

SILVA FENNICA



1990 · Vol. 24 N:o 2

SUOMEN METSÄTIETEELLINEN SEURA
SOCIETY OF FORESTRY IN FINLAND

SILVA FENNICA

A quarterly journal of forest science

PUBLISHER – JULKAISIJA

The Society of Forestry in Finland
Suomen Metsätieteellinen Seura r.y.

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Management planning system for tree plantations. A case study for *Pinus kesiya* in Zambia

Timo Pukkala, Jussi Saramäki & Owen Mubita

TIIVISTELMÄ: SUUNNITTELUKESKUSTELUJÄRJESTELMÄ: SAMBIAN *PINUS KESIYA* -VIILJELMÄT

Pukkala, T., Saramäki, J. & Mubita, O. 1990. Management planning system for tree plantations. A case study for *Pinus kesiya* in Zambia. Tiivistelmä: Suunnittelusysteemi istutusmetsiköille: Sambian *Pinus kesiya* -viljelmät. Silva Fennica 24(2): 171–180.

The paper presents a simple model of long-term forest management planning in tree plantations. The model is particularly suitable for developing countries where the research resources are limited. The management plan is prepared in two steps. First, one or several treatment schedules are simulated for each calculation unit (age class, compartment, etc.) over the selected planning period. Secondly, an optimal combination of treatment schedules according to the selected objectives and constraints is searched by mathematical programming. The simulation of growth is based on the prediction of the diameter distribution at a desired time point. All stand characteristics are derived from this distribution. The models needed in the yield simulation can be estimated from temporary sample plots. A case study management plan for 13 000 hectares of *Pinus kesiya* plantations in Zambia is presented to demonstrate the system.

Tutkimuksessa esitellään yksinkertainen menetelmä pitkän aikavälin metsätaloudelliseen suunnitteluun istutusmetsiköissä. Menetelmä soveltuu parhaiten oloihin, joissa tutkimusresurssit ovat rajalliset. Metsätaloussuunnitelma valmistetaan kahdessa vaiheessa. Ensin jokaiselle laskentayksikölle (esim. metsikkökuvio tai ikäluokka) simuloidaan yksi tai useampia suunnittelujakson kattavia käsittelyohjelmia. Toisessa vaiheessa käsittelyohjelmista valitaan optimiyhdistelmä matemaattisella ohjelmoinnilla. Kasvun simulointi perustuu läpimittajakauman ennustamiseen haluttuna ajankohtana. Metsikkötunnukset johdetaan läpimittajakaumasta. Simuloinnissa tarvittavat mallit voidaan laskea kertakoealoista. Tutkimuksen esimerkki-alueena on 13 000 hehtaarin laajuinen *Pinus kesiya* -viljelmä Sambiassa.

Keywords: *Pinus kesiya*, plantations, timber management planning, multiobjective optimization, yield model, simulation model, diameter distribution, Zambia. ODC 624.3+174.7 *Pinus kesiya*

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Accepted January 29, 1990

1. Introduction

In some cases the cheapest and most rapid method to increase benefits derived from the forest is to improve the management of existing resources. Good management is especially important when forest products are scarce.

One way to improve forest management is to develop and adopt efficient techniques for management planning. Compared to other means to affect production, like tree breeding, fertilization and afforestation, management planning has several advantages: it does not need heavy investments, its effects are immediate, and it may not increase the risk of production as much as e.g. fertilization or the introduction of new genotypes.

The task of forest management planning is to find for individual stands, treatments that fulfil the objectives set at the level of the whole forest. Forest management planning should be designed to meet the variability of the objectives. The use of forest resources should be efficient, i.e. the plan should show a way to get the maximum output with a given input. Today, mathematical programming promises to be the easiest way

to meet these requirements.

Most objectives of forestry concern the future. The best method for predicting the future stand development associated with different treatment alternatives is to simulate the growth and the treatments of the stand. Consequently, a simulation method is an essential part of any planning system.

This paper presents a planning system for long-term strategic planning using *Pinus kesiya* plantations in Zambia as an example. The system selects optimal treatments for each planning unit so that the restrictions and objectives set for the whole forest area will be met.

The aim was to prepare an economical system especially for developing countries with limited resources and technology. The planning programs thus run in a micro computer. The models needed in the growth prediction can be calculated from temporary sample plots.

The authors gratefully acknowledge the ZAFFICO Ltd and The Forest Department of Zambia for permitting the use of the inventory and sample plot data in the study.

2. Description of the method

The system consists of yield models, a set of computer programs that utilize these models and an optimization procedure for compiling the management plan (Fig. 1). The inventory system and the consecutive grouping of inventory plots or compartments into calculation units should produce for each unit at least the following information: the area of the unit, the average age, dominant height and number of stems per hectare.

The purpose of grouping inventory units into calculation units is to reduce computations to a level feasible with a micro computer (usually less than 100 calculation units). One unit is composed of inventory

plots or compartments which are similar; one age class in one site productivity class is an example of a calculation unit. If the number of inventory units is low, each of them can be used as a calculation unit and no grouping is needed.

The average stand characteristics of each calculation unit are the data source for the simulation. The simulation of treatment schedules provides predictions on the stand development along alternative management options (Siitonen 1983). The simulation covers an arbitrary time period which can be divided into two or more sub-periods.

At least one treatment schedule must be

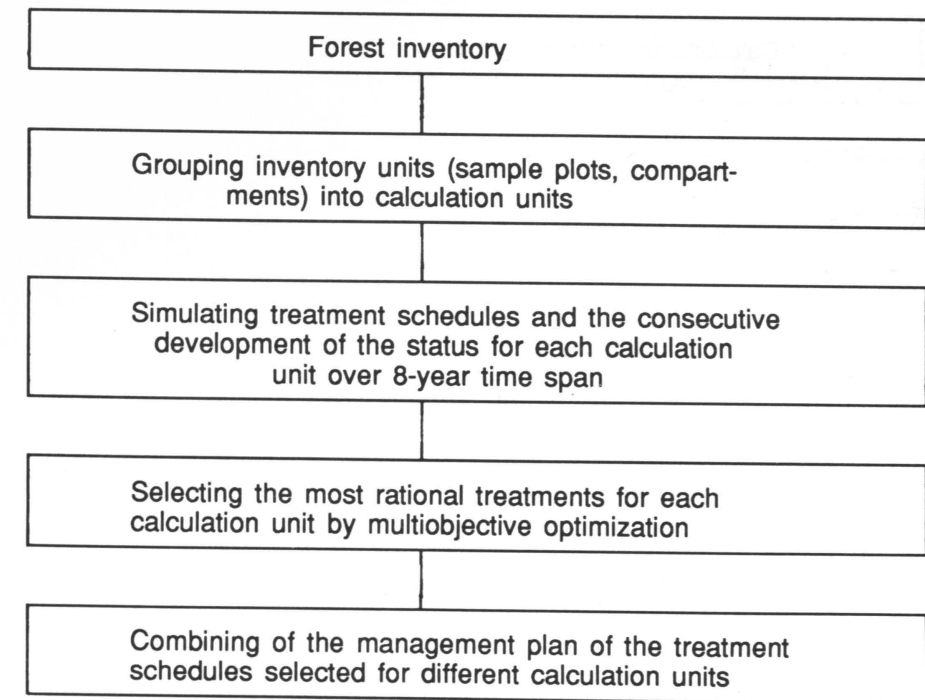


Fig. 1. Stages in the preparation of a management plan.

simulated for each calculation unit. The status according to a particular schedule is calculated at the beginning of each sub-period and at the end of the last sub-period (Fig. 2).

The growth is simulated by predicting the temporal change of diameter distribution. Using the relationships of stand characteristics, the diameter distribution can be derived from the age, dominant height and number of stems per hectare. The development of dominant height is most conveniently described by a site classification system which is based on age and dominant height. The number of stems per hectare is predicted from the planting density, thinnings and a survivor function. In the managed *P. kesiya* plantations the natural mortality can be assumed to be negligible.

The diameter distribution is most commonly modelled with the Weibull (e.g. Kilkki and Päivinen 1986) or beta distribution (e.g. Pukkala and Pohjonen 1990). They are simple and flexible enough,

so that many kinds of distributions can be described.

Each time when the status is calculated a new diameter distribution is predicted, from which the stand characteristics are calculated. The process of computing the stand characteristics has the following steps:

- (1) Calculate the theoretical diameter distribution from age, dominant height and number of stems per hectare.
- (2) Divide the distribution into classes and take the class-midpoint-tree to represent each class.
- (3) Calculate the number of trees in each diameter class.
- (4) For each class-midpoint-tree, calculate the tree height, stem volume and other relevant tree characteristics.
- (5) Calculate the stand characteristics as averages or sums of the tree characteristics.

The treatments are simulated in the middle of each sub-period. Cuttings are simulated by

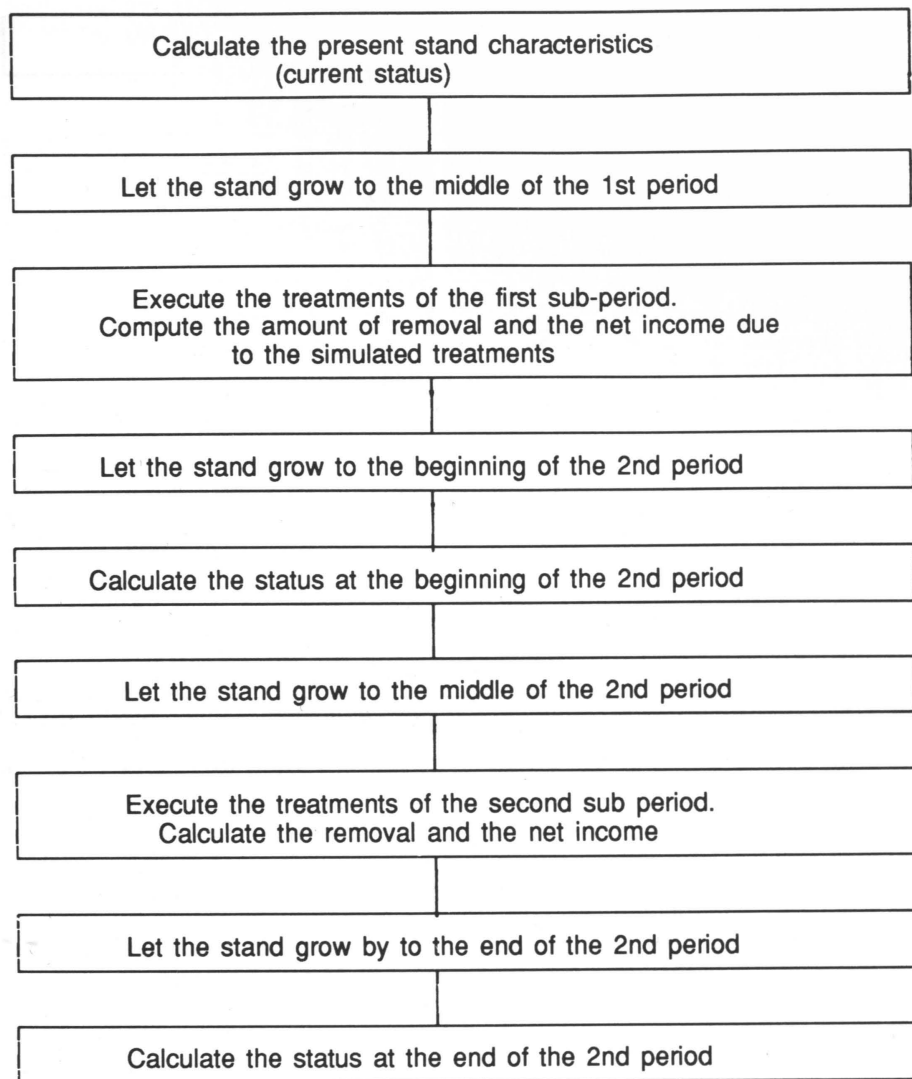


Fig. 2. Stages in the simulation of one treatment schedule over two 4-year management periods.

decreasing the number of trees in different diameter classes.

After the simulation, several management plans can be prepared by mathematical programming. Such a schedule is selected for each calculation unit that the results correspond to the objectives when viewed at the level of the whole forest. The optimization presupposes the specification of the variables to be used for evaluating the management plan, i.e. the objective and constraining variables (e.g. total volume in a

certain year or removal during a certain period). Linear programming is the simplest optimization procedure available (e.g. Kilkki et al. 1975) but other methods could be used as well (e.g. Pukkala 1988).

The treatments associated with the selected schedules are taken as treatment proposals. The grand totals of different sum characteristics at various points of time are computed from the predicted stand development along the selected treatment schedules.

3. A case study for *Pinus kesiya* in Zambia

3.1. Study material

The case study is based on earlier models of stem volume and the development of dominant height of *Pinus kesiya* (Sekeli and Saramäki 1983, Saramäki et al. 1987) and a set of new models needed for simulating stand development. The new models were calculated from 600 inventory plots and 149 measurements of permanent research plots in the *Pinus kesiya* plantations of ZAFFICO Ltd, Zambia (The Industrial ... 1969). The plots were selected to cover the whole range of variation in site, age and stocking of the *Pinus kesiya* stands of ZAFFICO Ltd. The predictors and the predicted variables of the stand models were calculated for each plot. The plot results were used as such for constructing the models, even though the plot extremes in diameter underestimate the range of variation in a stand.

3.2. Stand models and their use

The model used to predict the development of dominant height was (Saramäki et al. 1987):

$$H_{dom} = 10^{1.80084} (Si/10^{1.80084})^{(15/T)^{0.74}} \quad (1)$$

where H_{dom} = dominant height, m

T = stand age, years

Si = site index (dominant height at the age of 15 years)

The beta-distribution is used as a theoretical diameter distribution (e.g. Loetsch et al. 1973, Päivinen 1981, Gadow 1983). The diameter distribution is:

$$f(d) = c(d-D_{min})^\alpha (D_{max}-d)^\gamma \quad (2)$$

where $f(d)$ = frequency of diameter d

c = scaling factor to obtain a specified total number of stems

α, γ = parameters

For estimating the beta distribution corresponding to a certain age, dominant

height (H_{dom}) and number of stems per hectare (N), it is enough to have models for the minimum (D_{min}), mean (D_n), maximum (D_{max}) and variance (VAR) of diameter. In addition, models of tree height and stem volume are needed for calculating the necessary dimensions for trees sampled from the diameter distribution. The calculation of the diameter distribution begins with the estimation of mean height (H_n):

$$\ln(H_n) = -0.09202 + 1.070\ln(H_{dom}) - 0.02854\ln(N) \quad (3)$$

$$R^2 = 98\%, \quad F = 23727 (2, 746) \quad s_e = 0.054$$

(s_e is the relative standard error of estimate, calculated by $100 \sqrt{\exp(s_r^2/2) - 1}$ where s_r is the standard error of estimate)

Mean height is used for estimating the mean diameter:

$$\ln(D_n) = 1.9656 + 0.6170\ln(H_n - 1.3) - 0.09270\ln(N) \quad (4)$$

$$R^2 = 93\%, \quad F = 4752 (2, 746), \quad s_e = 0.087$$

The minimum, maximum and variance of the diameter distribution are estimated with the help of H_{dom} , N and D_n .

$$\ln(D_{max}) = 1.397 + 0.7353\ln(H_{dom}) - 0.02400\ln(N) \quad (5)$$

$$R^2 = 89\%, \quad F = 2878 (2, 746), \quad s_e = 0.108$$

$$D_{min} = 15.58 + 1.335D_n - 0.5010D_{max} - 2.615\ln(N) \quad (6)$$

$$R^2 = 82\%, \quad F = 1112 (3, 745), \quad s_e = 2.463$$

$$\ln(VAR) = 1.110 + 0.08121(D_{max} - D_{min}) - 0.1635\ln(N) + 0.4361\ln(H_{dom}) \quad (7)$$

$$R^2 = 88\%, \quad F = 1834 (3, 745), \quad s_e = 0.225$$

The parameters α and γ of the beta-distribution (Eqn 2) are calculated from the mean and variance of diameter by using the method of Loetsch et al. (1973, p. 53).

In the case study, the diameter distribution was divided into 15 equal intervals and the frequency computed in the middle of each interval. The tree corresponding to each class-midpoint diameter was taken to represent the class. The height of each class-midpoint tree was calculated by the Näslund's (1936) formula $h=1.3+d^2/(a+bd)^2$, the parameters of which are obtained by

$$\ln(b) = -1.916 + 0.3214\ln(D_n) - 0.03427H_{dom} \quad (8)$$

$$R_2 = 56\%, F = 475 (2, 746), s_e = 0.117$$

$$\ln(a) = -0.2648 - 3.000\ln(b) - 1.598\ln(H_{dom}) \quad (9)$$

$$R_2 = 63\%, F = 637 (2, 746), s_e = 0.368$$

The stem volume and the proportions of merchantable volume to 10, 15 and 20 cm utilization limits (minimum overbark top diameter) were calculated by the equations of Sekeli and Saramäki (1983). When calculating saw log volumes, the breast height diameter had to exceed the minimum top diameter by 5 cm, otherwise the log was considered too short.

33. Management planning

The case study management plan was produced to demonstrate the output of the system. The plan was compiled for a part of the ZAFFICO Ltd's *Pinus kesiya* plantations in Ndola, Zambia (The Industrial... 1969). The total case study area was 13 213 ha. The age of the stands varied from 2 to 25 years (Table 2). The age classes were taken as calculation units. This amounted to 23 units. The area, stocking, and dominant height of each calculation unit were obtained from the inventory results of ZAFFICO forests (Saramäki et al. 1987).

The management planning covered 8 years which were divided into two 4-year sub-periods. A total of 65 treatment schedules were simulated for the 23 calculation units by varying the timing and strength of the treatments. The following treatments were simulated: thinning, clear cutting and planting. With the thinning treatment, 20% (light thinning), 30% (moderate) or 40%

(heavy thinning) of the stand basal area was removed. The frequencies of different diameter classes were decreased so that the harvest proportion of a particular class was 95% of the harvest proportion of the previous (smaller) class.

The stand characteristics were recalculated after each treatment, separately for the remaining trees and for the removal. The amounts of different inputs and outputs associated with the management schedule were utilized in the optimization and when writing the management plan.

The optimization was done by the method of Korhonen (1987a, 1987b) designed to solve multiple objective decision problems. The method allows 10 objective variables and a great number of constraints. Production frontiers were calculated for large saw logs, which are the most significant product of the plantations. In the management plan, the aim was to increase the saw log volume and at the same time ensure a sufficient saw log harvest during the 2nd 4-year management period. These general aims were ensured by stating the following objectives and constraints:

- maximize saw log cut during the first 4-year period with the following constraints:
- 2nd period's saw log removal must be at least 0.8 mill. m³
- saw log volume must be at least 1 mill. m³ after 4 years
- saw log volume must be at least 1 mill. m³ after 8 years

All economic parameters were excluded because of the poor knowledge of the present and future unit prices and costs in the case study area.

34. Results

According to the production frontiers it is possible to cut either almost 1 mill. m³ saw logs (19 m³/ha/yr) during the first 4-year period, in one extreme (point A in Fig. 3), or about 1.85 mill. m³ (38 m³/ha/yr) during the second period in another extreme (point B), if there are no constraints. Cropping 0.6 mill. m³ during the 1st period allows 1.35 mill. m³ to be harvested during the 2nd period (point C). Harvesting 0.8 mill. m³ during the 1st period decreases the saw log cuttings of the 2nd period to 0.95 mill. m³ (point D).

SAWLOG REMOVAL (mill. m³)

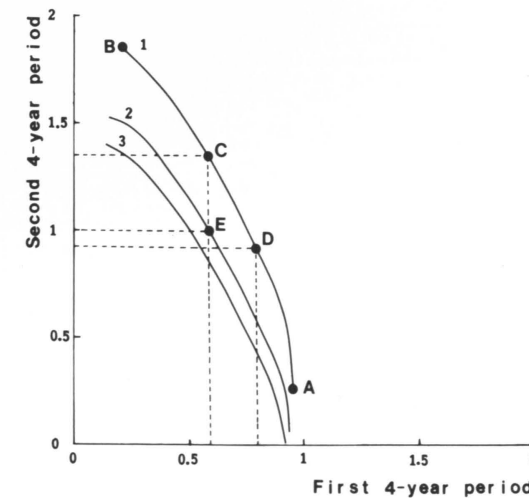


Fig. 3. Production frontiers showing the dependence of saw timber removal (top diameter 20 cm) during the 1st and 2nd 4-year period. Curve 1: No constraints, Curve 2: Final saw timber volume (after 8 years) = 1 000 000 m³, Curve 3: Final saw timber volume = 1 200 000 m³. Letters A...E refer to the explanation in the text.

The constraint that at the end of the planning period, i.e. after 8 years, the total saw log volume must exceed 1 mill. m³ (75.7 m³/ha) decreases cuttings; if e.g. 0.6 mill. m³ saw logs will be harvested during the 1st 4-year period, it is only possible to remove 1 mill. m³ during the second period (point E in Fig. 3) instead of 1.4 mill. m³ without the constraint concerning the final volume. The constraint of final saw log volume being at least 1.2 mill. m³ further decreases the saw timber cuttings by 0.1...0.2 mill. m³ (Curve 3 in Fig. 3).

In the presented management plan the saw log cuttings of the 1st 4-year period are 594 000 m³ (11.2 m³/ha/annum) and 800 000 m³ (15.1 m³/ha/annum) during the second period. These cuttings do not violate the other constraints (Table 1). The constraint concerning final saw timber volume was

Table 1. Development of total volume and removal (in m³) according to the management plan. An output of the planning system. '>10cm' = volume up to top diameter 10 cm of trees whose dbh exceeds 15 cm. '>15cm' and '>20cm' are defined correspondingly.

Status	1988	1992	1996
Volume, Total	2 357 722	2 392 962	2 361 637
Volume, >10cm	2 146 992	2 259 502	2 192 371
Volume, >15cm	1 489 921	1 794 703	1 874 071
Volume, >20cm	567 759	1 000 000	1 124 415
Removal		1st 4 yr	2nd 4 yr
Stems, number of		3 269 084	1 890 906
Volume, Total		1 406 931	1 230 883
Volume, >10cm		1 342 454	1 185 637
Volume, >15cm		1 099 029	1 064 560
Volume, >20cm		594 011	800 000
Areas to be treated (ha)		1st 4 yr	2nd 4 yr
Clearcut-Plant		1346	2260
Light thinning		863	0
Moderate thinning		2510	1962
Heavy thinning		5479	2143

unnecessary.

The objectives and constraints lead to a management where during the first four years the main emphasis is on thinnings; the area to be thinned is 8852 ha. Only the oldest age classes will be clear cut and planted (Tables 1 and 2). During the second period clear cuttings account for a greater proportion of the harvests. Although the harvest of large saw logs increases, the total harvested volume is greater during the 1st 4-year period (Table 2). This means that in the beginning, considerable amounts of small-sized trees should be harvested.

The age class distribution develops favorably during the 8-year planning period (Fig. 4). After 8 years the area and its management almost have reached a steady state enabling an annual saw timber cut of 0.2...0.25 mill. m³.

Table 2. Treatments selected for each calculation unit (age classes) for the two 4-year management periods as yielded by the planning procedure. Removal is expressed in m³/ha.

Unit	Area ha	Age yr	— Treatments for two 4-year periods —			
			1st period	Removal	2nd period	Removal
1	469	2	No treatments	0	No treatments	0
2	287	3	No treatments	0	No treatments	0
3	324	4	No treatments	0	No treatments	0
4	517	5	No treatments	0	No treatments	0
5	863	6	Light thinning	15	No treatments	0
6	831	7	No treatments	0	No treatments	0
7	518	8	No treatments	0	No treatments	0
8	753	9	Heavy thinning	60	No treatments	0
9	69	10	No treatments	0	No treatments	0
10	548	11	Moderate thinning	68	Heavy thinning	117
11	584	12	Moderate thinning	68	Moderate thinning	82
12	1378	13	Moderate thinning	66	Moderate thinning	78
13	1595	14	Heavy thinning	124	Heavy thinning	125
14	954	15	Heavy thinning	125	Clearcut-Plant	303
15	776	16	Heavy thinning	192	Clearcut-Plant	435
16	368	17	Heavy thinning	147	No treatments	0
16	457	17	Heavy thinning	147	Clearcut-Plant	338
17	503	18	Heavy thinning	120	No treatments	0
18	73	19	Heavy thinning	177	Clearcut-Plant	385
18	300	19	Clearcut-Plant	446	No treatments	0
19	495	20	Clearcut-Plant	447	No treatments	0
20	231	22	Clearcut-Plant	342	No treatments	0
21	160	23	Clearcut-Plant	222	No treatments	0
22	90	24	Clearcut-Plant	254	No treatments	0
23	70	25	Clearcut-Plant	341	No treatments	0

4. Discussion

The main purpose of the presented planning system is to evaluate the production alternatives of a tree plantation. The system is not particularly well-suited for an operational short-term planning where e.g. a detailed description of individual compartments is essential. This is because the compartments must be grouped into calculation units as the optimization procedure and the computer memory usually set a limit for the total number of treatment schedules.

The case study included models for pure *Pinus kesiya* stands only. The inclusion of

other species is, however, straightforward and easy. In the case study region in Zambia the most important additional species are *Pinus oocarpa* and *Eucalyptus grandis*.

The simulation of yield is based on the prediction of the diameter distribution at a desired age. The reason for selecting diameter distribution yield model over whole-stand models or individual-tree models is that it provides relatively inexpensive size-class information that can be used to make management decisions. The needed models can be calculated quickly from a set of temporary sample plots

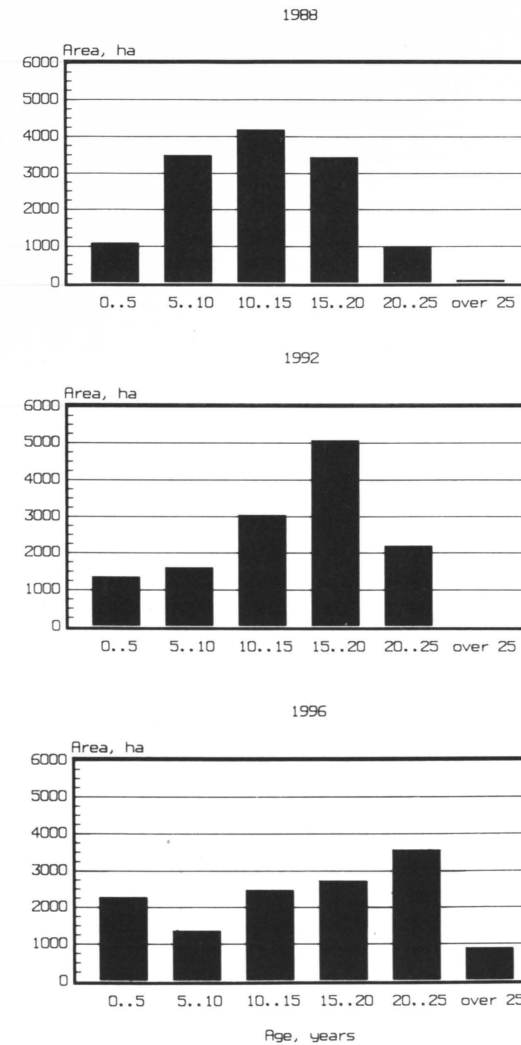


Fig. 4. Change in the areas of different age classes according to the selected management plan.

measured e.g. in the inventory of the area under planning (Pikkarainen 1986, Pukkala and Pohjonen 1987).

The simulation method uses static models.

The status of a stand depends on the site (through age and dominant height) and number of stems only; previous states affect only via number of stems. The method may not always give a reliable prediction of the stand development, like immediately after a sudden and abrupt change in the shape of the diameter distribution. The simulation method is most suitable for one-species plantations which are grown even-aged and without extremely strong treatments.

The prediction of the diameter distribution is based on a recursive system of equations: dependent variables appear as predictors in subsequent equations. Because of the omission of the estimation errors of predictors, the presented R² and s_e statistics overestimate the precision of the calculation of the diameter distribution. However, from the results of Pukkala and Pohjonen (1990) it can be concluded that the method is still reasonably precise and does not cause any systematic errors in the prediction of stand volume. The benefit of using recursive equations is that estimates can be replaced by measured values if available.

Only three different treatments were simulated in the case study management plan: planting, thinning and clear cutting. Other treatments (site preparation, fertilization, weeding, pruning etc.) can be included provided their effects on the future stand development are known, as well as the costs of the treatments.

The management plan was combined by using mathematical optimization. It is therefore known that the resulting plan is at the limit of the production possibilities of the forest, i.e. it uses the forest resources in an efficient way. The essential feature of the planning system is that the selection of treatment schedules, and also the recommendations proposed for different compartments, are decided at the level of the whole area under planning, not at the stand level.

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