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Lee, Jung-soo
Graduate School of Agricultural and Life Sciences, The University of Tokyo

Yoshida, Shigejiro

Tsuyuki, Satoshi
Graduate School of Agricultural and Life Sciences, The University of Tokyo

Minowa,Mitsuhiro
Faculty of Regional Environment Science, Tokyo University of Agticulture

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A Strategic Forest Planning Model for Integrating Economic and Ecological Management Goals

Jung-soo LEE[1]*, Shigejiro YOSHIDA, Satoshi TSUYUKI[1] and Mitsuhiro MINOWA[2]

Laboratory of Forest Planning, Division of Forest management, Department of Forest and Forest Products Sciences, Faculty of Agriculture, Kyushu University, Fukuoka 812–8581, Japan

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Timber harvest plan in forest management should be flexible to meet changing social and environmental needs. We need to collect and process the proper forest information, which will enhance the efficiency of working process in the harvest plan. Especially, GIS and RS techniques have been considered to have a benefit in processing the multidimensional information. The purpose of this study is to present strategic forest planning procedure that can support the identification of forest structures and the maximum use of forest functions through GIS, RS and LP techniques. In this study, forest information such as compartment structure and forest road was entered into GIS to construct FMIS. DEM was constructed using base maps of 1/5000 for the geographic analysis. Aerial photographs and DEMs were used to create orthophoto. Orthophoto was used to classify forest into 3 types, artificial, natural and bare forest. And then geographical attributes of each forest type were identified. Sugi (*Cryptomeria japonica*) forest area of each forest type was used in the harvest simulation. A spatial constraint, distance from a forest road, is taken into consideration in the LP. New grouping unit, so called "harvest unit", was introduced as the forest management unit. Strategic forest planning based on the "harvest unit" was proposed that considering both of the economic and environmental aspects of forest.

INTRODUCTION

Meeting social needs is a crucial factor in sustainable forest management. People put their values not only on the economic aspects of forest, but also on the environment sides. Therefore forest planning needs to consider these two issues. Forest planning should take into account not only the time and spatial constraints, but also the geographical factors. Short–term management planning requires policies that can maintain the flow and stock of forests together.

Along with the advance of mathematical programming and computer technology, forest management studies have been recommended to use the new models that have objectives of multidimensional resource uses rather focused on the production of timber. Using GIS (geographic information system) allows people to use time–series as well as spatial data collectively in forest planning.

In 1990s, GIS and mathematical programming have been hot issues in forest manage-

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[1] Graduate School of Agricultural and Life Sciences, The University of Tokyo, Tokyo 113–8657, Japan
[2] Faculty of Regional Environment Science, Tokyo University of Agriculture, Tokyo, 156–8502, Japan
* Corresponding author(E-mail: gandol@fr.a.u–tokyo.ac.jp)

ment planning. The enhancement of computer capacity and cost down of GIS software urged people to apply GIS in forest management.

In Japan, GIS have been used in prediction of forest change and forest planning. Abe (1993) developed thinning working plan by using the topographical function and overlay function of GIS. Zheng *et al.* (1995) developed forest planning system based on the workload distribution plan with linear programming. Nelson and Finn (1990) studied relationship of cut–block size and adjacency rules regarding harvest level and road network problems. Ohara (1989) and Nalli (1996) studied analyzed the changes of opportunity cost when timber harvest planning was applied to the spatial constraints. Naesset (1997) assessed the effectiveness of decision making by developing spatial decision support system (SDSS). Baskent and Jordan (1991) had used GIS for deriving spatial timber supply model. Through, Integrating GIS technology into forest management makes it possible to utilize the time and spatial information together. RS (remote sensing) techniques in identifying forest structure, exact location per forest type, and forest morphology can help people establish efficient forest planning.

The purpose of this study is to develop a new strategic planning approach based on the idea of a new harvest unit, together with forest cover data produced by GIS and RS techniques. The new harvest unit system provides the basic information on the cyclic aspect of forest management, which allows us to analyze the effectiveness of this approach from the economical and ecological points of view through harvest simulation.

Long–term harvest forecasts are made using new harvest unit generated from forest type polygons. Simulations are made using LP (linear programming) such as LINDO (linear interactive and discrete optimizer) technique, together with combinations of harvest order rules and spatial rules for harvesting units. The method consists of study area, GIS data sets, spatial design, and model simulations. Results of the simulations are presented in the form of the combinations of harvest order rules and spatial rules for harvest unit. The discussion of the paper refers to harvest volume, geographical characteristics of harvesting site and spatial allocation.

METHOD

Study area

Forest area (137～151 compartments) of Takefu city, Fukui prefecture was used in the analysis. Takefu city is located in the middle of Fukui prefecture (N 35° 48′ 18″ ～ 35° 56′ 14″ and E 136° 01′ 18″ ～136° 18′ 53″). Figure 1 shows the location of Takefu city. The size of Takefu city is about 18,532 ha. Sixty percent of the city area is covered with forest. Artificial forest and natural forest show similar sizes in the area. The most common type of forest stands (97%) is Sugi (*Cryptomeria japonica*).

Conventional data and processing

With the information derived from Orthophoto data and conventional data stored in GIS, forest structure analysis and harvest planning were carried out. Figure 2 shows the study framework.

(1) Figure 3 shows forest compartment based on forest planning map and forest register (scale: 1/5,000). It was derived from digitizing the compartment and subcompartment

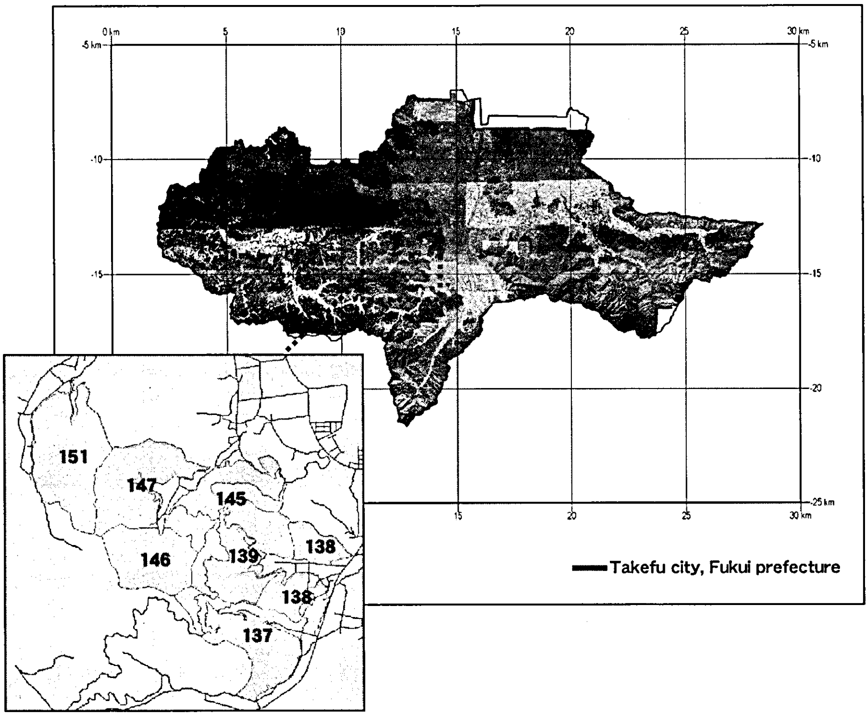

Fig. 1. Location of study area (The number in the small figure is a compartment number).

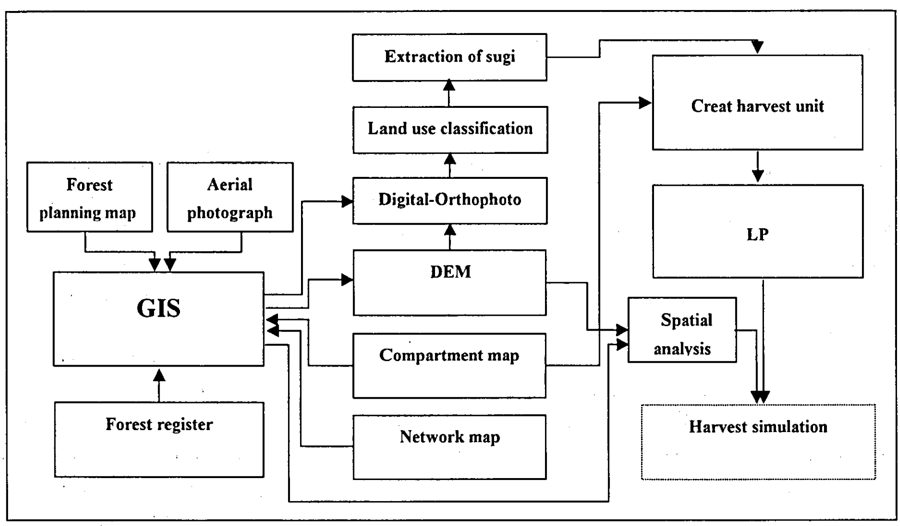

Fig. 2. Diagram of strategic forest planning based on RS, GIS and LP techniques.

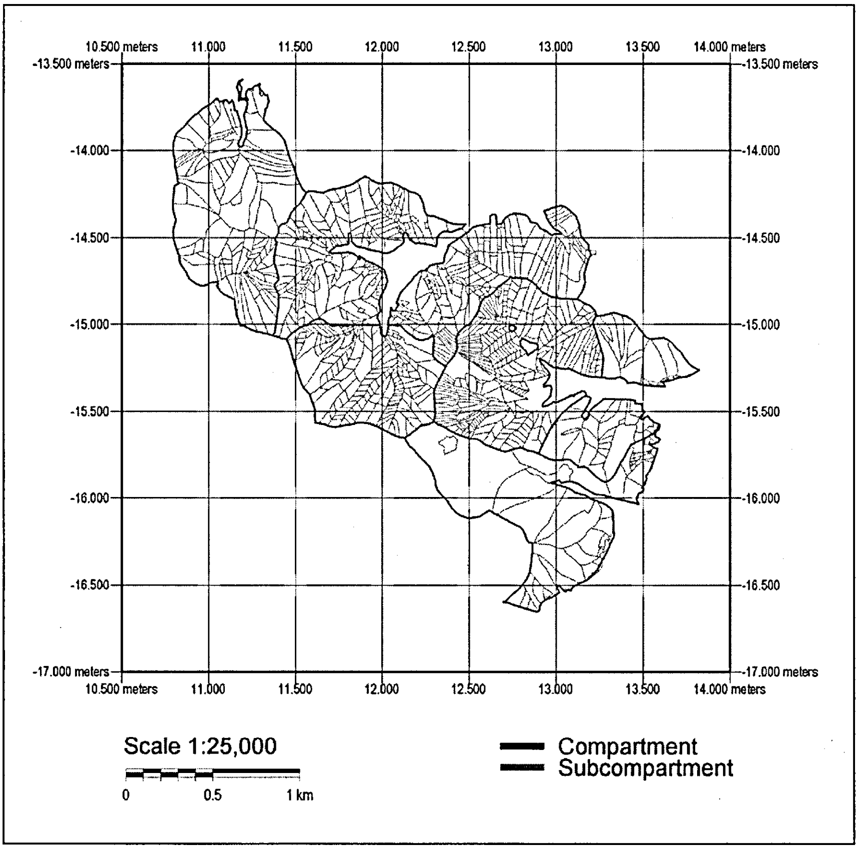

Fig. 3. Compartment.

information in GIS.

(2) DEM (digital elevation model) was developed through providing the contour information of basic map (scale: 1/5,000) to GIS. The resolution of DEM was build as 10 m by 10 m. The developed DEM is used to create slope map and calculate geographical indices. The distance from the road to the compartment was calculated by using DEM and road information, and it became a standard for selection of the harvesting area (Fig. 4).

(3) Digital–orthophoto: Forest register was mainly used in forest planning. Because it doesn't have spatial information, we need to used database linked RS and GIS. Aerial photographs and DEM were used to create digital–orthophotos. After the input of aerial photographs to GIS, selected road crossings and mountaintops were used as geographic control point. The coordinate of basic map and DEM values were recorded on the corresponding points of aerial photographs. Finally, digital–orthophotos were derived from the coordinate of principal point of aerial photographs, focal length of lens, and resolution factors. These digital–orthophotos were used for iden-

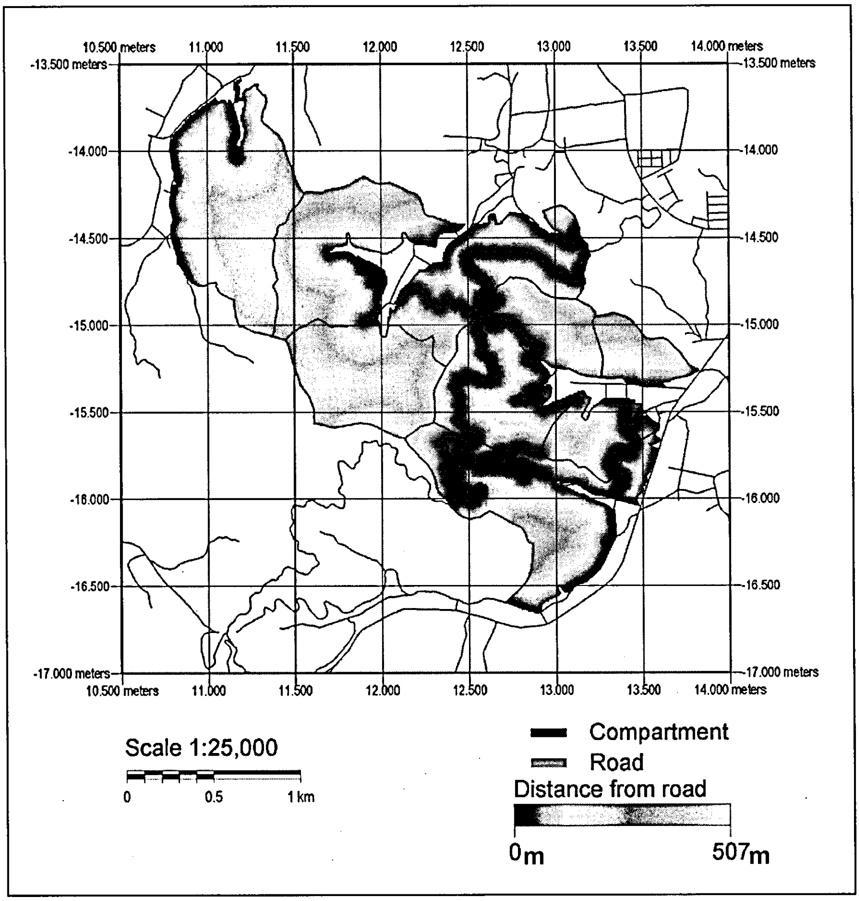

Fig. 4. Distance analysis using DEM and Road.

tifying forest structure and exact location of each forest stand, which will provide precise data for forest planning.

(4) Land use classification: Interpretation of digital–orthophotos to classify into artificial forest, artificial open stand, stand, cutting area, bare, grass, nature forest was made to create land use (classification) map. Artificial forests were divided into three types according to their status. When the tree crown was closed, it was classified into artificial stand, when the arrangement of crown was visible, it was categorized to artificial open stand, and when the crown was small and the ground surface was visible, it was defined as harvesting site. Bare class was the areas where there were no grass. Areas with lower grass and/or natural forest were designated as grass area. If the area was not classified into any of above categories, it was set to natural forest.

(5) Sugi forest areas were defined through two steps. First, three types of artificial

forests obtained in (4) and subcompartments defined as sugi forest by forest register were selected. Then, when areas of subcompartments and three types of artificial forests were overlapped, those overlapped regions were recognized as Sugi forest areas (Fig. 5). The 23% of study area was were recognized as Sugi forest areas.

(6) Spatial design: Forest management should be flexible for meeting the sustainable timber production with multidimensional use. Spatial relation of harvest unit such as harvest size, harvest order and schedule was important issue in the strategy forest management.

Spatial constraints were influence to harvest schedule and the identified characteristic of spatial relationship with adjacent forest were expected to efficiency of forest planning. GIS and RS techniques were very useful in analyzing forest condition such as spatial monitoring. It is can be thought that using grid units for forest management have an advantage applying GIS and RS technologies to forest planning. Therefore, forest is presented in a simplistic grid (30 m by 30 m; about 0.1 ha) using extracted Sugi forest

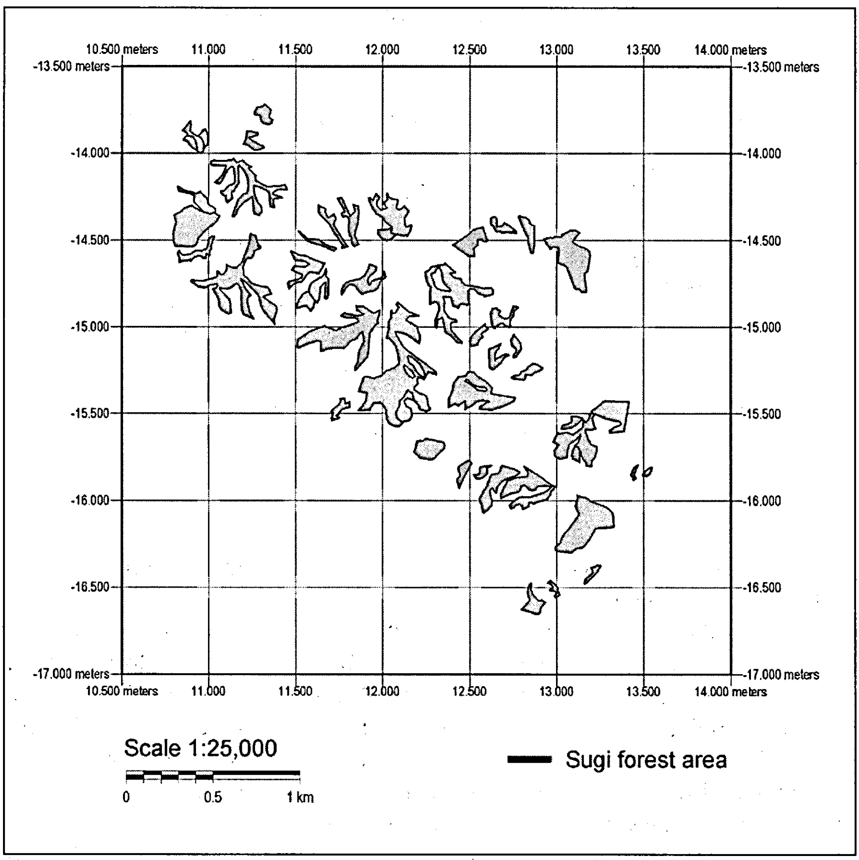

Fig. 5. Extraction of Sugi (*Cryptomeria japonica*) area.

area. This grouping unit, so called "harvest unit" was introduced as the forest management unit in this study. The grid unit is used as a new harvest management unit (Fig. 6). Harvest simulation is based on this harvest unit using LP method.

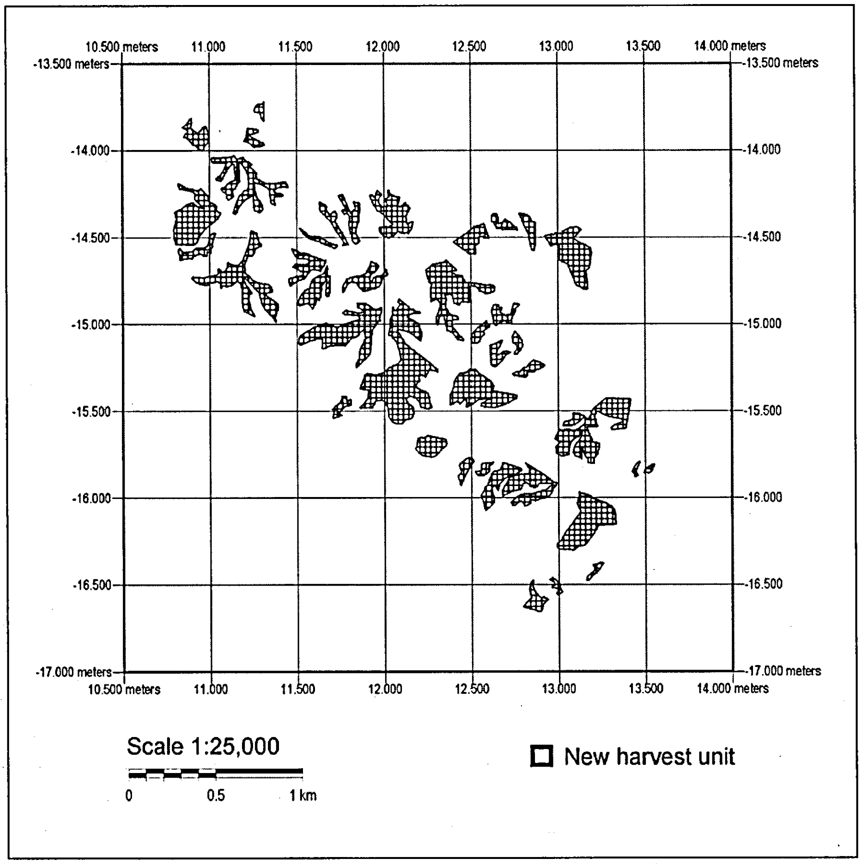

Fig. 6. New harvest unit.

Strategic forest planning model

Today, it is said that a central characteristic of ecosystem management is the deliberated act of defining and sustaining a desired future condition (DFC) of forests. Management goals should be created to realize the DFC in an integrated manner in terms of ecological, economic, and social values, which requires us to introduce strategic forest planning (SFP) including a mix of harvest methods, silvicultural prescriptions and zoning. We also need inventory data, GIS technology, and mathematical programming such as LP to create the suitable SFP model.

The model proposed here is characterized by using small–group selection system (SGSS) for silvicultural prescriptions and by combining economic and ecological values through LP technique with an economic objective function and environmental constrains over time and space. More concretely, each forest compartment can be visited for harvesting with a definite circulation length and some of the forest stands within the compartment will be scheduled to harvest with a desired rotation length. On the other hand, the objective function of the model is defined to maximize the amount of volume harvested over the planning period under the spatial and environmental constraints such as allowable harvest area and volume in terms of area–size and relationship.

The SGSS has properties of both even– aged and uneven–aged forest management. At stand level, the size and layout of regeneration (cut) unit play an important role in the implementation of the system. Opening size is an often–debated attribute of SGSS. If the regeneration units are very small and well distributed, then this would describe uneven–aged management where only a few tree are removed at each cutting cycle entry. On the other hand, when the regeneration unit is relatively large, we look at it as a large clearcut even–aged management. In any case, SGSS is capable of preventing us from concentrating harvests on the forest compartment and helping us keep the ecological diversity of the entire forest through the suitable selection of opening size, spatial allocation of regeneration units and the resulting appropriate distribution of forest stand age.

Therefore, we conclude that the combination of SGSS and the optimal decision process with LP model provides us with a suitable spatial design technique concerned with the layout of compartments at forest level and the balanced size of regeneration units at stand level. That is all the SFP model proposed here means.

The goal of the model is to maximize the amount of volume harvested over the planning period. Spatial and environmental constraints were considered together in the planning. The model supposed that harvesting was made in cycling compartments. Cycle constraint has properties of both even– and uneven–aged systems. It is purposed to prevent the concentration of harvesting in compartments. This approach also has an advantage to consider the spatial allocation of forest while limiting the environmental damage.

Now we first divide the study subject forest into 6 compartments. Planning horizon is assumed to be 60 years, each compartment will be entered with a 6–year cutting cycle. Figure 7 shows spatial layout of harvest units. Then three scenarios with different conditions are presented in the model. Outputs from each scenario are compared in the light of economic and environmental aspects, and finally a best plan can be selected.

Three priorities are assumed to determine the order of harvesting for each compartment (Table 1).

The first volume priority is concerned with the selection of compartment with higher timber volume. The second B/C (benefit/cost) priority works to harvest the compartment with higher B/C ratio where benefit and cost are determined from the data such as timber volume and price, and timber collecting cost depending on the distance from cut units to the forest road. The third distance priority is used to select the compartment with shorter average distance between road and compartments.

The basic harvest scheduling problem used in this paper is a model I formulation (Johnson and Scheurman, 1977), as follows:

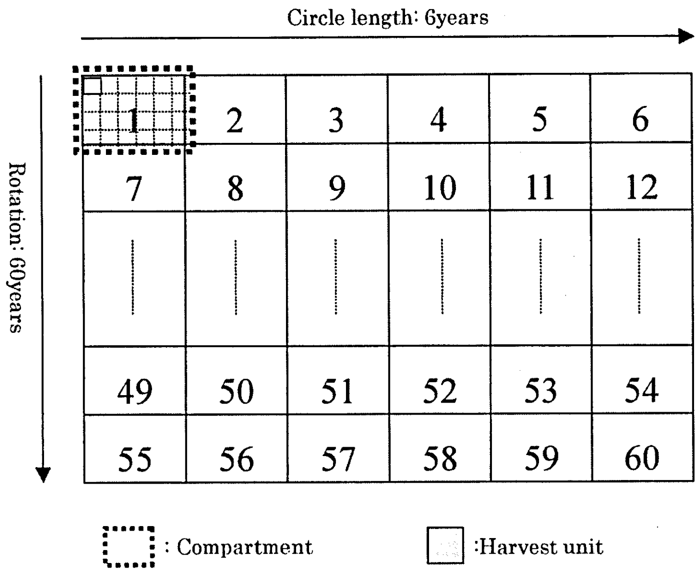

Fig. 7. Spatial layout of cut units.

Table 1. The order of harvesting in compartment.

The order of harvesting / Harvesting priority	1st	2nd	3rd	4th	5th	6th
Volume	146	145	151	147	138&139	137
B/C ratio	145	146	147	151	138&139	137
Distance from road	138&139	145	137	147	151	146

The number in the table is a compartment number.

Object function:

$$[1] \quad \mathrm{MAX} \sum_{i=1}^{m} \sum_{j=1}^{p} TOHAV$$

$$i=1, 2, \ldots\ldots\ldots\ldots, m$$
$$j=1, 2, \ldots\ldots\ldots\ldots, p$$

Constraints:

$$[2] \quad \sum_{i=1}^{m} THAR_i = TOHAV$$

[3] $\sum_{i=1}^{m} THAR_i - 1.2 \sum_{i=1}^{m} THAR_{i-1} \leq 0$

[4] $\sum_{i=1}^{m} THAR_i - 0.8 \sum_{i=1}^{m} THAR_{i-1} \geq 0$

[5] $\sum_{i=j}^{m} H_i = THAR_{k/6}$

$j=1, 7, 13, \ldots\ldots\ldots\ldots, 55$
$k=j+5$

[6] $AC_i \leq 1$

[7] $X_{i,k,l}=0$
$k=0, \ldots\ldots\ldots\ldots, 7$
$X_{i,k,l}$: uncut from site k, class age l at period i

TOHAV: Total Harvest
$THAR_i$: Sum of Volume harvested cutting at cycling i
H_i: Volume harvested cutting at period i
AC_{ik}: Cutting area from site k at period i

Object function
[1] The objective function maximizes the volume harvested over the planning horizon.

General constraints
[2] Total of the harvests is defined as *TOHAV*.
[3] Harvest flow policy that enables a maximum 20% increase in harvest volume between successive periods.
[4] Harvest flow policy that enables a maximum 20% decrease in harvest volume between successive periods.
[5] Sum of the harvests of one cycle (1C=6years) is defined as *THAR*
[6] Harvest area requires a maximum of 1 ha in each period.
[7] Stands that do not reach the cutting ages class is not harvest

Spatial constraints using Probability Proportional to Prediction (P.P.P) method

This study also included spatial constrains with P.P.P (3P) sampling method which is developed for forest survey by Grosenbaugh (1963). The sampling method is applied to derive a spatial index concerned with the selection of cut units with relatively efficient timber volume. We here pick up two factors such as the amount of timber volume and distance from the forest road for calculating the spatial index (α) which is defined as the ratio: amount of volume/distance to road in an area. If the index is within predetermined standard threshold, the area can be harvested. Amount of volume and distance from the forest road are assumed to be from 300 m^3 to 600 m^3, and 15 m to 300 m, respectively.

Consequently, the spatial index (α) has a range of $1<\alpha<40$ ($300\,m^3/300\,m=1$, $600\,m^3/15\,m=40$)(Fig. 8).

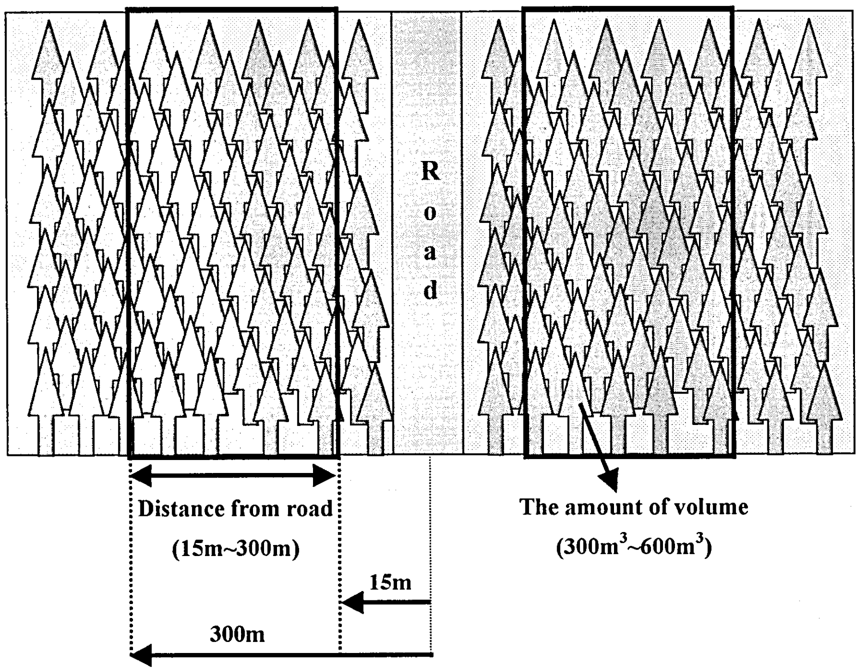

Fig. 8. Spatial constraints using P.P.P method.

RESULT AND DISCUSSION

Comparison of harvest

We first examine the result from three scenarios (volume priority, B/C priority, and distance priority) from the amount of harvest volume. Figure 9 shows the change of harvest volume for each scenario. No big difference was not found between volume and B/C priorities, but there is some $700\,m^3$ difference between volume and distance priority. The lowest harvest of distance priority scenario seems to be caused by high proportion of young forest in compartments with high forest road density. Harvesting young forest compartments at early period will result in the reduction of the yields. It is naturally concluded that volume priority and B/C priority can works best in terms of harvest volume and net revenue, respectively.

It is found that the volume of harvests tends to increase over time. For example, the harvest at the ending cycle can be 1.9 times larger than that of the beginning cycle, which seems to be caused by the constraints concerned with harvest flow policy (Fig. 10).

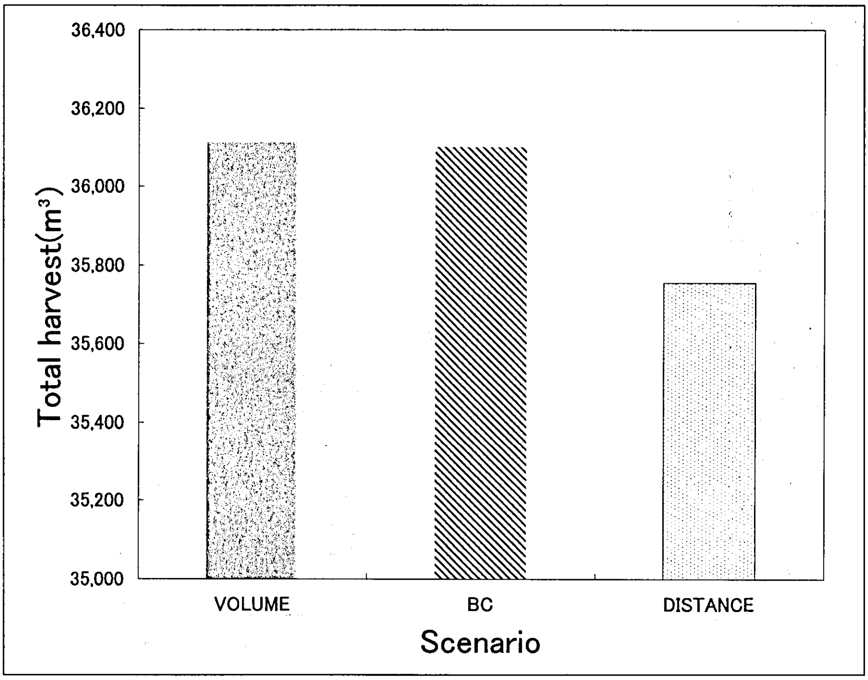

Fig. 9. Timber harvest volumes for three scenarios.

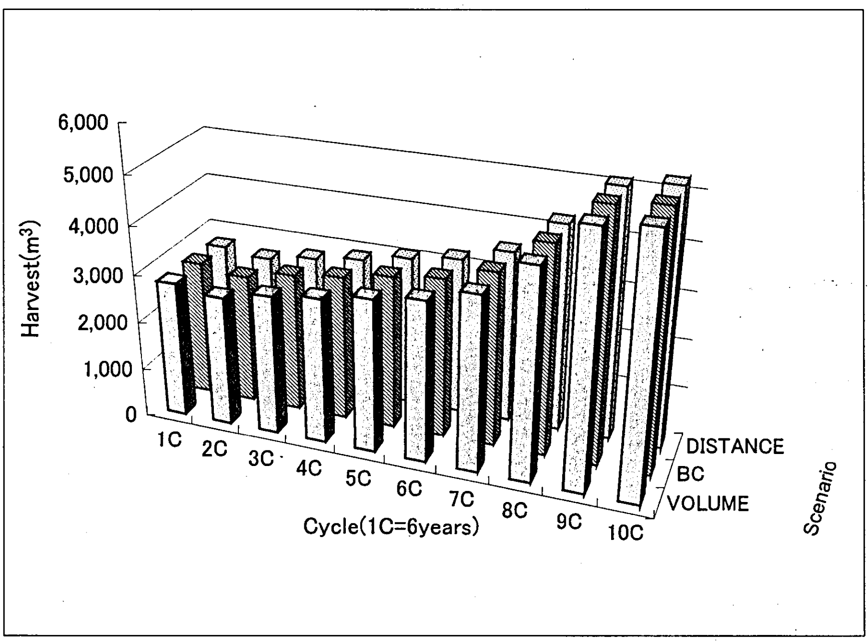

Fig. 10. Timber harvest flow by three scenarios.

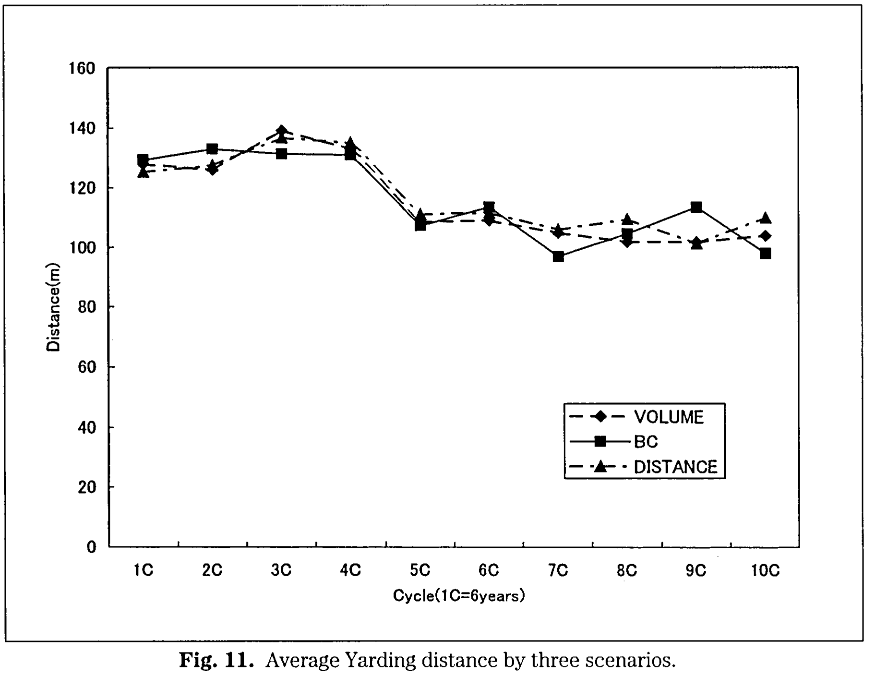

Fig. 11. Average Yarding distance by three scenarios.

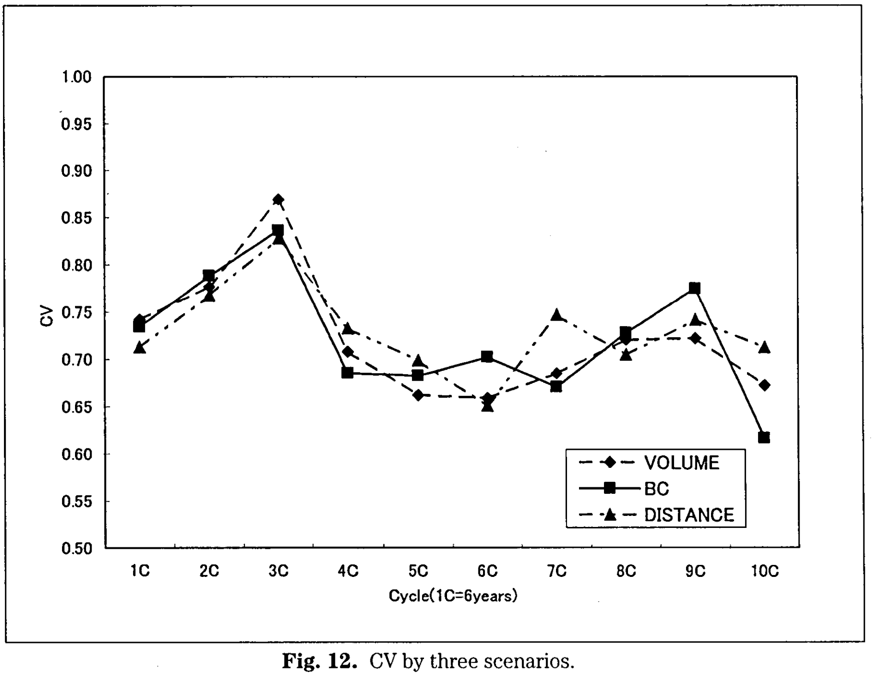

Fig. 12. CV by three scenarios.

Identifying geographical characteristics of harvesting unit

Geographical characteristics of harvesting units were identified with average yarding distance from road to harvesting unit and its coefficient of variation (CV). The Average of yarding distances represents the interval between units and road, and the CV measure the relative degree of dispersion. The average yarding distance of three scenarios was approximately 115m (Fig. 11), and it tends to reduce with successive cycles. The CV measures were distributed from 0.6 to 0.9 (Fig. 12).

Determining the opening size of harvesting sites

Compartments are visited with a 6-year circulation length over successive periods so that harvesting sites will not be concentrated on a compartment and have a wide range of dispersion. This circulative condition works to make smaller the canopy opening sizes and to have negative impacts on forest environment.

The magnitude of opening size of harvesting sites was expressed with scatter index which is calculated with dividing the number of neighboring harvesting sites by the number of harvesting sites. The scatter index (*SI*) becomes close to 1 when harvesting sites can be decentralized. Neighboring harvesting sites are represented by designating areas adjacent to a subject harvesting site (i, j) from four directions $((i+1, j)\ (i, j+1)\ (i-1, j)\ (i, j-1))$. *SI* ranges from 0.3 to 0.9, and it becomes close to 1 as the cycle advances (Fig. 13).

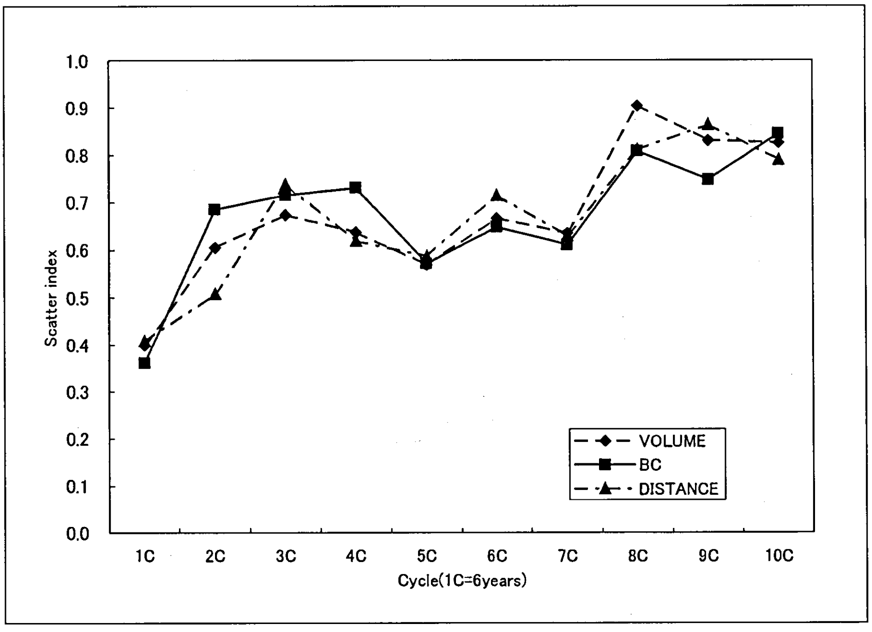

Fig. 13. Scatter index (*SI*) by three scenarios.

Spatial design

In this study, we introduced the newly defined harvesting units which are generally less than 0.1 ha in size, and griddled homogeneously by age differences with adjacent forest stands, forest roads, and compartment boundaries, which makes it easy to identify "how much", "when" and "where" to start harvest, and to increase the efficiency of works.

An aggregation of harvesting units, in contrast, organizes the entire forest into logical spatial units of measuring and controlling the cumulative effects and contains a forest structure or condition that is suitable to meet a specific management goal. One of the aggregation units is a management unit. This study is intended to make easy the measurement of cumulative effects at management level by using GIS, RS and LP technologies, which allowing us to grasp the relationships between geographic conditions and facilities, and providing us with the scientific understand of the mutual relationship of harvesting activities together with their impacts on the environment. For example, let us take the diversity of timber production that is measured in terms of forest structure, forest type and forest age distribution. There are little management units clustered on specific forest age and the introduction of a grid-type harvesting unit allows us to produce diversified forest age distribution with the help of GIS, RS an LP technologies. It is also expected that outcomes from the model can satisfy the economic and ecological conditions of sustainability at management unit level. The productivity of timber production may decrease on account of small-scaled management.

Further studies on the appropriate size of harvest units will be needed for more effective forest planning. Although the grid size was set to approximately 0.1 ha in this study. It may also need to taking into account the resolution of remotely-sensed data and size of compartments in producing harvesting units.

CONCLUSION

This study aims to construct strategic forest planning model with a view of integrating the economic and environmental aspects of forest management, which was realized through the combination of RS, GIS and LP technologies, and the simulation techniques with three scenarios on forest management.

The model can be characterized by introducing the idea of "harvesting unit" which helps us identify the location and size of harvest areas and by combining the two kinds of concepts of circulation, one is concerned with forest (compartment) level and the other stand (unit) level, which may work to not to concentrate harvests on the compartment and decrease the impacts on environments at management level. More concretely, together with the use of harvest unit, we assumed three restrictions such as circulation condition, spatial condition, and P.P.P condition to determine the location and size of harvest areas, which allows us to save time and cost for determining harvest areas as well as for monitoring the plan and the forest condition.

Three alternative forest management scenarios were assumed for the case-study. Volume priority scenario represents a traditional forest management plan emphasizing sustainable timber production, while B/C priority and Distance priority scenarios are concerned with economic efficiency of working in forest operation. Scenario-based analysis of forest planning found effective to predict the future condition of forests and to select the desirable strategic forest plan in an integrated manner.

We believe that the SFP model proposed here can provide some new perspectives of forest planning technologies from the theoretical and practical aspects.

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