A Long-Term Harvest Scheduling Model Involving Two Types of Rotation and Variable Labour Requirements

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ABSTRACT

The objectives of this study were to formulate a long-term harvest scheduling model, involving two types of rotation constrained by the available size of the work force, using 0-1 integer programming and then apply the model to plantation forests in the University of Tokyo Chiba Forest as a case study. The following three silvicultural systems were considered: an 80-year and a 160-year rotation clearcutting system and a non-clearcutting system. The minimum amount of labour required to harvest the minimum area was calculated and then that figure was increased to model its effect on harvesting. Subcompartments better suited to timber production tended to be assigned to clearcutting. There was a tendency for subcompartments with a better site class to be assigned to the shorter rotation and subcompartments with a shorter yarding distance to be assigned to the longer rotation. As the size of the available work force increased, subcompartments less well suited to timber production were also assigned to clearcutting and the harvest volume per person-day and the clear cut area per person-day decreased. The longer rotation was efficient with a smaller work force and the shorter rotation appeared more efficient as the size of the work force increased.

Keywords: long rotation, long-term plan, plantation forest, 0-1 integer programming

INTRODUCTION

Low timber prices have forced forest owners to delay the final cutting of coniferous plantations in Japan. They would like to reduce the number of person-days required for forest management in order to cut costs. Moreover, the population of sika deer (*Cervus nippon* Temminck) has increased in many areas in Japan and this had made forest owners reticent to clearcut the plantation forests because of the additional costs involved in erecting fences to protect seedlings from the deer after clearcutting. Thus, long rotation silvicultural systems have been considered in order to reduce the required number of person-days. The required number of person-days per volume decreases as the rotation is lengthened (Tatsuhara and Doi, 2006). Lengthening rotation immediately, however, leads to unsustainable timber production from plantation forests. Introducing multiple rotations to avoid this is one method to adapt plantation forest management to such social and ecological changes. The term “multiple rotations” means to apply more than one rotation length to plantation forests in a management area.

Harvesting timber needs scheduling in order to sustain both the growing stock and the harvest volume over the time horizon. One of the methodologies used for harvest scheduling is optimization using mathematical programming. Johnson and Scheurman (1977) formulated harvest scheduling models using linear programming and quadratic programming to maximize the discounted net income over the time horizon. There have been many other studies into the optimal long-term planning of harvest scheduling, such as managing plantation forests to match the age class distribution of “normal forests” (Nagumo and Koike, 1981), maximizing yield and income and equalizing them in each working period (Buogiorno and Gilless, 1987) and restricting the harvesting of adjacent stands for environmental protection purposes (Yoshimoto et al., 1994). Næsset (1996) developed a spatial decision support system for long-term planning by combining GIS and linear programming. Most of the studies of harvest scheduling were carried out assuming that the necessary work force was available, although Yamatsu and Ishibashi(2000) used linear programming to consider constraints on the size of the work force in the long-term scheduling of harvesting an area by using age classes to match the age class distribution of a management area with its goal. It is important to learn the size of areas that can be managed with a limited work force and how many workers are necessary to undertake a forest...
management plan. Moreover, it is preferable to schedule harvesting whilst taking into account the variation of income from different silvicultural systems and the number of person-days required for those different silvicultural systems because of variations in site quality and the accessibility of stands for logging. Thus, it is more effective to schedule the harvesting of each subcompartment than to schedule harvest areas based on age classes.

The objectives of this paper were to formulate a long-term harvest scheduling model of clearcutting silvicultural systems with two different rotation lengths with restricted amounts of available labour, then to apply the model to coniferous plantations as a case study. The harvest scheduling model was formulated using 0-1 integer programming. The case study for the model was conducted in the coniferous plantations in the University of Tokyo Chiba Forest (hereafter called Chiba Forest). Harvest volume and required person-days were predicted for each silvicultural system according to the subcompartments’ attributes such as site quality, yarding distance and slope angle, determined using GIS. The minimum amount of labour required to harvest the minimum area was calculated and then the amount of labour available in the model was increased from that minimum level. How the subcompartments were subsequently assigned to different silvicultural systems was then analysed.

MATERIALS AND METHODS

Study Area

The study area was composed of 251 subcompartments of sugi (Cryptomeria japonica D. Don) plantation and 116 subcompartments of hinoki (Chamaecyparis obtusa (Sieb. et Zucc.) Endlicher) plantation in Chiba Forest, located in the southern part of the Boso Peninsula, Japan (35°9′−13′ N, 140°6′−10′ E). Chiba Forest covers approximately 2,200 ha with about 800 ha being covered by plantation forests. Most of the plantations are sugi and hinoki; sugi and hinoki plantations cover 60% and 30% of the total area of plantation forests, respectively. The age distribution of the plantations has a peak around 50 years old but matured plantations also make up about 40% of the plantation area (Fig. 1). The average stand age is about 70 years and the plantation forest is becoming overmature. Situated at elevations of 50 to 370 m above sea level, Chiba Forest has generally steep slopes and complex topographic features. Thus, it is recommended that cable yarding is used when harvesting from the plantation forests there. With a large sika deer population in Chiba Forest, the damage caused by the deer to seedlings planted there has been a big problem.

Deciding on the Silvicultural Systems to Use

In Chiba Forest, two rotations for the sugi and hinoki plantation forests are used, defined by timber price, age distribution and available work force: 80 years and 160 years. In this study, the following simplified two silvicultural systems were assumed: an 80-year rotation system where there is 30% thinning at 25 and 40 years and 40% thinning at 60 years and the other, a 160-year rotation system with 40% thinning at 30 years and 50% thinning at 90 years. The thinning ratios are based on the number of trees. It was also assumed that every thinning was non-commercial and that the same species was planted the following year after clearcutting. Moreover, non-clearcutting was added as a choice of silvicultural system because not all plantation forests could be clearcut as the required work force was unavailable. Thus, using harvest schedules that maximize total harvest volume from plantation forests over the time horizon, the subcompartments of the plantation forests were assigned to one of three systems: an 80-year rotation system, a 160-year rotation system and a non-clearcutting system.

Obtaining Attributes of the Subcompartments

The attributes of each subcompartment were obtained so that the harvest volume from each subcompartment to be harvested and the number of person-days required to harvest each subcompartment could be calculated. The area being studied was categorized into site classes shown in Table 1 using 10 m by 10 m cells from both topographic and topographically-derived factors using a GIS (Watanabe and Tatsuhara, 2011). The site class of each subcompartment was then determined from the average over cells contained in the subcompartment using a zonal statistics function of the GIS; the site index was determined from the site class as shown in Table 1. Stand age, species and area were obtained from inventory data relating to Chiba Forest and geographical characteristics such as perimeter, slope angle, distance to road, maximum yarding distance and average yarding distance were calculated using GIS data (Table 2). ESRI ArcGIS 9.3.1 was used as the GIS mapping system.

Predicting Yield and Harvest Volume

The yield from each subcompartment was predicted for
each silvicultural system using stand density control diagrams for sugi in Southern Kanto and Tokai Region (JAFTA, 1981) and for hinoki in Kanto and Chubu Region (JAFTA, 1982). Height growth curves were used that had been developed from permanent experimental plots in Chiba Forest using the following model:

\[ H_t = SI \frac{1 + \exp(a + b \ln(t + c))}{1 + \exp(a + b \ln(T + c))} - \ln SI, \]

where \( H_t \) is the average height of dominant and co-dominant trees, \( SI \) is the site index, \( t \) is the stand age and \( a, b, \) and \( c \) are parameters whose values are shown in Table 3. The density was calculated, taking thinning and self-thinning into consideration. Harvest volume was calculated, weighting yield by the ratio of the species’ average log price. The parameters used for predicting adjusted harvest volume are shown in Table 2.

Calculating Person-days

The total person-days required for each subcompartment was calculated for each silvicultural system. The person-days required for tending activities was calculated from the tending productivity tables relating to the 13th working period of Chiba Forest, as shown in Table 4. Also, the person-days required for setting fences against deer was added to the total person-days required. The person-days for thinning and harvesting were calculated as shown in Table 5, assuming the following logging operation system:

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

The actual person-days required for each stand was estimated by multiplying standard person-days by a distance coefficient calculated from the slope and the distance to the nearest road (Zheng et al., 1995; Takahashi et al., 1996).

Problem Formulation

The problem of harvest scheduling was formulated using 0-1 integer programming. Both the length of working periods and the width of age classes were set at 20 years and the length of the time horizon was set at 160 years i.e. eight working periods. It was assumed that all subcompartments

Table 1  

| Site class | Height at 60 years (m) | Site index |
|------------|------------------------|------------|
| Sugi       | 25–26                  | 20–22      |
| Hinoki     | 16–22                  | 14         |

Note: Site class category was determined with reference to Tanaka (1984).

were not broken up for harvesting.

Maximize

\[ z = \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T M_{ij,t} X_{ij} \]

subject to

\[ \sum_{i=1}^I V_{ij} \leq \sum_{i=1}^I \sum_{j=1}^J L_{ij} X_{ij} \]

\[ (1 - a)G \leq \sum_{i=1}^I \sum_{j=1}^J L_{ij} X_{ij}(1 + a)G \]

\[ \sum_{i=1}^I \sum_{j=1}^J M_{ij,t} X_{ij} \leq \sum_{i=1}^I \sum_{j=1}^J M_{ij,8} X_{ij} \quad t = 2, 3, \ldots, T \]

\[ 20 \leq \sum_{i=1}^I \sum_{j=1}^J A_{ij} X_{ij} \]

\[ X_{ij} \in \{0, 1\} \]

where \( z \) is the objective function; \( I \) is the number of subcompartments (367); \( J \) is the number of alternative silvicultural systems (3); \( t \) is the number of the working period; \( T \) is the total number of working periods (8); \( M_{ij,t} \) is the adjusted harvest volume in the \( t \)th working period when subcompartment \( i \) is assigned to silvicultural system \( j \); \( V_{ij} \) is the stand volume of subcompartment \( i \) at the beginning of the time horizon; \( V_{ij,8} \) is the volume of subcompartment \( i \) at the end of the time horizon; \( G \) is the standard amount of labour available; \( a \) is the tolerable level of fluctuation in the standard amount of labour available (0.05); \( L_{ij} \) are the person-days required when subcompartment \( i \) is assigned to silvicultural system \( j \); \( X_{ij} = 1 \) when subcompartment \( i \) is assigned to

| Table 2  Attributes of subcompartments |
|----------------------------------------|
| **Symbol** | **Unit** | **Value or equation** |
| Site index | SI | m |
| Area | A | ha |
| Perimeter | P | m |
| Stand age | t | year |
| Slope angle | s | degree |
| Distance to road | S_{mix} | m |
| Maximum yarding distance | S_{max} | m |
| Average yarding distance | S_{ave} | m |
| Average lateral yarding distance | l_{i} | m |
| Lateral yarding distance | m | 60 |
| Number of cable changes | n | L/60 rounded down to nearest integer |

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### Table 3 Parameters used to predict adjusted harvest volume

| Symbol | Unit | Value or equation |
|--------|------|-------------------|
| Planting density | \( N_0 \) | trees/ha | 3500 |
| Density | \( N_s \) | trees/ha | Stand density control diagrams *1 |
| Average height | \( H_s \) | m | \( a=11.092, b=1-1.905, \) and \( c=21.473 \) for sugi; \( a=7.587, b=1-1.004, \) and \( c=4.893 \) for hinoki *2 |
| Stand volume per ha | \( V_s \) | m\(^3\)/ha | \( (0.082249H_s^{0.92201}+306.16H_s^{0.87625}/N_s) \) for sugi; \( (0.035514H_s^{0.18677}+4711.2H_s^{0.02889}/N_s) \) for hinoki |
| Stand volume | \( V_b \) | m\(^3\) | \( V_s A \) |
| Average tree volume | \( v \) | m\(^3\) | \( V_s/N_s \) |
| Ratio of average log prices | \( r \) | 1.000 for sugi; 2.059 for hinoki *3 |
| Adjusted harvest volume | \( M_y \) | m\(^3\) | \( V_b r \) |

Note: *1, cited from JAFTA (1981) and JAFTA (1982); *2, \( a, b, \) and \( c \), parameters of Eq. (1); *3, the ratio calculated from the average log prices cited from Chiba Prefectural Government (2011).

### Table 4 Person-days required for tending plantation forests

| Stand age (year) | Operation | Person-days (person-day/ha) |
|------------------|-----------|-----------------------------|
|                  |           | Sugi | Hinoki |
| 1                | Land preparation | 25   |        |
|                  | Transporting seedlings | 3    |        |
|                  | Planting | 40   |        |
|                  | Setting fences | 0.0236 \( P + 0.0593 \) *1 |        |
| 2                | Weeding | 11   |        |
| 3                | Weeding | 11   |        |
| 4                | Weeding | 11   |        |
| 5                | Weeding | 11   |        |
| 15               | Pre-commercial thinning with pruning | 20   |        |
| 20               | Pruning | –    | 37    |

Note: *1, derived from the records of past operations in Chiba Forest.

### Table 5 Equations used to calculate person-days for thinning and harvesting

| Unit | Value or equation |
|------|-------------------|
| Productivity of felling | m\(^3\)/ (crew-day) | 12.295 \( v^{0.5} - 0.564 \) *1 |
| Productivity of yarding | m\(^3\)/ (crew-day) | \( S_{max}^{0.6286} h^{1.5507} y^{0.4995} \) *10\(^{0.011} \) |
| Person-days to install and remove a yarder | person-day | \( (0.0763 S_{max} + 2.4) (1 + 0.35 + 0.7 n) \) *3 |
| Productivity of non-commercial thinning | m\(^3\)/ (person-day) | \( 1/(22.817 v^{0.685}) \) *4 |
| Number of people in a yarding crew | person | 4 *1 |

Note: \( v, \) average tree volume (m\(^3\)); \( S_{max}, \) average yarding distance (m); \( S_{max}, \) maximum yarding distance (m); \( h, \) average lateral yarding distance (m); \( n, \) the number of cable changes. *1, cited from Umeda et al. (1982); *2, cited from Toyama and Tatsuhara (2007); *3, cited from Sawaguchi (1996); *4, cited Mizuta and Mitobe (2008).
silvicultural system \( j \), otherwise it is 0; \( A_{i,j} \) is the harvest area in the \( t \)-th working period when subcompartment \( i \) is assigned to silvicultural system \( j \) and the values in parentheses are the values used in this study.

Objective function (Eq. (2)): We were selling two types of timber that had different prices. We maximized the total harvest volume adjusted by the ratio of the species’ average log prices across the time horizon as the objective function. The harvest volume was weighted 1.0 for sugi and 2.059 for hinoki.

Constraints for growing stock (Eq. (3)): The quantity of growing stock at the end of the time horizon should be larger than or equal to that at the beginning of the time horizon.

Constraints for labour (Eq. (4)): The number of person-days in each working period was allowed to vary by up to 5% (the tolerable level of fluctuation) to keep the person-days required constant for all working periods.

Constraints for harvest volume (Eq. (5)): The adjusted harvest volume in each working period should be larger than or equal to that in its previous working period so that the harvest volume does not change drastically across the working periods.

Constraints for harvest area (Eq. (6)): Chiba Forest intends to clearcut about 1 ha of plantation forests every year. Thus, the minimum area harvested was set at 20 ha during each 20 year working period.

Constraints for the number of silvicultural system to be assigned (Eq. (7)): The summation of \( x_{i,j} \) over \( i \) should be 1 so that each subcompartment could be assigned only one silvicultural system.

Solving the Problem

The number of variables was 1,101 (= 367 subcompartments \( \times \) three alternative silvicultural systems) and the number of constraints was 401. The model was solved using IBM ILOG CPLEX Optimization Studio V12.3 on a personal computer equipped with 64 bit Windows 7, Intel Core i3-2120 3.3 GHz processor and 8.0 GB RAM. First, the minimum amount of labour required to satisfy the constraints for clearcutting a harvest area of at least 20 ha in each working period was obtained by solving the equations by changing the standard amount of labour available. Then, the standard amount of labour available was increased from the minimum number. The distribution of site classes and species in the subcompartments assigned to each of the silvicultural systems was obtained for each size of work force; the geographical characteristics of the subcompartments, as shown above, were averaged for each size of work force. The solutions were imported into GIS to map the layouts of subcompartments assigned to each of the silvicultural systems.

RESULTS

The minimum amount of labour required was 350 person-days/year. The standard amount of labour available was set initially at 400 person-days/year and then increased by 200 person-days/year. Iterations were stopped at 1,200 person-days/year because no feasible solution was obtained in that case. Figure 2 shows the layouts of subcompartments assigned to the three silvicultural systems. As the standard amount of labour available increased, the total harvest volume over the time horizon increased but the total harvest volume per person-day decreased after a peak at 400 person-days/year (Fig. 3). As the standard amount of labour available increased, the total area harvested over the time horizon increased but the total area harvested per person-day decreased (Fig. 4).

At the minimum labour levels, 80-year rotation and 160-year rotation were assigned to 17 and 40 subcompartments, respectively. Only 15% of the subcompartments were assigned to clearcutting and 85% were assigned to non-clearcutting across the time horizon (Table 6). The subcompartments assigned to clearcutting tended to have a larger area, a gentler slope, a shorter distance to the road, a shorter yarding distance, a shorter average yarding distance, a longer lateral yarding distance and a larger number of cable changes (Table 7). The subcompartments assigned to an 80-year rotation were concentrated on hinoki plantations and better site classes; those assigned to a 160-year rotation did not tend to favour a particular species with a particular site class and had a smaller area, a shorter distance to the road and a shorter average yarding distance when compared to the subcompartments assigned to an 80-year rotation.

As the standard amount of labour available increased, both the 80-year rotation and the 160-year rotation were assigned to increasing numbers of subcompartments; this was particularly true of the 80-year rotation whilst sugi plantations and lower site class plantations were assigned more often (Table 6). Subcompartments assigned to a 160-year rotation tended to have larger areas than subcompartments assigned to an 80-year rotation but a similar distance to road, maximum yarding distance and average yarding distance when compared to subcompartments assigned to an 80-year rotation. When the standard amount of labour available was relatively small, such as 400 and 600 person-days/year, the attributes of subcompartments assigned to clearcutting tended to be similar to those in the case of the minimum amount of labour. As the standard amount of labour available increased, the relationships between subcompartments assigned to clearcutting and subcompartments assigned to non-clearcutting of area, slope angle, average lateral yarding distance, and the number of cable changes reversed (Table 7).

DISCUSSION

Labour constraints have been considered in medium-term and short-term plans so that the labour available was assigned equally to each year (Nagumo et al., 1993; Zheng et al., 1995). In this study, we incorporated labour constraints into long-term plans to assign subcompartments to the three silvicultural systems and eight working periods for clearcutting and optimized adjusted harvest volume over the time horizon with equal labour requirements in each working period. An 80-year rotation yields more harvest volume over the time horizon than a 160-year rotation, although the latter rotation requires a smaller number of person-days...
Fig. 2  Layouts of subcompartments assigned to the silvicultural systems with restrictions on the amount of labour available (a) 350 person-days/year; (b) 400 person-days/year; (c) 600 person-days/year; (d) 800 person-day/year; and (e) 1,000 person-days/year.
per volume than the 80-year rotation. Because maximizing harvest volume by restricting work force was a trade-off, the subcompartments were assigned to the different silvicultural systems. In this case, there were few subcompartments over 120 years old at the beginning of the time horizon (Fig. 1). There were not enough overmature subcompartments that could be assigned to a 160-year rotation. Thus, some subcompartments were assigned to a 80-year rotation despite the limited size of work force, even though a 160-year rotation required a smaller number of person-days per volume than an 80-year rotation. Most subcompartments assigned to an 80-year rotation had to be harvested in the first and second working periods.

The subcompartments assigned to clearcutting tended to have a better site class and be hinoki plantations rather than sugi plantations. Stands with a better site class yield more timber and are more profitable. Hinoki is more profitable than sugi because of the timber price, though it grows more slowly than sugi does. The subcompartments assigned to clearcutting tended to be better suited, geographically, for timber production i.e. have a larger area, a gentler slope, a shorter maximum yarding distance and a shorter average yarding distance. A gentler slope gives better productivity when tending the plantation; a shorter maximum yarding distance and a shorter average yarding distance give better productivity when logging. Larger stand areas also give better productivity when logging because more timber can be harvested at once. Subcompartments with these attributes require less person-days to manage. In contrast, the subcompartments assigned to clearcutting tended to need more cable changes, which results in poorer productivity. However, the decrease in productivity as a result of an increase in the number of cable changes would be smaller than the increase in productivity as a result of an increase in area. In general, subcompartments which were better suited for timber production were assigned to clearcutting.

When comparing the subcompartments assigned to an 80-year rotation and a 160-year rotation, the subcompartments assigned to an 80-year rotation tended to have better site class but a longer distance to road, a greater maximum yarding distance and a greater average yarding distance. Site class took priority over yarding distance when choosing between the two types of rotation. This is consistent with the analysis by Tatsuhara and Dobashi (2006) that concluded that site class was more important than yarding distance for timber production.

When subcompartments assigned to clearcutting had labour available at levels of 800 and 1,000 person-days/year, it can be seen that, with these increased levels of labour, the total harvest volume increased but the total harvest volume per person-day decreased. This happened because a greater number of subcompartments, less suited to clearcutting, were assigned to clearcutting and a greater number were assigned to an 80-year rotation which is less profitable than a 160-year rotation in terms of harvest volume per person-day. The clearcut area per person-day decreased as the standard amount of labour available increased. This meant that the average productivity in the clearcutting silvicultural systems decreased as the standard amount of labour available increased. These results suggested that it was better to concentrate on clearcutting subcompartments that had good conditions with a small work force than to try to clearcut a greater number of subcompartments with a larger work force. Toyama et al. (2012) showed that good conditions such as shorter skidding distances and larger stand areas were preferable to gain a positive soil expectation value from sugi plantation management for timber production in Japan. From the viewpoints of both work force size and finance, it would be preferable to choose and focus on profitable stands for clearcutting than to clearcut large areas.

When the available labour was small, 160-year rotation was the method most often assigned. As the amount of labour available increased, so did the number of subcompartments assigned to an 80-year rotation. Tatsuhara and Doi (2006) showed that the yield per person-day increased as the rotation period increased. In other words, person-days per yield decreased as the rotation period lengthened from 80 years to

![Harvest volume per person-day](image)

**Fig. 3** Change of the total adjusted harvest volume over the time horizon using the standard amount of labour available

![Area per person-day](image)

**Fig. 4** Change of the total area of subcompartments assigned to clearcutting over the time horizon using the standard amount of labour available

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160 years. As we mentioned above, 160-year rotation requires a smaller number of person-days per volume than the 80-year rotation. Thus, many subcompartments were assigned to a 160-year rotation with a smaller work force and more subcompartments were assigned to an 80-year rotation as the work force size increased.

This study dealt with long-term planning. The person-days required for tending and harvesting plantation forests in Figs. 4 and 5 may change in the future, due to technological changes and new labour-saving devices. This study showed that the amount of labour available affected the optimal solution of long-term planning. Decreasing the required person-days has the same effect on the optimal solution as increasing the amount of labour available.

### Table 6 Distribution of site classes and species in subcompartments assigned to the different silvicultural systems

| Available labour (person-day/year) | Silvicultural system | Species | Site class | Total |
|-----------------------------------|---------------------|---------|------------|-------|
|                                   |                     | Species | 1 2 3 4 5  |       |
|                                   |                     | Sugi    | 2 1 0 0 0  | 3     |
|                                   |                     | Hinoki  | 9 5 0 0 0  | 14    |
| 350                               | 80-year rotation    | Sugi    | 8 5 6 0 1  | 20    |
|                                   |                     | Hinoki  | 8 9 3 - -  | 20    |
|                                   | Non-clearcutting    | Sugi    | 81 56 78 12| 228   |
|                                   |                     | Hinoki  | 27 43 12 - | 82    |
|                                   | 80-year rotation    | Sugi    | 3 0 0 0 0  | 3     |
|                                   |                     | Hinoki  | 12 5 0 - -  | 17    |
|                                   | 160-year rotation   | Sugi    | 7 5 6 0 0  | 18    |
|                                   |                     | Hinoki  | 11 9 4 - -  | 24    |
|                                   | Non-clearcutting    | Sugi    | 81 57 78 13| 230   |
|                                   |                     | Hinoki  | 21 43 11 - | 75    |
|                                   | 80-year rotation    | Sugi    | 15 1 0 0 0  | 16    |
|                                   |                     | Hinoki  | 20 6 0 - -  | 26    |
|                                   | 160-year rotation   | Sugi    | 8 6 7 0 0  | 21    |
|                                   |                     | Hinoki  | 14 19 3 - -  | 36    |
|                                   | Non-clearcutting    | Sugi    | 68 55 77 13| 214   |
|                                   |                     | Hinoki  | 10 32 12 - | 54    |
|                                   | 80-year rotation    | Sugi    | 19 8 9 0 1  | 37    |
|                                   |                     | Hinoki  | 23 15 3 - -  | 41    |
|                                   | 160-year rotation   | Sugi    | 13 13 18 1 4| 49    |
|                                   |                     | Hinoki  | 7 13 4 - -  | 24    |
|                                   | Non-clearcutting    | Sugi    | 59 41 57 0 8| 165   |
|                                   |                     | Hinoki  | 14 29 8 - -  | 51    |
|                                   | 80-year rotation    | Sugi    | 42 20 26 1 3| 92    |
|                                   |                     | Hinoki  | 22 19 7 - -  | 48    |
|                                   | 160-year rotation   | Sugi    | 10 18 28 0 2| 58    |
|                                   |                     | Hinoki  | 2 11 3 - -  | 16    |
|                                   | Non-clearcutting    | Sugi    | 39 24 30 0 8| 101   |
|                                   |                     | Hinoki  | 20 27 5 - -  | 52    |
|                                   |                         | Sugi    | 91 62 84 1 13| 251   |
|                                   |                         | Hinoki  | 44 57 15 - - | 116   |

## CONCLUSIONS

In this study, we used 0-1 integer programming to simulate the scheduling of the harvesting of subcompartments using two types of rotation and with various restrictions on the size of the available work force. Subcompartments which were better suited to timber production tended to be assigned to clearcutting. There was a tendency for those subcompartments with a better site class to be assigned a shorter rotation and subcompartments with a shorter yarding distance to be assigned a longer rotation. As the amount of available labour increased, subcompartments less well suited to timber production were also assigned to be clearcut; the harvest volume per person-day and the clearcut area per person-day decreased. Longer rotation was efficient with a smaller work force whereas shorter rotation was assigned more often as the size of the work force increased. We
have calculated the size of work force required for a given management plan and the area which can be clearcut using a known size of work force. GIS was essential in creating the simulation, helping to identify the difference between the stands in terms of site quality, accessibility and other geographical properties. The combination of GIS and mathematical programming would be effective to help with forest management planning.

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