartment themes using the 'Intersect' command in order to divide merged stands according to compartment boundaries. Then only candidate FMUs with an area of at least 3 ha were selected as FMUs for the traditional strategy.

Conversely, a logging system that uses vehicle-type forestry machines is less affected by ridges, but it is difficult to operate these machines on steep slopes, so we also stipulated that the efficient strategy could only be assigned to FMUs on a slope of 30 degrees or less. Thus, we used DEM to create a 10-m slope angle layer and slope angles were averaged in each candidate FMU. Then only candidate FMUs with an average slope angle of at

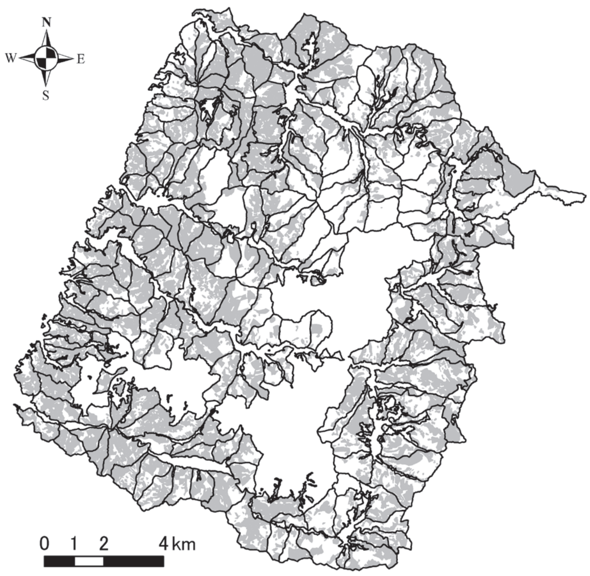

Fig. 2 Map of the study site.
Lines represent compartment boundaries and gray sections represent sugi plantations.

most 30 degrees were selected as FMUs for the efficient strategy.

Attributes of the FMUs selected for the simulation, which may include stands of various ages, were obtained using the GIS (Table 3). In this study, the average age of each FMU was calculated as a weighted average, using the age and area of each stand. An FMU should not be harvested until all the stands it contains reach rotation age. The average age of each FMU was used to construct a 5-year age-class distribution. We introduced the parameter 'base age', defined as the average age of the FMU when the age of the youngest stand in the FMU is 50 years, and set a condition that no FMU should be harvested until its average age reached the base age.

Setting Candidate Rotation Ages and Predicting Harvests, Labour Requirements, and Profits

Sixteen variants of each forestry management strategy were considered in the simulations: 15 with rotation ages of 50 to 120 years in increments of 5 years, and one with no clearcutting within a 120-year timeframe. The thinning regime was assumed to be pre-commercial low thinning, with a thinning ratio of 30% in terms of stem numbers at the age of 20 and 40 years, and commercial low thinning with a thinning ratio of 25% in terms of stem numbers at the age of 70 years in cases with rotation ages of 75 years or more. Only rotation ages that yielded a positive profit per hectare per year were considered as possible rotation ages for each FMU.

Table 1 Log types bucked in the traditional strategy

Order of priority	Log type	Length (m)	Top-end diameter class (cm)	Unit price (yen/m^3)
1	A-grade long log	6	30 – 70	18,000
2	A-grade long log	5	30 – 70	16,000
3	A-grade large log	4	48 – 70	25,200
4	A-grade large log	4	40 – 46	23,400
5	A-grade large log	4	36 – 38	19,800
6	A-grade regular log	4	16 – 34	10,800
7	A-grade regular log	3	16 – 34	10,800
8	B-grade log	2	26 – 70	7,200
9	B-grade log	2	18 – 24	6,550
10	B-grade log	2	14 – 16	4,500
	Wood biomass	Unit price per weight (yen/t)		5,000

from Suzuki et al. (2018)

Table 2 Log types bucked in the efficiency strategy

Order of priority	Log type	Length (m)	Top-end diameter class (cm)	Unit price (yen/m^3)
1	A-grade regular log	4	16 – 34	10,800
2	A-grade regular log	3	16 – 34	10,800
3	B-grade log	2	26 – 70	7,200
4	B-grade log	2	18 – 24	6,550
5	B-grade log	2	14 – 16	4,500
	Wood biomass	Unit price per weight (yen/t)		5,000

from Suzuki et al. (2018)

Table 3 The methods used to obtain attributes of each FMU

Attribute	Method
Area	Obtained using GIS
Site class	Area-weighted average of stands
Average age	Area-weighted average of stands
Base age	Average age when the age of the youngest stand reaches 50 years
Distance to the road	Traditional strategy, obtained using GIS;
	Efficient strategy, 30 m (assumed from the forest road density of 100 m/ha)
Average yarding or forwarding distance	Obtained using GIS
Average slop angle	Obtained using GIS

Fig. 3 Height-age curves by site class for sugi plantations in the study site.

Harvest, labour requirements, and profitability for each FMU, with each rotation age that met this criterion, were predicted using the methods described by Suzuki et al. (2018) and attributes of each FMU shown in Table 3. The yield from each FMU for each rotation age was predicted using height-age curves (Fig. 3) estimated from yield tables published by the Yamagata Prefectural Government (1980) and the stand density control diagram published by the Forestry Agency of Japan (1979). The yield was specified in terms of the numbers and volumes of logs of each length and top-end diameter class from final cutting and commercial thinning harvests. The labour requirements (numbers of person-days required) and costs required in each FMU for both pre-commercial and commercial thinning and final cutting were calculated for each rotation age, using the same methods as Suzuki and Tatsuhara (2016) for the traditional strategy and Oka (2006) and Nakajima et al. (2017) for the efficient strategy. The efficient strategy requires the construction of new roads. We assumed these roads would be built at the time of final cutting. The cost, C_{con}, of constructing new roads was included in the logging costs and calculated using the following equation:

$$C_{con} = U_{con}\left(\left(1+r\right)S_{ave} + DA\right) \quad (1)$$

where U_{con} is the unit cost to construct roads (2,500 yen/m); r is the correction factor to account for roads' deviations from straight lines (0.75); S_{ave} is the forwarding distance (m); D is the road density (100 m/ha); and A is the area (ha).

The labour requirements and costs required for regeneration and subsidies for regeneration and thinning were estimated from data supplied by the Yamagata Prefectural Government (2016). Profit over a rotation in each FMU was calculated by subtracting the costs for regeneration and logging from the revenues from selling logs and subsidies for regeneration.

Five-year age-classes of the FMUs moved in accordance with the set rotation ages during the 120-year planning horizon in the simulations. If no rotation age could be assigned to a FMU because its base age was over 120 years, its age class was assumed to increase throughout the whole timeframe. The harvest, labour requirements, and profit during each planning period for each FMU and each rotation age were then calculated, according to these age class transitions, as described below.

Forest Management Simulations Based on the Two Strategies

To simulate forest management of the study site, a harvest scheduling model was formulated. In the context of forest planning, strategic planning is concerned with sustainable harvest and operational planning considers the use and location of staff (Bettinger at al., 2009). The unimodal age-class distribution in the study site leads to large variations in yield, resulting in large variations in the amount of labour required. In addition, a significant amount of labour is required for planting and tending a forest in the 12 years following final cutting. However, the mobility of labour is low in Japan, where long-term employment and seniority-based wage are characteristics of the employment system (Hattori and Maeda, 2000). Moreover, stable employment is desirable in especially depopulated areas. Thus, labour constraints were included in the strategic planning in addition to harvest constraints. The profitability of final cutting FMUs was evaluated one by one, taking into account the geographic attributes shown in Table 3, and then only profitable rotation ages were assigned to FMUs. Thus, 0-1 integer programming (Greenberg, 1971) was applied to formulate the long-term harvest scheduling model. We set age classes of the FMUs (as described above) and the length of a planning period at 5 years and the length of the planning horizon at 120 years (24 planning periods).

In our model, the objective function is the maximization of total profit over the planning horizon. The current interest rate is close to zero in Japan as the average interest rate of 10-year Japanese government bonds was 0.05% in fiscal year 2017 (Ministry of Finance, 2018). Providing the areas of mature age classes are larger than those of normal forest, the sustainable harvest level to maximize net present value of total profit under a harvest even-flow constraint coincides with the sustainable maximal average volume growth, regardless of positive discount rate, and the sustainable harvest schedule to maximize forest rent coincides with the sustainable harvest schedule to maximize net present value under a profit even-flow constraint (Oka, 1995). This is because harvest or profit in the first planning period is not allowed to exceed the perpetual sustainable harvest level or profit level, even though current profit has a higher value than future profit with a positive discount rate (Oka, 1995). In this study, the effect of discount rate is small because the study site has a surplus of mature stands, as explained below, and a harvest even-flow constraint was set in our model. Thus, we set discount rate at zero for calculation of the total profit.

The average age of FMUs at the study site currently follows a bell-shaped distribution, concentrated around age classes 10–14 in the current age class distribution, and the labour requirements for harvesting will increase as the average age of the FMUs reaches standard rotation ages. If the workforce remains constant, many FMUs in these age classes will probably not be harvested within the 120-year planning horizon, and thus will reach age class 24 (121 years old) from planning period 11, and be excluded from final cutting, thereby reducing the harvest and revenue. Hence, there is a trade-off between expenditure on additional staff and increased revenue from greater yields. Therefore, we allowed larger fluctuation until planning period 10 to deal with the bell-shaped age class distribution, and then aimed to assure stability after planning period 11. Accordingly, we split the 24 planning periods of the planning horizon into two parts: an early *transition* part comprising 10 planning periods, where labour and harvest could fluctuate considerably; and a late *stable* part comprising 14 planning periods, where labour and harvest could fluctuate much less. The fluctuation tolerance during the stable planning periods was set at ±10% in the same way as the deviation which Nelson et al. (1991) allowed for harvest and net revenue in three decade-periods in integrated short-term and long-term plans. Then the fluctuation tolerance during the transition planning periods was set at ±30%, which was found to be the minimal feasible value by iterative trials to solve the harvest scheduling problem with raising the value of fluctuation tolerance from ±10%.

We introduce the following variables to formulate the problem: *LStandard* and *VStandard* represent person-days and harvest, respectively, during the planning horizon; *LStart* and *VStart* represent labour requirements and harvest, respectively, at planning period 1; I, J and T are the numbers of FMUs, distinct rotation ages (16) and planning periods (24), respectively; t_s represents the starting period of the stable planning periods (set at 11); $P_{i,j,t}$, $L_{i,j,t}$ and $V_{i,j,t}$ represent, respectively, profit, labour requirements and harvest in planning period t when FMU i is assigned to rotation age j; $x_{i,j}$ is 1 when FMU i is assigned to rotation age j, and otherwise 0; $y_{i,j}$ is 1 when rotation age j is a candidate for FMU i, and otherwise 0; r_{trans} is the fluctuation tolerances during the transition planning periods (set at ±30%); r_{stable} is the fluctuation tolerances during the stable planning periods (set at ±10%).

Our integer programming problem may then be formulated as follows:

Maximize

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} P_{i,j,t}x_{i,j} \tag{2}$$

Subject to

$$\sum_{i=1}^{I}\sum_{j=1}^{J} L_{i,j,t}x_{i,j} \le (1+r_{trans})LStandard \quad \forall t \in \{1,\cdots,t_s-1\} \tag{3}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} L_{i,j,t}x_{i,j} \ge LStart \quad \forall t \in \{1,\cdots,t_s-1\} \tag{4}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} V_{i,j,t}x_{i,j} \le (1+r_{trans})VStandard \quad \forall t \in \{1,\cdots,t_s-1\} \tag{5}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} V_{i,j,t}x_{i,j} \ge VStart \quad \forall t \in \{1,\cdots,t_s-1\} \tag{6}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} L_{i,j,t}x_{i,j} \le (1+r_{stable})LStandard \quad \forall t \in \{t_s,\cdots,T\} \tag{7}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} L_{i,j,t}x_{i,j} \ge (1-r_{stable})LStandard \quad \forall t \in \{t_s,\cdots,T\} \tag{8}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} V_{i,j,t}x_{i,j} \le (1+r_{stable})VStandard \quad \forall t \in \{t_s,\cdots,T\} \tag{9}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} V_{i,j,t}x_{i,j} \ge (1-r_{stable})VStandard \quad \forall t \in \{t_s,\cdots,T\} \tag{10}$$

$$\sum_{j=1}^{J} x_{i,j} = 1 \quad \forall i \tag{11}$$

$$y_{i,j} \ge x_{i,j} \quad \forall i,j \tag{12}$$

Table 4 Values of parameters set in the simulation

Parameter	Traditional strategy	Efficient strategy
LStatt	10,000	
VStart	100,000	
I	857	657
J	16	
T	24	
r_{trans}	0.3	
r_{stable}	0.1	

$$x_{i,j}, y_{i,j} \in \{0,1\} \quad \forall i, j \qquad (13)$$

The above equations may be interpreted informally in the following way.

Eq. (2): objective function, maximizing the total profit over the planning horizon.

Eqs. (3) and (4): labour constraints during the transition planning periods.

Eqs. (5) and (6): harvest constraints during the transition planning periods.

Eqs. (7) and (8): labour constraints during the stable planning periods.

Eqs. (9) and (10): harvest constraints during the stable planning periods.

Eq. (11): constraints for assignment of a single rotation age; each FMU can be assigned only one of the rotation ages.

Eq. (12): constraints for possible rotation ages; only possible rotation ages, as determined in the previous section, were assigned as candidate rotation ages to each FMU.

Eq. (13): variables $x_{i,j}$ and $y_{i,j}$ can only take the value 0 or 1.

Using the model we simulated the two strategies. Candidate rotation ages, harvest, person-days, and profit corresponding to the rotation ages were calculated for each FMU identified in the previous section and input to the model. Then the resulting integer programming problems were solved using IBM ILOG CPLEX Optimization Studio ver12.5.1 running on a personal computer with a Windows 8.1 64-bit operating system, an Intel Core i3-4130 CPU @ 3.40 GHz processor, and 4-GB RAM. Our objective was to compare the two strategies, rather than obtain exact solutions. Thus, we rounded the profits to the nearest 1,000, and obtained approximate solutions by applying the branch-and-cut method with a relative gap tolerance of 0.1%.

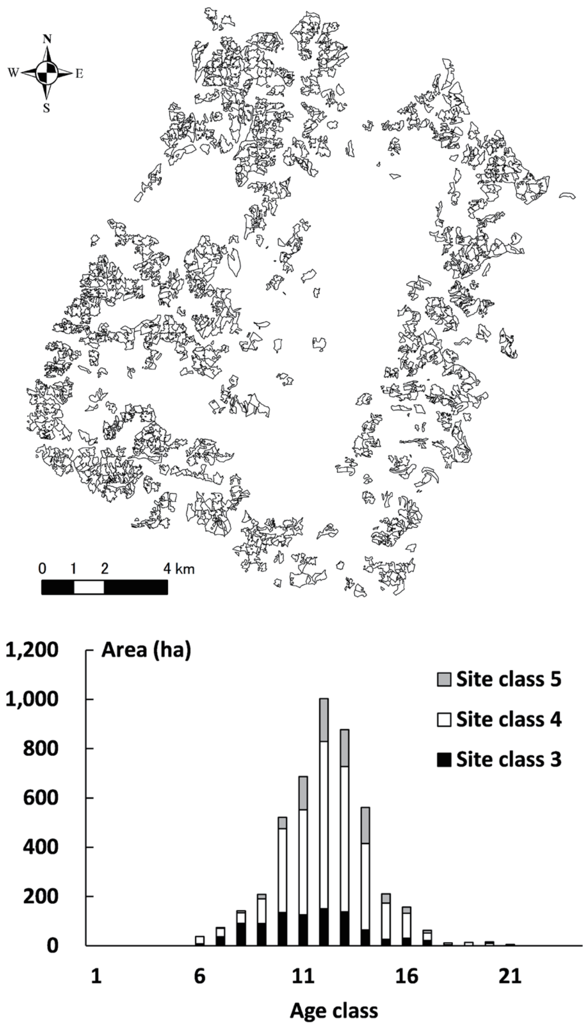

Fig. 4 Locations of candidate FMUs (top) and their age class distribution at the beginning of the planning horizon (bottom) for the traditional strategy.

RESULTS

The total area of the candidate FMUs was 5,169 ha. The topographic conditions reduced the total area of FMUs for the traditional strategy by 581 ha to 4,588 ha, with 857 FMUs being used in the simulation (Table 4). The age class distribution for these FMUs was bell-shaped (Fig. 4). The problem size was reduced to 771 rows and 6955 columns, and the solution time was 3 minutes. The total area of FMUs for the traditional strategy was further reduced by 868 ha because of negative profitability, leaving 3,720 ha. Next, the topographic conditions reduced the total area of FMUs for the efficient strategy by 1,526 ha to 3,643 ha. This resulted in 657 FMUs being used in the simulation (Table 4). The age class distribution of these FMUs was also bell-shaped (Fig. 5). The problem size was reduced to 749 rows and 7293 columns, and the solution time was 54 minutes. The

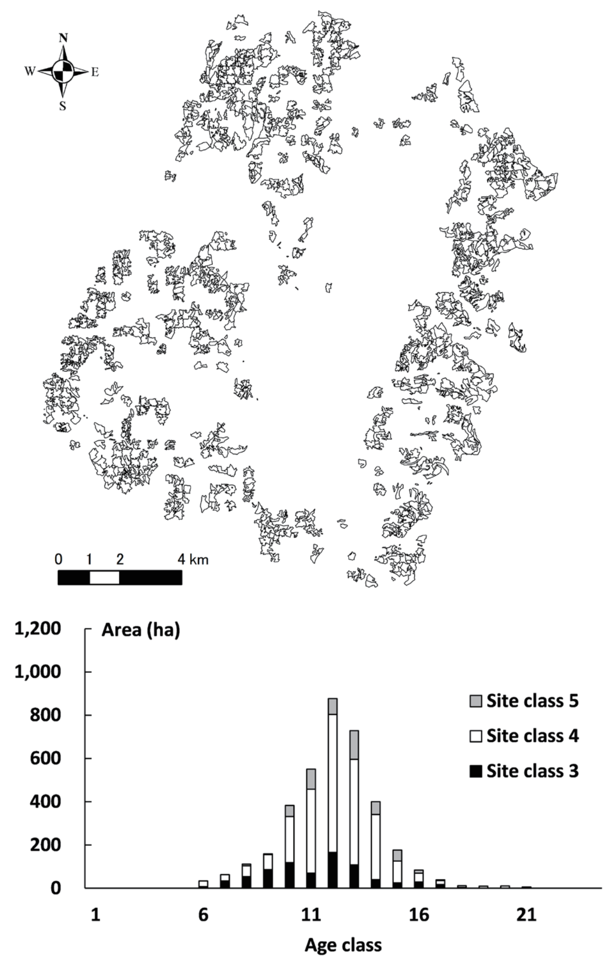

Fig. 5 Locations of candidate FMUs (top) and their age class distribution at the beginning of the planning horizon (bottom) for the efficient strategy.

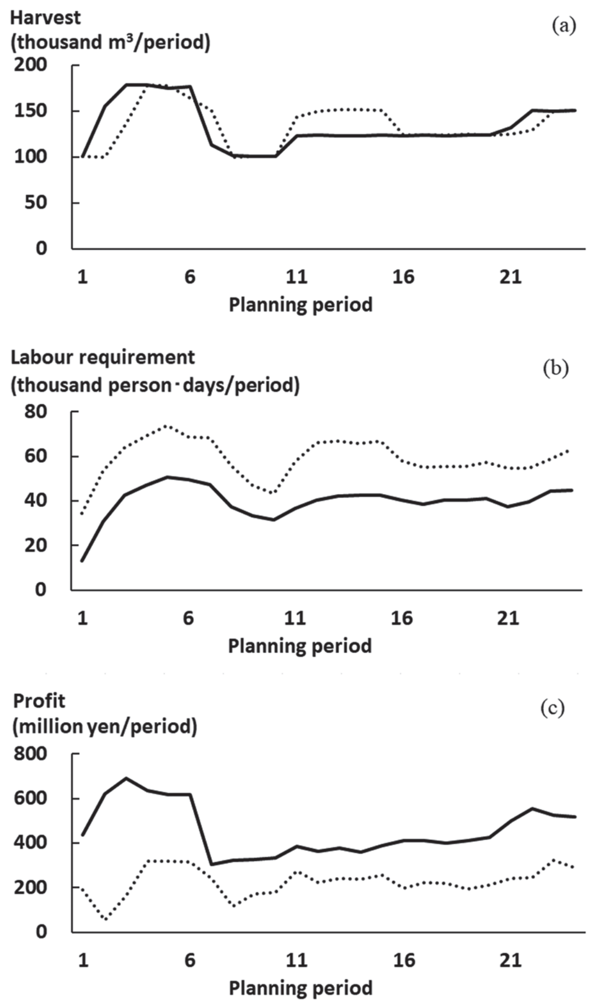

Fig. 6 Changes in periodic harvests (a), periodic labour requirements (b), and periodic proft (c).
Solid and dotted lines indicate changes under traditional and efficient strategies, respectively.

total area of FMUs for the efficient strategy was further reduced to 3,633 ha, as a result of excluding 10 ha because the base age was too young.

The total area of FMUs for the efficient strategy was further reduced to 3,633 ha, as a result of excluding 10 ha because the base age was too young.

The two strategies resulted in similar periodic harvests (Fig. 6a) and harvest levels (Table 5). The current harvest (in fiscal year 2015) from privately owned sugi plantations in the study site amounted to 21,000 m^3, and thus 105,000 m^3/period. Under both strategies, the harvest levels became approximately 1.3 times greater than the current harvest. However, the traditional strategy required more person-days (Fig. 6b), and generated less periodic profit (Fig. 6c) than the efficient strategy throughout the planning horizon. The labour level of the efficient strategy was about two thirds of that of the traditional strategy (Table 6b). Atsumi Town Forest Owners' Cooperative has 13 employees at present, corresponding to 16,250 person-days/period, assuming that each employee works 250 days a year. Thus, the traditional strategy and efficient strategy need about 3.7 times and about 2.5 times more person-days, respectively, than are currently available.

Under both strategies, the periodic harvests of logs of all grades, especially B-grade, increased rapidly in the early planning periods. The periodic harvest of B-grade logs reached a maximum later than those of other two grades. The periodic harvest of B-grade logs also varied substantially in the stable planning periods, although the periodic harvest of A-grade logs varied little. The wood biomass harvest fluctuated less than the log harvests (grades A and B) and leveled out at slight lower than that in planning period 1 after a relatively small increase in the transition phase (Fig. 7).

For the traditional strategy, the highest proportions of FMUs were assigned to a rotation age of 120 years, followed by a rotation age of 80 years and no clearcutting (Fig. 8a). The total area of FMUs for the traditional strategy was further reduced by not clearcutting 868 ha because of negative profitability, leaving 3,720 ha. For the efficient strategy, the highest proportions were assigned to a rotation age of 120 years, followed by rotation ages

Table 5 Results of the two strategies

Result	Traditional strategy	Efficient strategy
Total profit (million yen)	5,449	10,939
Harvest level (m^3/period)	137,940	136,913
Labour requirements level (person-days/period)	60,813	40,884

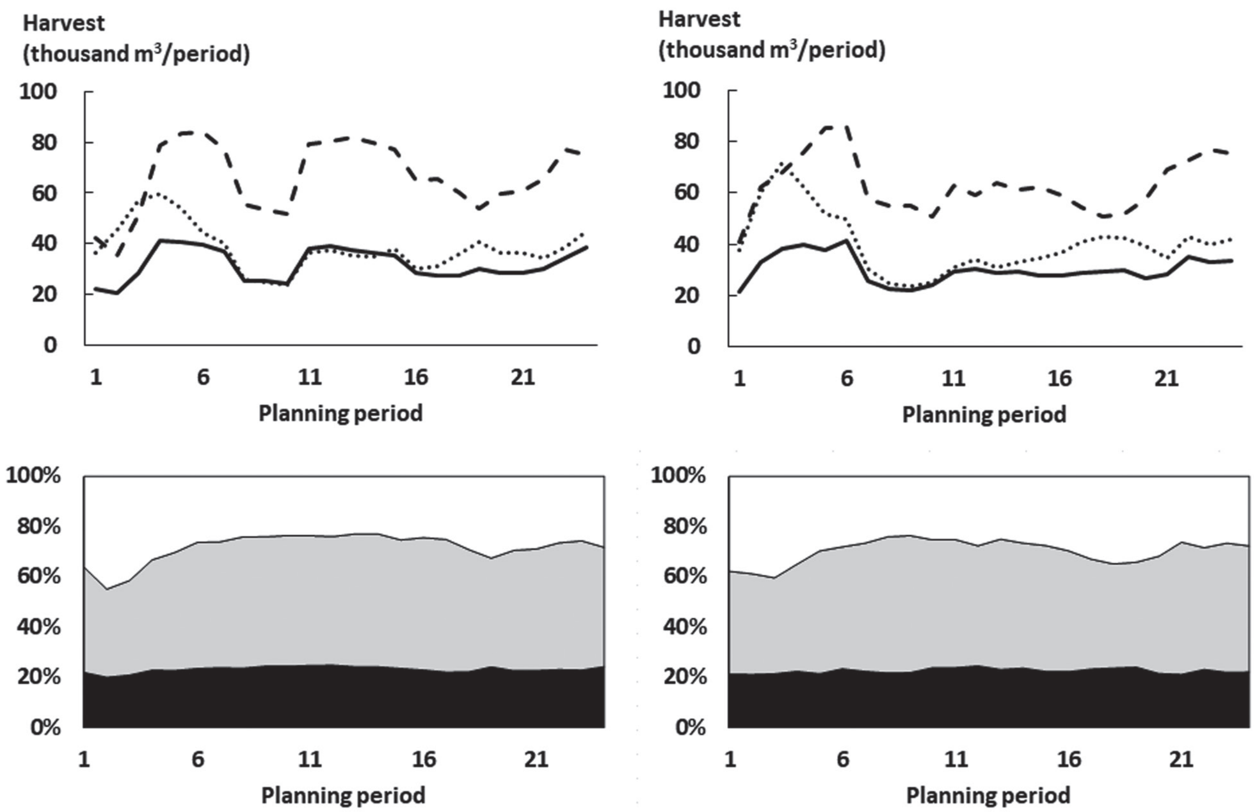

Fig. 7 Changes in periodic harvests by log types (top) and their proportions (bottom) under the traditional strategy (left) and efficient strategy (right).
Solid, broken, and dotted lines on top figures indicate A-grade logs, B-grade logs, and wood biomass, respectively. Black, gray, and white parts on bottom figures indicate A-grade logs, B-grade logs, and wood biomass, respectively.

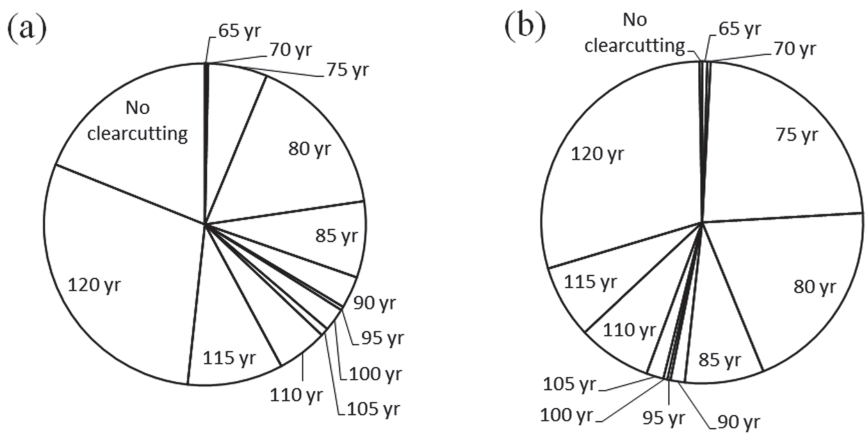

Fig. 8 Proportions of areas of FMUs assigned to indicated rotation ages under the traditional strategy (a) and efficient strategy (b).

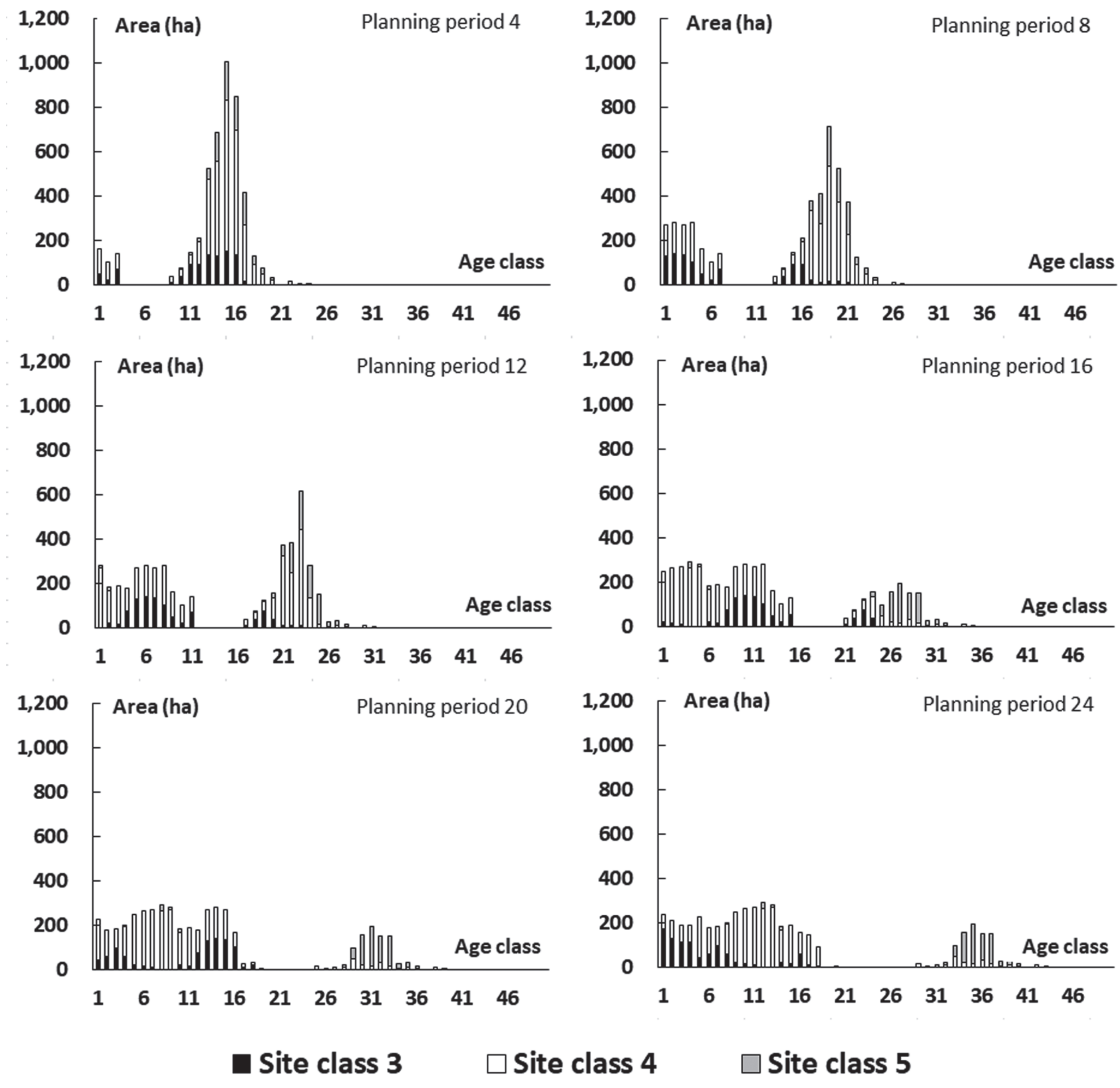

Fig. 9 Changes in age class distributions under the traditional strategy.

of 75 and 80 years, while only a few FMUs were assigned to no clearcutting (Fig. 8b). The total area of FMUs for the efficient strategy was further reduced to 3,633 ha, as a result of excluding not clearcutting 10 ha because the base age was too young.

Under the traditional strategy, the changes of age class distributions (see Fig. 9) showed that FMUs of site class 5 remained unharvested and most of the other FMUs were harvested and regenerated once by the 20th planning period. Under the efficient strategy, the changes of age class distributions (Fig. 10) showed that most FMUs were harvested and regenerated once by the 16th planning period. Under both strategies, the age class distributions at the end of the planning horizon were more even than those at the beginning of the planning horizon.

DISCUSSION

The harvest levels increased to about 1.3 times greater than present levels under both strategies, while the labour requirements for the traditional and efficient strategies were respectively about 3.7 times and 2.5 times greater than currently available levels. The labour requirements increased more than harvest levels because of the increase in person-days required for regeneration operations. (To date, few final cuttings have been carried out in the focal district, so few person-days have been required for regeneration.) The small workforce used to be enough to manage the large area of forests, even though the timber resource is mature, but our results suggest the present workforce is too small for the successful future management of these forests.

The reason why the efficient strategy yielded more profit

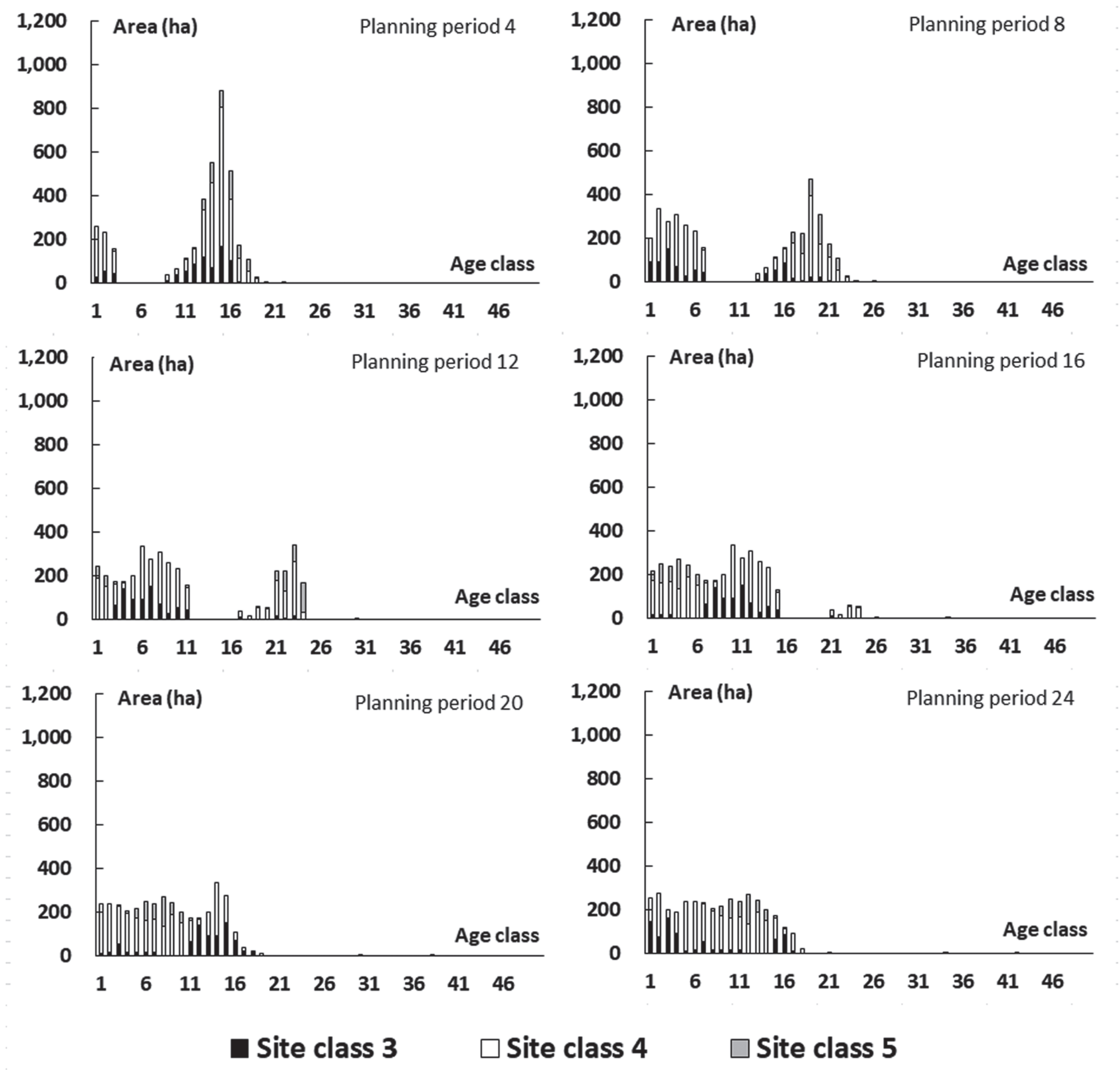

Fig. 10 Changes in age class distributions under the efficient strategy.

than the traditional strategy was that basically the former was more profitable than the latter at stand level under most conditions, as Suzuki et al. (2018) showed. The changes in periodic profit were closely related to those in periodic harvest under both strategies. Around planning period 7, the periodic profits dropped drastically because regeneration costs increased substantially as the area of forests that required replanting increased. Generally, relatively stable profits are desirable for sustainable management, and we should be concerned about the large fluctuations in periodic profit. It would be possible to add a constraint of profit stability to our harvest schedule model, but that would probably decrease harvest and labour requirements. Nevertheless, it could potentially be beneficial to allow profits to fluctuate to some extent during the transition periods, leading to increases in harvest during the stable periods (given the present unimodal age class distribution).

The periodic harvest rose dramatically in the transition planning periods. The objective function in the harvest scheduling model was to maximize the total profit over the planning horizon. Thus, the optimal solution sought by the model involved clearcutting as large an area of forests as possible, particularly stands in the peak of the current unimodal age-class distribution, within the maximal timeframe of 120 years.

The main customers for A-grade logs produced in the focal district are a sawmill and a laminated wood manufacturing factory, which consumes about 13,000 m^3 of timber produced annually in Sampoku district. The factory, which currently has difficulty acquiring enough logs to operate at full capacity 24,000

m^3, could provide a ready market for the additional A-grade logs harvested during the transition period. The main demand for B-grade logs comes from the other sawmill operated by the Atsumi Town Forest Owners' Cooperative, for the production of 2 m long lamina. Moreover, a laminated wood manufacturing factory has been recently built in the district. The factory's annual capacity for B-grade logs is 120,000 m^3, thereby providing a ready market for the increased harvest of B-grade logs. There would be sufficient demand for the increased wood biomass yielded by our two strategies because the power station in Tsuruoka City consumes 35,000 tonnes of wood biomass annually. Therefore, there would be sufficient demand for the increased harvest of all grades of logs in this district.

The changes in age class distributions under the traditional strategy showed that FMUs of site class 3 were final-cut and replanted in relatively early planning periods, whereas FMUs in site class 5 were not harvested because it would not have been profitable to do so (Fig. 9). FMUs of site class 3 were mainly assigned to rotation ages 75–85 years, and FMUs of site class 5 were assigned to no clearcutting. Under the efficient strategy, the ages of FMUs of site classes 3 and 5 were mainly older than 30 years and 30 years or younger, respectively, in planning period 16. The changes in age class distributions under both strategies suggest that assigned rotation ages depended on site quality, confirming previous results of Watanabe and Tatsuhara (2013). The GIS data for this district show that the spatial distribution of site quality is not uniform. Thus, there may be significant local variation in possible timeframes of final cuts. There is no legal limit on areas that can be clear-cut in Japan, except for protected forests. However, it would not be desirable for a large area to become unstocked at once. If adjacency constraints are added to a harvest scheduling model, it is possible to avoid this spatial problem, which could severely impair local biodiversity (Yoshimoto and Brodie 1994). We would like to incorporate such adjacency constraints in our future work.

CONCLUSIONS

We have predicted regional-scale effects of two forestry management strategies on harvest, labour requirements and profitability, taking into account variables including stand age, site quality, logging accessibility, and topography. Our simulations indicate that the traditional and efficient strategies would have similar effects on periodic harvest, although the efficient strategy would require fewer person-days and generates greater profits than the traditional strategy. However, a potential advantage of the traditional strategy is that it requires a larger workforce, thereby creating more employment opportunities. The efficient strategy could generate more profits with a smaller workforce, but it is not suitable for all topographical conditions.

However, an assumption underlying the simulation model we developed in this study is that silvicultural regimes such as thinning would be uniform. Moreover, the objective function of the harvest scheduling model maximized the total profit over the planning horizon, assuming that the forest owners would make (and collectively adhere to) corresponding decisions. In reality, many forest owners make decisions based on their personal values and barely consider optimal regional-scale solutions. Nevertheless, due to increasing integration of adjacent, privately owned forest areas and forest trusts, a method such as the one presented in this paper for predicting profits, yields and labour requirements, could support collective decision-making and thus improve forestry management in Japan.

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LITERATURE CITED

Bettinger, P., Boston, K., Siry, J.P. and Grebner, D.L. (2009) Forest management and planning. Academic Press, Burlington, MA, USA, 331 pp

Forestry Agency of Japan (1979) Ura tohoku · hokuriku chiho sugi rinbun mitsudo kanrizu [Stand density control diagram for sugi in the Sea of Japan coastal Tohoku and Hokuriku regions*]. Japan Forest Technology Association, Tokyo (in Japanese)

Forestry Agency of Japan (2016) Annual report on forest and forestry in Japan: Fiscal Year 2015. National Forestry Improvement and Dissemination Association, Tokyo (in Japanese)

Geospatial Information Authority of Japan (2016) Fundamental geospatial data. http://fgd.gsi.go.jp/download/ (accessed 19 December 2016)

Greenberg, H. (1971) Integer programming. Academic Press, New York, 196 pp

Hattori, R. and Maeda, E. (2000) The Japanese employment system. Bank Jpn. Mon. Bull. **January 2000**: 31–71 (in Japanese; English abstract is available at https://www.boj.or.jp/en/research/brp/ron_2000/ron0001a.htm/)

Hiroshima, T. (1999) Setting objectives of sustainable forest management using linear programming: A case study of criteria and indicators accepted at a meeting of Montreal Process countries. J. Jpn. For. Soc. **81**: 245–249 (in Japanese with English abstract)

Ijichi, M. and Endo, K. (2010) Research on effective profit use of cryptomeria large diameter material. Res. Bull. Kagoshima

Univ. For. **37**: 79–92 (in Japanese with English abstract)

Ministry of Finance, Japan (2018) Interest rate. https://www.mof.go.jp/english/jgbs/reference/interest_rate/index.htm (accessed 9 August 2018)

Moriya, T. and Tatsuhara, S. (2014) Predicting of sustainable timber supply level considering stability of profits. J. Jpn. For. Soc. **96**: 109–116 (in Japanese with English abstract)

Moriya, T. and Tatsuhara, S. (2017) Effects of harvest restraint periods and fluctuation tolerances of profits and harvests on sustainable timber supply levels from private forests in a district. Forest Sci. Technol. **13**: 17–24

Nagumo, H. and Koike, A. (1981) Studies on the construction of management plans for private forests (I) Determination of harvests and cutting areas of artificial forests for constructing a district forest plan. J. Jpn. For. Soc. **63**: 79–89 (in Japanese with English abstract)

Nagumo, H. and Minowa, M. (1967) Analysis of the regulation of yield by linear programming. Bull. Univ. Tokyo For. **63**: 235–265 (in Japanese with English abstract)

Nakajima, T., Shiraishi, N., Kanomata, H. and Matsumoto, M.(2017) A method to maximise forest profitability through optimal rotation period selection under various economic, site and silvicultural conditions. N. Z. J. For. Sci. **47**: 4

Nelson, J., Brodie, J.D. and Sessions, J. (1991) Integrating short-term, area-based logging plans with long-term harvest schedules. Forest Sci. **37**: 101–122

Oka, H. (1995) Discount rate and decision making in forest management. Ringyo Keizai Kenkyu [J. For. Econ.] **127**: 203–208 (in Japanese)

Oka, M. (2006) Studies on the analysis and evaluation on mechanized yarding. Ph. D. Thesis, the University of Tokyo, Tokyo, 203 pp (in Japanese with English abstract)

Suzuki, K., Tatsuhara, S. (2016) Effects of cross-cutting strategies and management conditions on profits from sugi (*Cryptomeria japonica*) plantations: Case studies of private forests in Sampoku District, Murakami City, Niigata Prefecture. Jpn. J. For. Plann. **50**: 27–40 (in Japanese with English abstract)

Suzuki, K., Tatsuhara, S., Nakajima, T., Kanomata, H. and Oka, M. (2018) Effects of logging systems and bucking strategies on profits from sugi (*Cryptomeria japonica*) plantations: Case studies of private forests in Atsumi District, Tsuruoka City, Yamagata Prefecture. Jpn. J. For. Plann. **51**: 69–79 (in Japanese with English abstract)

Tanaka, K. (1996) Shinrin keikakugaku nyumon [An introduction to forest planning*]. Japanese Society of Forest Planning Press, Fuchu, Tokyo,192 pp (in Japanese)

Toyama, K. (2011) Study on economic evaluation of forest management using simulations*. PhD Thesis, the University of Tokyo, Tokyo, 97 pp (in Japanese)

Toyama, K., Tatsuhara, S. and Shiraishi, N. (2012) Simulation under diverse conditions for profitable thinning regime and clearcutting age in planted *Cryptomeria japonica* forest. J. Jpn. For. Soc. **94**: 269–279 (in Japanese with English abstract)

Watanabe, S. and Tatsuhara, S. (2013) A long-term harvest scheduling model involving two types of rotation and variable labour requirements. J. For. Plann. **19**: 17–26

Yamagata Prefectural Government (1980) Yamagata-ken sugi rinbun zaisekihyo, Yamagata-ken sugi rinbun shukaku-yosohyo [Volume tables and yield tables for sugi (*Cryptomeria japonica*) in Yamagata Prefecture*]. Yamagata Prefectural Government, Yamagata (in Japanese)

Yamagata Prefectural Government (2016) Heisei 28 nendo Yamagata-ken sinrin segyo shien jigyo hyojun tankahyo: Shinrin seibi [Standard unit cost tables of forest operation subsidies in Yamagata Prefecture for the fiscal year 2016*]. Yamagata Prefectural Government, Yamagata (in Japanese)

Yoshimoto, A. and Brodie, J.D. (1994) Short- and long-term impacts of spatial restrictions on harvest scheduling with reference to riparian zone planning. Can. J. For. Res. **24**: 1617–1628

Yoshimoto, A. (2003) A dynamic programming model for forest stand management using MSPATH algorithm. Proceedings of the Institute of Statistical Mathematics **51**: 73–94 (in Japanese with English abstract)

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