Bowang Chen (Autor)

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1 Introduction

The purpose of forest planning is to evaluate alternative management options in order to find some optimum combination of treatments and to ensure sustainable development. Today, the meaning of sustainable forest management covers not only the ability of sustainable timber yield, but also other functions including the maintenance of biodiversity, recreation facilities and wildlife habitat. New planning techniques can ensure optimum use of forest resources, in different regions of the world. The applications in this thesis include examples from China and Germany.

1.1 Problem statement

Chinese fir (*Cunninghamia Lanceolata* (Lamb) Hook) is an important conifer and native species in China, distributed in sixteen provinces or districts and covering a wide range of growing sites in the subtropical zone. The species is fast growing, pest resistant, very adaptable and resistant to decay. It is widely used in architecture, bridge, construction, paper, pole and furniture. The total timber output amounts to between one-fourth and one-fifth of the commercial timber in the country every year. Altogether about 400 000 hectares are subject to silvicultural treatment, including thinnings and prunings every year. This area is equal to one-tenth of the total area under silvicultural treatment in China.

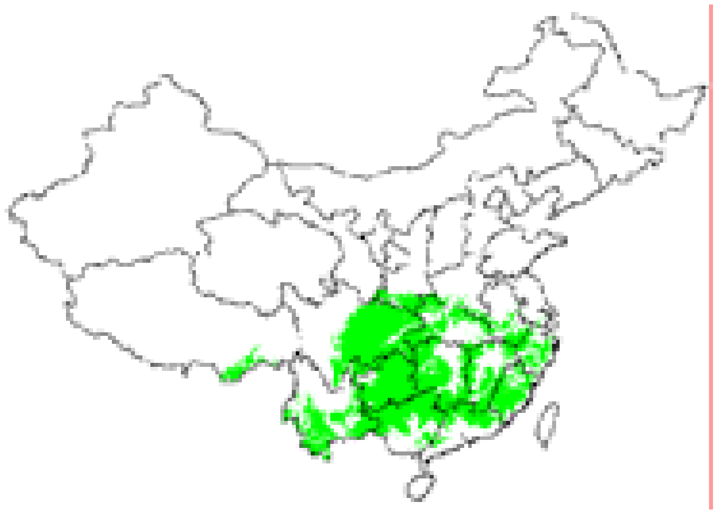

Fig. 1.1. Estimated natural distribution of Chinese fir (dark shading) under current climatic conditions.

The silvicultural history of Chinese fir dates back more than 2000 years (Wu, 1984). Chinese fir has been clonally propagated from stem sprouts for at least 800 years (Ritchie, 1997). This has been reported in many ancient references (Wu, 1984). The planting history of Chinese fir is, to some degree, the history of vegetative propagation. Many history books mention the vegetative propagation of Chinese fir which is probably the tree species most influenced by human beings for a long time in history. There is evidence that it is difficult to find a natural Chinese fir. What can be found is some individual King Chinese fir trees that are protected by local people as their sign of luck and happiness.

The main problem in Chinese fir production forestry is the very high timber demand which cannot be met by the supply. The age structure is unbalanced with a high proportion of young man-made forests and few mature stands. The high demand results in irregular exploitations and utilization and often in environmental degradation. Sound management planning is necessary to ensure sustainable forest practice. The first step towards this objective is to evaluate alternative silvicultural treatment schedules, including different planting densities, different rotations, different spaces and different thinning treatments.

To overcome the conflict of demand and supply, the Chinese Government has taken a policy to ban logging in natural forests. Thus the demand for establishing man-made forests will increase. Chinese fir is the main plantation tree species in China. Sustainable forest management of Chinese fir plantations is the way to resolve the serious problems of wood demand and environmental degradation.

The forest management problems in Germany are different. There is no danger of overexploitation and plantation forestry is not a desirable choice. Norway spruce (*Picea abies*) and beech (*Fagus sylvatica* L.) are two main tree species found in Germany. Continuous cover forestry (CCF) and near-natural forest management are the preferred management options. Although biodiversity is an objective, it appears that in Germany there is a tendency of prescribing standard CCF treatment options over large areas. There is good evidence that a standard mix of treatments practiced on a large scale does lead to a loss of forest diversity. What the two environments have in common, therefore, is a clear need for evaluating silvicultural alternatives on a small scale for spatially defined land parcels. Specific optimization models can be used to achieve this objective.

1.2 Current state of Research

The theory of sustainable forest management provides a rich assortment of models for planning and harvest control. The Normal Forest Model for example, proposed by Hundeshagen (1826), is used to calculate a sustainable harvest volume, based on the mean annual increment and the ratio of current to normal growing stock. The growing stock which is available for final harvest increases with increasing rotation age, which affects the annual cutting area, the total land area required to deliver a sustainable volume of timber, the total growing stock volume, the relative sustainable harvest rate and the mean annual increment. The model of the normal forest is a standard which can be used for comparisons of a current situation with an ideal one. It is a static concept and for this reason its value as a planning tool is limited.

Quite useful, though almost equally simple, are methods based on **age class simulation**. In the simplest simulation approach, the forest area is subdivided into m age classes each covering an area of a_{ij} ha in the j'th felling period ($i=l..m;\ j=0..n$). The available timber volume in the i'th age class is equal to v_{ij} , and the planned total harvest volume for the j'th felling period is h_j. Applications of the technique, which is easily implemented as a spreadsheet program, has been demonstrated for various forest types, including fast-growing timber plantations in the tropics and boreal forests, based on a variety of yield models (Gadow and Puumalainen, 2000). Obviously, the method involves considerable aggregation over growing sites, forest types and management options and the predictions have to be interpreted with caution. However, an age-class simulation is often the only feasible way to predict the dynamic development of a forest resource for a large timber growing region.

A third approach in traditional forest planning involves the use of an **area change model**. Area change models predict transitions of forest states through time. They project the historical harvesting practice and including random effects have been used for timber supply projections in Japan (Konohira and Amano, 1986) and in Europe (Kurth and Dittrich, 1987; Kouba, 1989; Kolenka et al., 1996). One of the most famous applications is Suzuki's (1971) *Gentan* model. We may define $p_i(n)$ as the probability that a randomly selected forest area is in state i at time n and t_{ji} as the conditional probability that state i moves to state j within a given time step, i.e. as the conditional probability that j will be reached provided the system is currently in i. Let $t_{j,1}$ be the probability that a forest stand which belongs to the j'th age class is harvested and thus moves to age class 1 (reforestation). Then $t_{j,j+1}$ is the conditional probability that a stand which belongs to the j'th age class survives and grows into the $(j+1)$'th age class. The area change approach may have some potential as a tool for forecasting the development of age classes and other strata on a regional and national scale (Salnäs, 1990; Nabuurs and Päivinen, 1996). However, some work needs to be done to predict the transition probabilities more accurately (Suzuki, 1971; Blandon, 1985). The transition probabilities are not independent of the current distribution of forest strata, which is a major problem associated with their use (Randall and Gadow, 1990).

The application of new silvicultural systems has become a political reality in many parts of the world. This involves a gradual transformation of traditional silvicultural practice towards *Continuous Cover Forestry.* In a forest managed under the selection system, the stand age is undefined. Forest development does not follow a cyclic harvest-and-regeneration pattern. Instead, it *oscillates* around some ideal level of growing stock. The mean annual increment is not appropriate for measuring productivity and the *Normal Forest* concept and the traditional sustainability criteria are not applicable. Various techniques have been devised for ensuring sustainable harvests in *CCF* systems. The most common type involves recurring visits to a given compartment and to simply skim off the accumulated increment at each visit.

The main problem in a continuous cover forest is to determine which trees are to be removed and which are to remain. The decision may concern tree size or a combination of competition status, tree size, species and timber quality. The aim of the traditional *Plenterwald* harvesting systems practiced in Switzerland, France, Italy, Slowenia and Germany, is to define an optimum forest structure by using an inverse J-shaped diameter distribution model. The target distribution is re-established by periodic removal of trees in the different diameter classes. In mixed fir, spruce and beech forests of the Trentino region of the Italian Alps trees are harvested with reference to the model defined by Susmel (1980; see also Virgilietti and Buorgiorno, 1997). Meyer (1933) proposed the function $\ln(n) \mid \zeta \ 4 \ \eta \ \int D$ for specifying the ideal diameter distribution. In a *Femel* forest which is characterized by group harvesting and gap regeneration Meyer's η parameter assumes values ranging from 0.08 to 0.15, depending on the maximum diameter of harvestable trees. In a *Plenter* forest the η-values are usually much lower, ranging between 0.05 and 0.07.

Leak (1964, 1965) proposed the BDq method for Northern Hardwoods in New England. If research data are not available, the target values for *B*, *D* and *q* are established using silvicultural considerations. Guldin (1991) proposed a target basal area of 180 ft^2/acre, a maximum retained diameter of 36 ins. and a *q*-factor of 1.21 for the mixed conifer stand on the Challenge Experimental Forest in Northern California (for details of the method refer to Cancino and Gadow, 2002).

In theory, the approach is very simple and logical. By comparing the real and the ideal diameter distributions, it is possible to determine the number of trees that should be harvested in each diameter class. Unfortunately, however, there is no generally accepted ideal distribution of tree sizes, but a rather wide range of distributions found in stable *Plenter* and

Femel forests (cf. Mitscherlich, 1952). The Plenter guide curves are thus of limited use. The same is true for the so-called basal area normality-approach practiced in some tropical forests (Gadow and Puumalainen, 2000).

There is an increasing need on biodiversity conservation in forest management. Avoiding large clear-cutting areas is a way to protect wildlife habitat and optimizing the spatial distribution of forest management (Öhman et al., 2000; Van Deusen, 2001). The relative spatial arrangement of patches and interconnections among patches, also plays an important role in maintaining the biodiversity of the forest (Baskent and Jordan, 1996).When the old forest is fragmented into isolated patches, it provides marginal conditions for species that inhabit forest interiors (Harris, 1984; Temple, 1985). A possible approach to help reduce the amount of edge habitats and minimize the fragmentation is to establish large areas of old forest, free from edge effects (Franklin and Forman, 1987; Gustafson and Crow, 1994; Gustafson and Crow 1996; Esseen and Renhorn 1998). A criterion related to the amount of interior habitats is the core-area concept. Öhman et al. (Öhman 1998; Öhman et al .2000) investigated the possibility of using the core-area concept in long-term planning of an actuall landscape. The planning problem consists of maximizing the net present value (NPV) and minimizing the fragmentation of old forest. The core-area is defined as the area of old forest free of edge effects from surrounding habitats (Zipper 1993; Baskent and Jordan 1995).

Öhman (1998) solved the model using the method of *Simulated Annealing*. The results indicate that the degree to which stands are clustered depends on the amount of core area demanded and the edge width. The amount of new core area that is allocated adjacent to an existing core area, indicating a continuity of core area information, is increased with core area demand, the minimum age of old forest, and the existence of a U-shaped initial age structure. The cost of attaining the spatial pattern appears to be low compared with the cost of retaining the old forest. Her other research results shows that distinct continuous patches of old forest are created when both a core area requirement and consideration of the amount of edge habitats are included in the problem formulation. The cost of creating a continuous area of old forest was found to be significant.

Another relevant research is Yoshimoto' risk analysis (Yoshimoto 2000). Events related to forest management are associated with uncertainty. This affects he management decision for forest level planning as well as stand level planning. Yoshimoto used stochastic dynamic programming and estimation of linear models to stochastic phenomena in his risk analysis about timber harvest planning.

Van Deusen (2001) studied scheduling spatial arrangement and harvest simultaneously based on the Metropolis algorithm. Spatial configurations are loosely specified and stochastically attained, which contrasts with other adjacency constraints based on a specific block size limit. *Simulated Annealing* was the basic tool in solving the problem. In his simulated example of 40Δ40 grid of cells, 1090 polygons present forest stands and the remaining ones are ponds. Each of the non-pond polygons is considered to be forested and of an age proportional to its class assignment. (1) When the harvest scheduling objective function contains only an even-flow component, the spatial aspects of the schedule are not controlled; (2) then when the spatial component is added to encourage do-nothing regimes to be close to pond regimes, this has some impact on the spatial juxtaposition of ponds and do-nothing regimes; (3) moreover, when more weight is given to the spatial component, the result shows a very distinct spatial pattern where ponds are almost completely surrounded by do-nothing regimes; (4) Finally, an additional modification is added in the form of a second spatial component to keep do-nothing regimes apart from each other, this cause the do-nothing buffers around the ponds to be somewhat smaller and clusters of do-nothing polygons that are not adjacent to ponds are smaller. This method makes it possible to improve habitat and connectivity, and to create buffer zones as part of the scheduling process.

Heuristics such as *SA* are increasingly used to solve harvest scheduling problems (see for example, Yoshimoto et al., 1994; Murray and Church, 1995; Bettinger et al., 1997; Öhman and Eriksson, 1998; Van Deusen, 2001). They can generate feasible solutions to large problems that traditional mathematical programming techniques are unable to solve. A common complaint about the heuristic algorithms is that the quality of the solutions is unknown. In response to this argument, Boston and Bettinger (1999) compared three heuristic techniques commonly used to solve harvest scheduling problems: *Monte Carlo* integer programming, *simulated annealing*, and *tabu search*. In addition to the heuristic solutions, the optimal solution value was found for each problem using integer programming. *SA* found the highest solution value for three of four problems, and was less than 1% from the highest objective function value in one of the problems.

1.3 General scenario modeling techniques

1.3.1 Area Change Models

Area change models are suitable for generating forest development scenarios. But its use-requires the transition probability matrix to be known. We can define

$p_i(n)$ = the probability that a randomly selected forest area is in state *i* at time *n,*

t_{ij} = the conditional probability that state *i* moves to state *j* within a given time step,

$t_{j,1}$ = the probability that a forest stand which belongs to *j*th age class is harvested and thus moves to age class 1,

$t_{j,j+1}$ = the conditional probability that a forest stand which belongs to *j*th age class survives and grows into the *(j+1)*th age class,

Normally $t_{j,1} + t_{j,j+1} = 1$.

The general matrix of transition probabilities may thus be written as follows:

$$T= \begin{bmatrix} t_{1,1} & t_{1,2} & 0 & 0 & \cdots & 0 \\ t_{2,1} & 0 & t_{2,3} & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ T_{n-1,1} & 0 & 0 & 0 & \cdots & tn\text{-}_{1,1} \\ 1 & 0 & 0 & 0 & \cdots & 0 \end{bmatrix}$$

1.3.2 Rule-Based Modeling

Thinning is an important practice in the silviculture of plantation forests influencing both their stability and productivity. A thinning regime is uniquely defined by the number, times, intensity and the final felling. In practice, stands have to be felled to meet periodic timber requirements, not because optimum silviculture demands it. Consequently, it is more useful to specify a set of feasible regimes for each stand, in contrast to one optimum regime, thereby boosting the flexibility for meeting forest-wide constraints (Gadow, 1989).

Many phenomena can be adequately described by a relation between objects as a mathematical model. For example, in South African pulpwood stands, the basal area removed during a thinning (Bat) can be predicted by the equation: Bat = -0.07228 + 7.88 /D.

A rule is a logical connection between statements and thus a higher order concept, it is combination of English and mathematics (both categorical statements and quantitative statements). In the above example, if the main product is pulpwood, if at least 5 m^2 of the available basal area (BA) cab be removed and if the stability factor exceeds 1.15, then the may be thinned. The rule can be written as follows:

The main product is pulpwood
&
BA(-0.07228 2 7.88/D) } $5m^2$ ♥ Thin the stand
&
Stability (D/H) } 1.15

Where H and D refer to the mean stand height and diameter.

A decision tree is a convenient framework for building a system of rules for thinning regime selection (Grayburn, 1986; Brand, 1981; Pelkki, 1988).

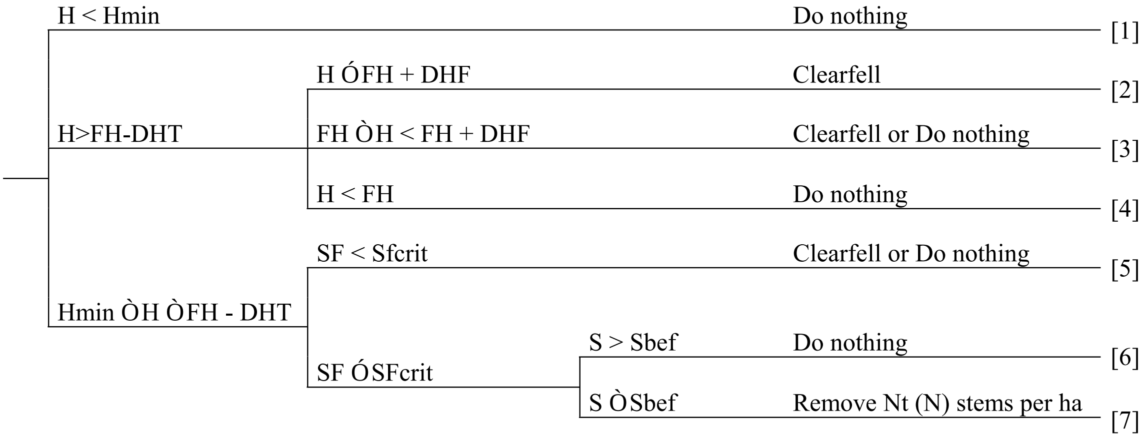

Fig. 1.2. Specific example of a decision tree for regime selection of Pinus radiata

Multiple regimes will be generated if the decision is clear-fell or do-nothing. If the planning period is shorter than the rotation age, the decision tree will only produce one regime. However, considering the alternative thinning weights at leaf node [7] the number of regimes will be increased.

1.3.3 A model for any type of forest management

A model for any type of forest management has been specified as follows (Gadow and Puumalainen, 2000):

Model Elements

Variables	X_{ij}	= the area (ha) of stand i (i = 1...I) managed with regime j (j = 1...J_i)
Constants	M_{pt}	= the total output of product p (p = 1...P) in period t (t = 1...T)
	A_i	= total area (ha) of stand i
Coefficients	u_{ij}	= the utility value per ha of assigning stand i to regime j
	v_{ijpt}	= the per ha yield of product p in period t, if stand i is managed with regime j

Model Formulation

objective function $\sum_{i=1}^{I}\sum_{j=1}^{J_i} u_{ij}X_{ij} \Rightarrow max.$

constraints

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} v_{ijpt}X_{ij} = M_{pt} \qquad \forall t, p$$

$$\sum_{j=1}^{J_i} X_{ij} = A_i \qquad \forall i$$

and $X_{ij} \geq 0.$

The advantage of this model is the fact it can be applied in any forest type and management strategy and that it combines stand level objectives and forest level constraints.

Another advantage of this model is that all kinds of forest management problems can be described with it and then resolved with general methods. Linear programming, Simulated Annealing, Genetic Algorithm and Tabu Search are some powerful methods in dealing with this kind of optimization problems. They will be studied and compared in this thesis. A computer software (*SAGALP*) is developed for implementing these algorithms.

1.4 Determining operation preferences

One of the methods that has been widely used for establishing preferences is Saaty's Analytical Hierarchy Process (AHP; Saaty, 1980). Saaty's method is based on a ratio scale. There is a assessment scale of *m* classes. The criteria are lined up in $n(n-1)=2$ pairs. In each pair of criteria, one out of the *m* preferences of the item on the left over the item on the right is assigned. The quantified judgments on the pairs *i, j* are represented by an *n* by *n* matrix.

The scale values are added up for each criterion to obtain *n* row sums. Then, the row sums are normalized through division by the sum of weights.

1.4.1 Hierarchical prioritization

Imagine two finite sets, G and A. G is a set of independent properties, A is a set of objects characterized by the properties. We assume that a numerical weight $w_i > 0, (i= 1,\ldots,n)$ is associated with each $g_i \subset G$ and that

$$\sum_{i}^{n} W_i = 1$$

If the weights associated with $a_j \subset A$, relative to g_i are denoted as $u_{ij} > 0, j=1,\ldots,m,$ then the relative weight of u_{ij} with respect to g_i is equal to

$$W_i = \sum_{j}^{m} u_{ij} a_i$$

In a multilevel hierarchy, this principle generalizes to a chain of sets (Saaty, 1980 p76). In a forest planning problem the objective function coefficients are additive utility values assigned by field staff. We assume an additive utility function of the following form:

$$W_i = \sum_{j=1}^{2} u_{ij} a_i$$

where $W_i =$ utility coefficient for option i