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Integrating stand and landscape decisions for multi-purposes of forest harvesting

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Abstract

Forests on Changbai Mountain provide important ecological and economic services to the eastern Eurasian Continent. During the past decades, many of the forests have been harvested, mainly with clearcutting methods. Since 1998, new forest policies have required that forests be harvested with selective cutting methods. This paper demonstrates how to use a decision support system, FORESTAR, to select harvesting targets at a landscape level and to determine cutting intensity and cycle at a stand level. The study site is the Baihe Forestry Bureau, a typical forestry enterprise in northeast China. Based on the considerations of costs, timber production, and landscape integrity, three options are used to select forests for harvesting. An index called Priority Order is used to sort out all the selected forest stands with the three options. A diameter transition matrix model is then used to simulate and compare outcomes of different cutting intensities and cycles. The two decision steps are integrated as an interactive decision-making loop. The final logging plans worked out with such a decision-making process facilitate the realization of spatially- and temporally-sound forest management.

Keywords: Changbai Mountain; Decision support systems; Forest management; Forest planning; Geographic information systems; Selective cutting

1. Introduction

There used to be contiguous and nearly undisturbed natural forests in northeast China at the beginning of the 20th century (Shaw, 1914). Extensive forest logging in China did not occur until 1949, when the new China was founded. Since the 1960s, 135 state-owned forestry bureaus (industrial forestry enterprises) have been established across the nation's forested areas (Zhao and Shao, 2002). Several forest cutting methods have been used in northeast China (Dai et al., 2003). As the demand for timber increased, forests were cut

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largely with clearcutting methods. Although the volume logged did not exceed the growth of the remaining forests, forested landscapes were fragmented (Shao and Zhao, 1998), forest ecosystem quality was degraded (Shao et al., 2001), and the age structure of the remaining forests became unsuitable for sustainable forestry (Zhao and Shao, 2002). During the past decades, in parallel with the continued extensive forest logging in the upper reaches of major rivers, flash flooding increased in both frequency and intensity across China. This helped convince the central government to change the forestry policy to restrict forest logging and protect natural forests in 18 provinces (Zhang et al., 2000). Accordingly, forest management plans are being changed throughout various administration levels. These changes provide unique opportunities to pursue ecosystem management of forests in China (Zhao and Shao, 2002). Today's ecosystem management remains primarily a philosophical concept for dealing with larger spatial scales and long-time frames. One concrete method to implement ecosystem management is to design and implement effective decision-support tools (Rauscher, 1999).

Changbai Mountain, located on the border of China and North Korea, is centrally located in the broadleaf-conifer mixed forest of the eastern Eurasian continent (Nakashizuka and Iida, 1995). Forests on Changbai Mountain provide important ecological and economic services to the region (Wu et al., 2002). The dominant tree species include *Acer mono*, *Fraxinus mandshurica*, *Juglans mandshurica*, *Pinus koraiensis*, *Quercus mongolica*, *Tilia amurensis*, and *Ulmus japonica* (Barnes et al., 1993).

State-owned forest industries in Changbai Mountain area were founded in 1970s. Before 1996, so-called small-area clearcutting was a common practice in the region (Shao and Zhao, 1998). Both field and remote-sensing data have revealed that the clearcutting has fragmented the contiguous forest landscape into isolated forest patches (Shao et al., 2001; Shao and Zhao, 1998). Since 1996, and particularly in 1998, when the Natural Forest Conservation Program became effective, clearcutting has almost been eliminated and selective-cutting methods have been used (Dai et al., 2003). Forests are now grouped into three major categories: Special Ecological Forest (protection targets), General Ecological Forest (manageable), and Commodity Forest (timber production). The major difference in forest cutting between the General Ecological Forest and Commodity Forest is cutting intensity, which cannot exceed 30% for the former and 40% for the latter. Different cutting intensities and intervals have different effects on timber production and forest sustainability.

Practically useful, decision-support systems (DSS) need to be developed based on forest models. A series of forest models have been developed to simulate forest growth and succession on Changbai Mountain, including individual tree, stand, and landscape forest models (Shao et al., 1994; Shao et al., 1996). Each model is theoretically suitable for a unique forest-management purpose, but they are rarely used. Uneven-aged forest management practices required by the Natural Forest Conservation Program can be simulated with matrix models (Buongiorno, 2001; Buongiorno and Gilless, 2003).

2. Needs, principles, and demonstrations of DSS

Decision making in forestry is critical because, in part, forests have a long lifespan and incautious decisions can lead to ecological and economic disasters that have spatial and temporal chain-reactions. Many efforts have been made worldwide in developing DSS in forestry. The fundamental benefit of DSS for forest managers is to provide efficient, explicit, and explainable means of choosing among alternative courses of action, based on available information and outcome preferences (Rauscher, 1999). Different DSS share common generic theories but focus on different forestry tasks. For example, BOREAL (Puttock et al., 1998) aids forest managers in developing site-specific management schedules consistent with planning objectives and environmental standards; LEEMATH (Li et al., 2000) is used to evaluate alternative management strategies from both economic and ecological perspectives; SBW DSS (MacLean et al., 2001) incorporates the effects of insect damage into forest management planning; and REGEN (Haddon et al., 1996) reports on forest regeneration activities and conditions on harvested lands. Rauscher (1999) classified 33 DSS developed in the United States into regional, forest, and project-level applications.

Prior to the Natural Forest Conservation Program, forestry in China was characterized with excessive exploitation of natural forests and countrywide development of monoculture forest plantations (Zhao and Shao, 2002). Although forest plantations have helped triple forest cover in China during the past 50 years, they could not help prevent ecological disasters caused by the loss of natural forests on high mountains, the origins of major river systems in China. In 1998, the most destructive flooding in China's recent history took place in the major river systems, causing at least US$20 billion in damage. The Three Gorge Dam under construction on Yangtze River will be the largest dam in the world when it is completed in 2009. Its functional life will be threatened by increasingly more sediment accumulation in the river. The conservation of natural forests is becoming a sociopolitical issue and is challenging forest managers and scientists (Zhang et al., 2000). At a national level, DSS need to be developed to assist the implementations of the Natural Forest Conservation Program.

A decision support system, FORESTAR (Forest Operation and Restoration for Enhancing Services in a Temperate Asian Region; Shao et al., 2003), contains both landscape- and stand-level forest-management options and provides useful tools to help achieve the multiple purposes of forest-management practices of state-owned forest industries in China. Each forest industry, called a forestry bureau, is a cost-accounting unit. The immediate lower level unit is a forestry farm. The forest-planning unit at a forestry farm is a compartment, which contains multiple sub-compartments or stands as management units. Streams and mountain ridges normally define boundaries of compartments; sub-compartments are defined by forest conditions. FORESTAR can be used at the forestry-bureau or forestry-farm level.

For the purposes of forest harvesting, the framework of FORESTAR is designed to perform bi-step decision-making (Fig. 1). The first-step decision-making is made at a landscape level. FORESTAR contains four options to locate forests for harvesting. The selection of cutting targets can be made based on the considerations of timber production, landscape diversity and integrity, and/or non-wood products. Geospatial overlays are used to compare these options and prioritize forest stands suitable for timber production. The landscape-level planning is performed with forest-inventory data that are collected from all the sub-compartments and renewed every 10 years. The forest-inventory data contain tens of items useful for the first-step decision making, including management type, species composition, mean age, mean diameter, mean height, crown cover, stand volume, stand density, growth status, silviculture history, mortality, seedling species, seedling density, forest floor vegetation type, slope, aspect, soil type, and soil depth.

The second-step decision-making is made at a stand level. Corresponding to uneven-aged forest management, FORESTAR employs a semi-density-dependent diameter transition model or matrix model developed by Shao et al. (1996). The diameter-distribution data from forest inventories are used for running the model. More accurate data can be obtained with intensive, individual-tree measurements at each selected sub-compartment following the first-step decision-making. A graphic interface allows interactions between user-defined cutting options and forest responses (Fig. 2). The model predicts how long it will take for a forest stand that has been cut with a selective-cutting method to recover to the original stocking levels, and what is the averaged annual timber yield by the year of recovery. Users can conduct and compare a series of simulation experiments and figure out what cutting intensity and interval can provide the highest timber production while sustaining forest resources in the long run.

To better explain the bi-step decision-making processes, we demonstrate the use of FORESTAR at Baihe Forestry Bureau, which is located on the north-facing slope of Changbai Mountain. Baihe Forestry Bureau is a typical state-owned forest enterprise, managing about 190,000 ha of forest. The center of the bureau is located at 42°26.63′N, 128°26.56′E. Ranging from 600 to 1200 m in elevation, the native forest type in Baihe Forestry Bureau is mainly temperate mixed-species forest. Extensive forest felling started after 1972 when this bureau was established. The forests are important not only for timber resources, but also for the habitat of endangered plant and animal species, such as the North China or Manchurian tiger (*Panthera tigris altaica*) and Chinese merganser (*Mergus squamatus*).

3. The first-step decision making

FORESTAR contains three sub-modules: forest harvesting, forest regeneration, and forest protection.

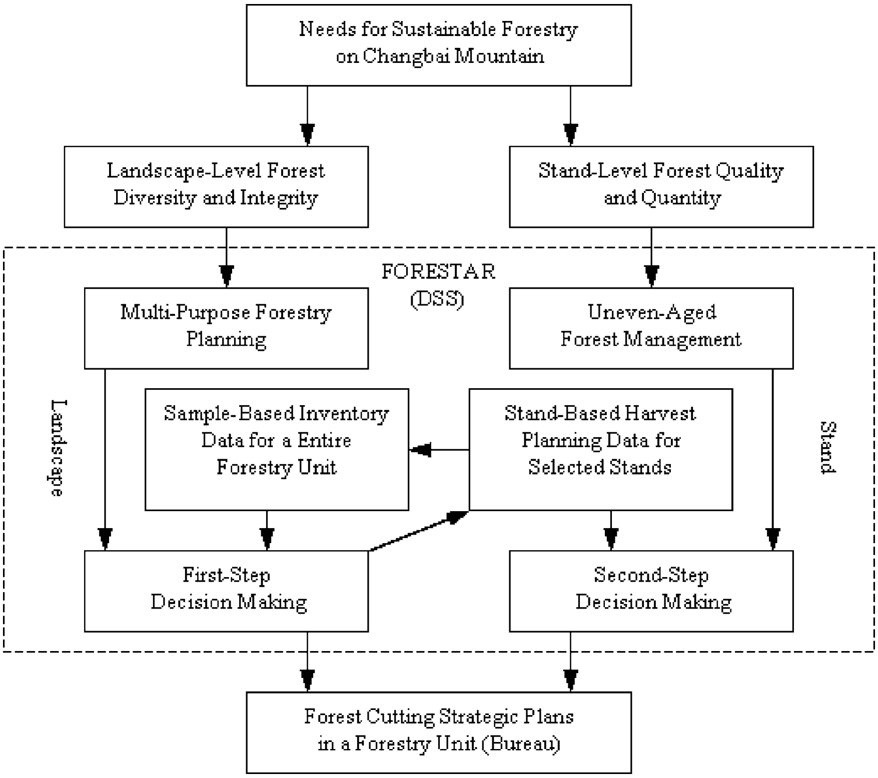
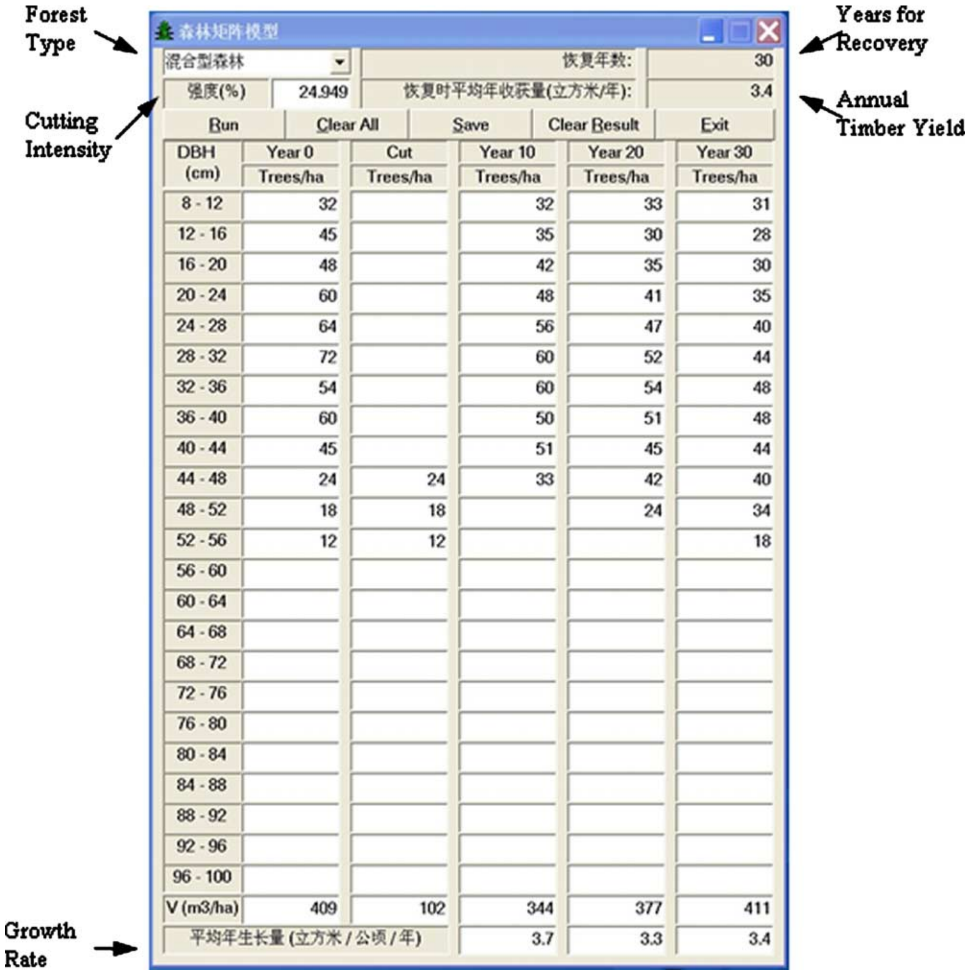


Fig. 1. A flowchart of the decision-making processes of the decision-support system FORESTAR applied on Changbai Mountain.

In this paper, we use the forest-harvesting sub-module to demonstrate how to consider multiple purposes of forest harvesting. In this sub-module, the DSS includes four options for selecting cutting targets. The first option selects sub-compartments based on overall forest conditions within specific compartments; the second option selects sub-compartments directly, based on forest conditions within them; the third option is intended to select sub-compartments to assure landscape diversity and integrity; and the fourth option selects sub-compartments to increase non-wood products, such as ferns and frogs. Due to limited data availability for option 4, we applied the first three options in Baihe Forestry Bureau (Fig. 3).

The new national forestry regulation has restricted forest logging (Zhao and Shao, 2002). The timber production from the Baihe Forestry Bureau was reduced from 181,000 m^3/year in 2001 to 153,000 m^3/year in 2003 and will remain at this level into the future. The example FORESTAR application is based on this actual timber production limit. The Baihe Forestry Bureau has 10 forestry farms, composed of 994 compartments, and 13,777 sub-compartments. The sizes of the forestry farms range from 7582 to 34,862 ha. The Forestry Planning Institute at Baihe Forestry Bureau allocates timber productions to forestry farms based on labor and machine capabilities available at each farm.

After the allocations of timber production to each forestry farm, the Forestry Bureau helps forestry farms select cutting targets. To simplify annual forest-operation planning, compartments that contain a higher proportion of harvestable sub-compartments are normally selected. The major drawback of this strategy is that it may create large, contiguous cutting areas that may cause more soil erosion and damage wildlife habitat. The first option of the example application (Fig. 3) represents the traditional practices of forest harvesting of forest industries in northeast China. In the second option, the selection of sub-compartments bypasses compartments, that is, sub-compartments are selected without considering



DBH (cm)	Year 0 Trees/ha	Cut Trees/ha	Year 10 Trees/ha	Year 20 Trees/ha	Year 30 Trees/ha
8 - 12	32		32	33	31
12 - 16	45		35	30	28
16 - 20	48		42	35	30
20 - 24	60		48	41	35
24 - 28	64		56	47	40
28 - 32	72		60	52	44
32 - 36	54		60	54	48
36 - 40	60		50	51	48
40 - 44	45		51	45	44
44 - 48	24	24	33	42	40
48 - 52	18	18		24	34
52 - 56	12	12			18
56 - 60					
60 - 64					
64 - 68					
68 - 72					
72 - 76					
76 - 80					
80 - 84					
84 - 88					
88 - 92					
92 - 96					
96 - 100					
V (m3/ha)	409	102	344	377	411
平均年生长量 (立方米 / 公顷 / 年)			3.7	3.3	3.4

Fig. 2. A matrix model interface associated with the decision-support system FORESTAR.

which compartments they belong to. The advantage of this option is that the stands with the highest timber stocking within a forestry unit are cut. The option also considers forest age, tree size, and species composition. However, this option does not consider the spatial locations of the cutting targets. The third option is used to prioritize sub-compartment selection based on the conservation of landscape diversity and integrity. The sub-compartments selected with this option are not necessarily the most productive for timber, but logging of these sub-compartments will increase landscape diversity and retain landscape integrity. One primary consideration is to skip at least one sub-compartment between harvested sub-compartments.

After the selection of eligible forests for cutting with each option, a new item called Option1 (O_1), Option2 (O_2), or Option3 (O_3), is added to the data table. The new item has one of two values: 1 representing ‘‘selected’’ and 0 representing ‘‘non-selected’’. A second item called Priority Order (*PO*) was also added to the data table. The value of *PO* was computed with the following formula:

$$PO = \sum_{i=1}^{3} O_i w_i$$

where O_i is the value (0 or 1) for option i and w_i is the weight (default values = 1) of option i. The value of *PO* ranges from 0 to 3 when $w_i = 1$. If option i is more important, $w_i > 1$. The greater the value of *PO*, the

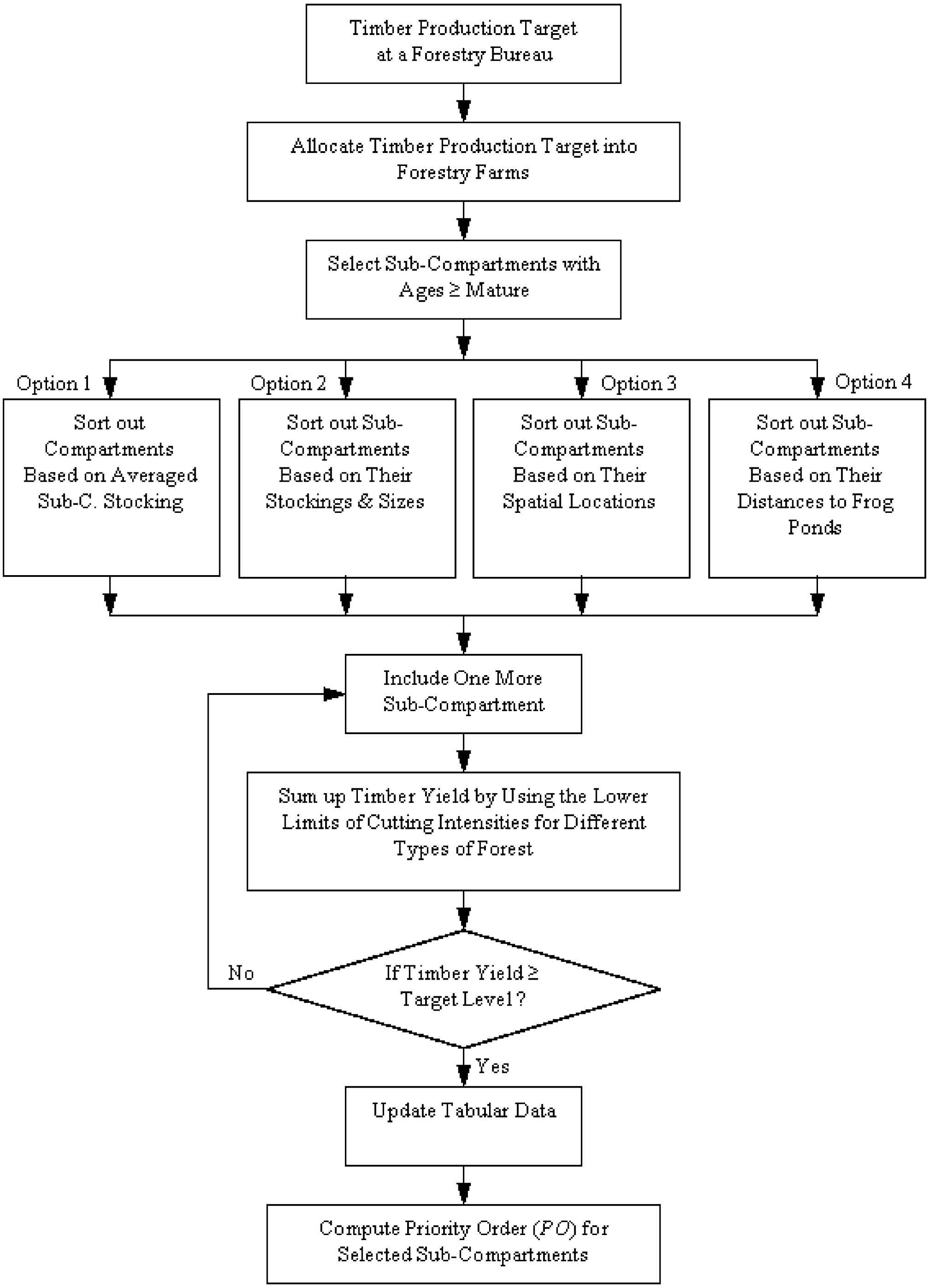


Fig. 3. A flowchart of an example application of the first-step decision-making procedure for the Baihe Forestry Bureau on Changbai Mountain. In this example, only the first three options for forest cutting were used.

Table 1
A summary of the numbers of selected sub-compartments for forest harvesting under different options, singly and in combination, based on 120% of 153,000 m^3/year timber production

Combinations	Number of sub-compartments	Total area (ha)	Total timber stocking (m^3)	Potential timber yield (m^3)*
Option 1	145	2587	757148	194370
Option 2	104	2090	738265	197392
Option 3	117	2398	760793	188164
Options 1 and 2	48	985	305121	72113
Options 1 and 3	30	534	159596	38592
Options 2 and 3	34	635	221589	58507
Any one option ($PO = 1$)	187	5206	1653574	429125
Any two options ($PO = 2$)	67	1584	518958	132391
All three options ($PO = 3$)	15	285	83674	18410

**Note*. A cutting intensity of 15% is used for general ecological forests and 30% for commodity forests.

higher the priority for selection of a given sub-compartment.

Due to expected errors in forest inventory data of up to a 20%, the first-step forest planning is made based on a target of 120% of annual timber production, or 183,600 m^3/year. By using 15 and 30% as cutting intensities for the General Ecological Forest and Commodity Forest, respectively, 145 sub-compartments are eligible for cutting if only the first option is considered, 104 sub-compartments under option 2, and 117 under option 3 (Table 1). The three options result in different spatial distribution patterns of selected harvesting targets (Fig. 4). Some sub-compartments were selected by two or more options. Options 1 and 2 share 48 sub-compartments, options 1 and 3 share 30 sub-compartments, and options 2 and 3 share 34 sub-compartments (Table 1).

There are 187 sub-compartments with $PO = 1$, 67 sub-compartments with $PO = 2$, and 15 sub-compartments with $PO = 3$. Sub-compartments with higher *PO* values have higher priorities for harvesting. Sub-compartments with $PO = 3$ yield an estimated harvest of only 18,410 m^3/year. However, all the sub-compartments with $PO \geq 2$ would generate harvests of 150,000 m^3/year, which is close to annual timber production (Table 1). The intensive, tree-by-tree inventory is carried out following the selection of sub-compartments. Sub-compartments with higher *PO* values are surveyed first to avoid measuring excess forests. More accurate data are obtained with the intensive survey that follows the first-step decision making, resulting in more accurate estimates of timber production.

4. The second-step decision making

Determining cutting schemes is the major task in the second-step decision-making. Clearcutting is used in Commodity Forest stands that have less than 100 young trees (DBH < 24 cm) and where these trees contain less than 30% of desired tree species, such as *J. mandshurica*, *P. koraiensis*, *T. amurensis* and *Phellodendron amurense*. Forests that satisfy the clearcutting criteria account for only 1% of the Baihe Forestry Bureau; therefore, selective cutting is used.

The selective cutting methods used to harvest the two classes of forest have no major differences except for cutting intensity, which is normally between 15 and 30% for the General Ecological Forest and 30–40% for the Commodity Forest. The cutting interval of the selective-cutting methods is normally greater than 10 years. There are no systematic procedures available for local foresters to determine stand-specific and optimal cutting intensities and intervals. A high cutting intensity and/or short cutting interval can harm the sustainability of forest resources whereas a low cutting intensity and/or long cutting interval may waste forest resources. Sound decisions should be made on a stand-by-stand basis. FORESTAR provides the tools that can be used to plan forest cutting intensity and interval (Fig. 2).

A variety of forest models have been successfully used to simulate forest growth and succession and forest management in Changbai Mountain area (Shao et al., 1996). The selective-cutting decision-support

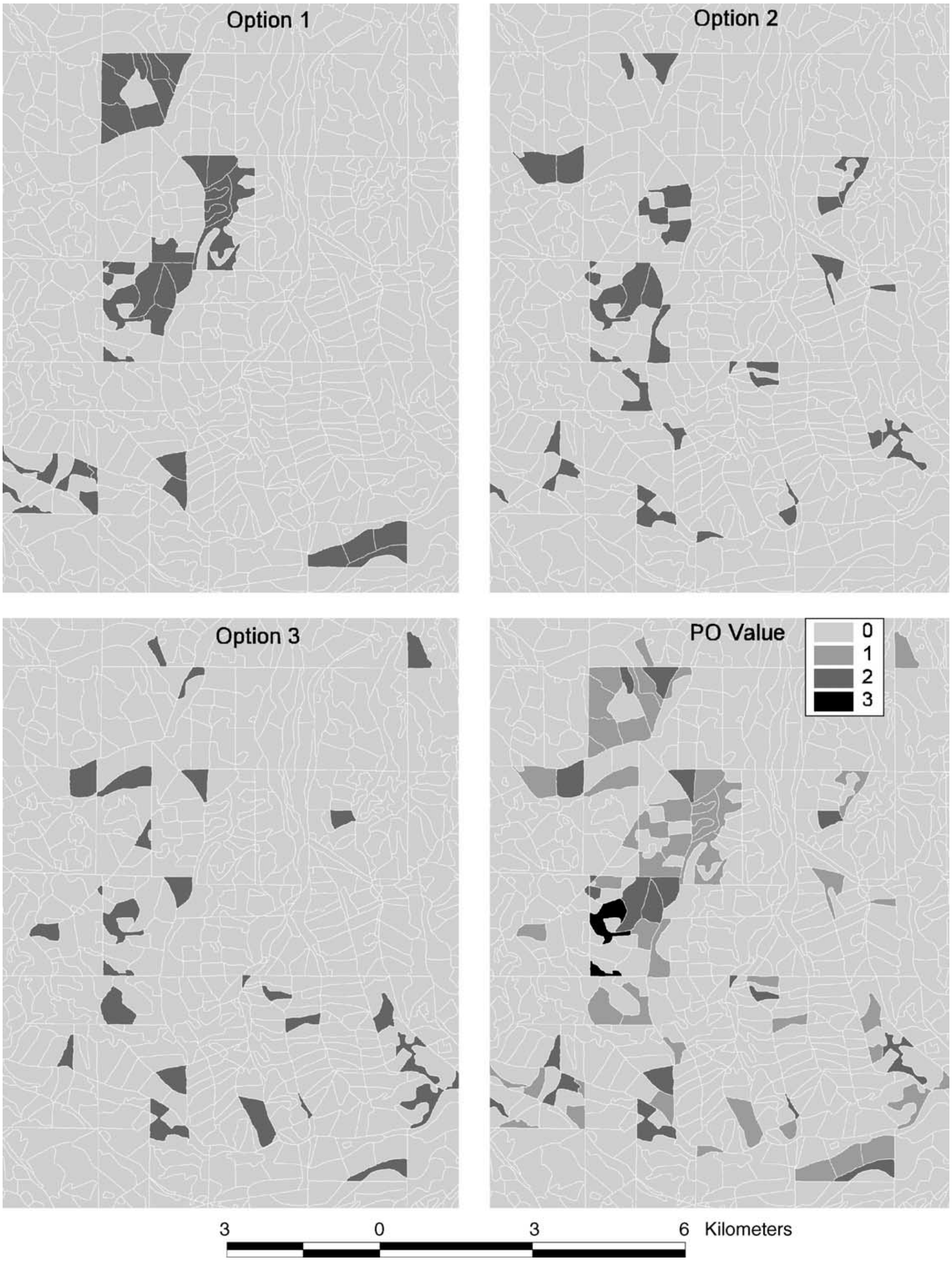


Fig. 4. A map of sub-compartments selected for harvesting by the three individual options and by priority option value.

Table 2
An example of upward shift of trees after harvesting the largest trees from a forest stand on Changbai Mountain

Diameter class	Parameter a[a]	Parameter b[b]	Trees/ha (original)	Harvest	Trees/ha (shifted)
Largest	0.21	0.74	12	12	24
2nd largest	0.25	0.69	18	18	45
3rd largest	0.29	0.65	24		60
4th largest	0.33	0.61	45		54
5th largest	0.38	0.57	60		72
6th largest	0.42	0.52	54		64
7th largest	0.46	0.48	72		60
8th largest	0.50	0.44	64		48
9th largest	0.55	0.40	60		45
10th largest	0.59	0.35	48		32
11th largest	0.63	0.31	45		
Smallest[c]	0.67	0.27	32		

[a] Probabilities that a live tree of a diameter class stays in that same diameter class from t to $t + 10$ year.
[b] Probabilities that a live tree of a diameter class moves from that diameter class to a larger diameter class from t to $t + 10$ years.
[c] In this example, the smallest diameter class is 10 cm and diameter class interval is 4 cm.

tool in FORESTAR employs the matrix model (Usher, 1969) that can be represented as:

$$\boldsymbol{y}_{t+1} = \boldsymbol{G}_t(\boldsymbol{y}_t - \boldsymbol{h}_t) + \boldsymbol{c}$$

where, $\mathbf{y}_t$ is a vector describing the diameter distribution of trees per area unit for a stand at time t; $\boldsymbol{h}_t$ is the harvest vector (i.e., the number of trees of each diameter class that are cut at time t); $\boldsymbol{c}$ is a vector representing artificial regeneration that is independent of stand state; and $\boldsymbol{G}_t$ is a matrix of diameter-transition probability parameters: 1) probabilities that a live tree of a diameter class stays in that same diameter class from t to $t + 1$; 2) probabilities that a live tree of a diameter class moves from that diameter class to a larger diameter class from t to $t + 1$; and 3) in-growth rate from natural regeneration that is dependent on stand density and stocking.

One important advantage of selective cutting is that the removal of canopy trees provides sub-canopy trees with more space that allows the residual trees to grow faster. However, these sub-canopy trees may not grow as fast as open-grown trees of the same diameter because they do not have as high leaf biomass as the open-grown trees (Shao, 1991). Such a dynamic stand mechanism cannot be accurately simulated with the traditional matrix models with constant transition probabilities. Shao et al. (1996) found that larger trees normally have higher growth rate than smaller trees in an uneven-aged forest stand in Changbai Mountain area unless stand density was low. To accurately simulate the effects of selective cutting on forest growth, the matrix model is modified, such that the diameter transition probability is a function of relative tree-size class. In other words, different transition probabilities for a specific forest type are assigned to different relative diameter classes that are labeled from the largest to smallest rather than by specific diameters. When selective cutting is applied to remove trees from larger diameter classes, the transition probabilities of the residual trees are updated by shifting these trees' positions upwards (Table 2). This simple procedure assures higher growth rate of the residual trees after cutting the larger trees.

The interface for running the matrix model contains simple input and output options (Fig. 2). By comparing cutting intensities, defined by users, with some outcomes, including the required number of years for recovery and the mean annual yield at recovery, users will be able to have a better understanding of the effects of cutting intensity and interval. For example, we used data from the stands identified in Table 1 to run the matrix model four times. The first run used a cutting intensity of 5%, removing some of the trees in the largest diameter class; the second run used a cutting intensity of 15%, removing all the trees in top two diameter classes; the third run used a cutting intensity of 25%, removing all the trees in top three diameter classes; and a fourth run used a cutting intensity of 35%, removing all the trees in top three diameter classes and 3/4 trees in the 4th largest

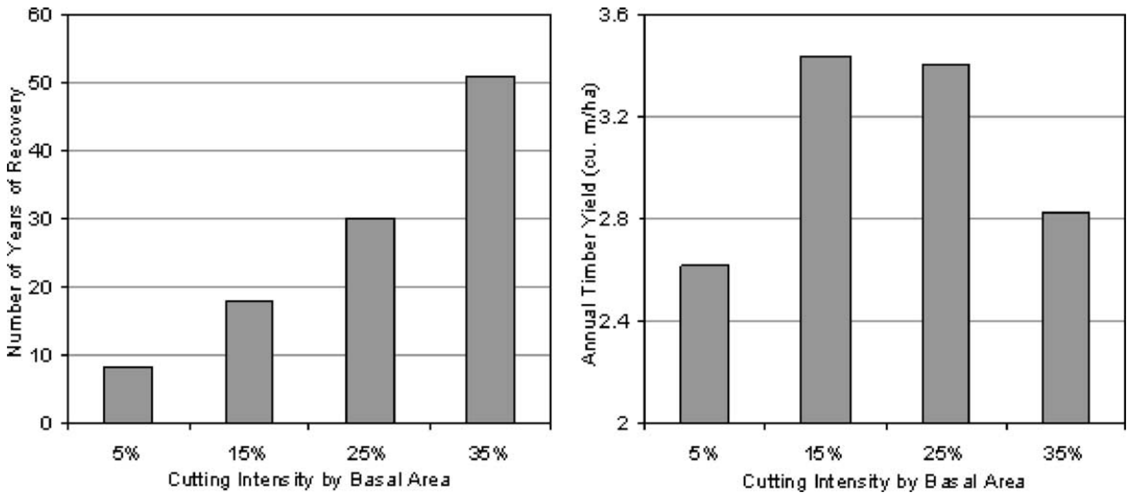


Fig. 5. Estimated years to recovery and annual yield following selective cutting at different cutting intensities.

diameter class. For the purposes of forest sustainability and high yield of timber, the extremely low and high cutting intensities were not preferable. Rather, a sound or approximately optimal cutting intensity should be around 15–25% with a cutting cycle 18–30 years (Fig. 5).

5. Conclusions

The bi-step decision-making process is developed according to the needs for sustainable forestry at two spatial scales. At the landscape scale, cutting targets can be selected and located, considering timber production, economic benefit, soil-water conservation, habitat protection, and/or non-wood products. At the stand scale, a specific cutting intensity and interval can be determined for sustainable utilization of forest resources and obtaining high timber production. After the second step, the total yield of timber can be precisely computed and then compared with the planned timber budget from the first step. This helps revise the selection and location of cutting targets with the first step. Therefore, the two steps are integrated as an interactive decision-making loop (Fig. 1). The final logging plans worked out with such a decision-making process facilitate spatially- and temporally-sound forest management.

The use of FORESTAR is intended to improve the existing decision-making processes for multiple-purpose forest management, rather than to introduce a totally new forest-management system in northeast China. Technically, FORESTAR is designed to have a user-friendly interface and forester-convincing content. The user-friendly interface makes the decision-analysis process transparent and clearly understandable to local foresters. The interface also encourages forestry professionals at different levels to "play" with the system. Chinese foresters have little experience in using decision-support computer programs. They can be scared away with complicated interfaces or operational processes before they can recognize the benefits of using DSS. The forester-convincing content represents the power Chinese foresters urgently need to find alternative solutions in forest-management planning. A powerful DSS can convince foresters that sophisticated forest-management decisions can be easily made with computer-aided planning that would be unachievable without the DSS.

By comparing the differences and similarities in forest management among different choices, as demonstrated by Rauscher et al. (2000), users are able to point out the advantages and disadvantages of each option of forest management. Users can particularly compare the existing forest-management options with the improved options at both the first- and second-step decision-making processes. Such an exercise not only helps field foresters, forest managers, and policy makers make sound and consistent decisions in forest management planning, but also helps them change the way they think, communicate, and work. It is not the decision-support system, but users that will make the final decision on how to manage the forests. The DSS attempts to bring together the intellectual flexibility and imagination of humans with the speed, accuracy, and tirelessness of the computer. In the beginning stage, the learning or educational process within the decision-support system may be more important than the decision-making process itself. The ''educated'' users will have more information, knowledge, and skills, and therefore, be more able to work together and avoid making conflicted plans. As the decision-support system becomes better understood, the DSS itself will be improved. Such a task is compatible with the open-architecture design of FORESTAR.

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