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Evaluation of Thinning Schedules for Beech Forests using Dynamic Programming

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Abstract

The paper presents an analysis of thinning schedules for beech (Fagus sylvatica L.), using a two-state dynamic programming model and a growth model based on yield table data. Mortality is estimated through an algorithm based on the maximum density line. Thinning intensity and periodicity is evaluated within the traditional Dynamic Programming (DP) framework. The thinning type is defined by the NG index, which describes the ratio of the removed stem number and basal area proportions. Given the infinite number of possible NG values for each thinning intensity, the NG must be optimized at each state. Such an optimization is performed by using the PATH algorithm, developed by Paredes and Brodie, within a range of NG values defined by the stand's physical attributes. The results show that the combination of a simple growth and yield model within a DP framework in conjunction with NG values as indicators of thinning type yield good estimates of practical thinning schedules. The approach is limited to the traditional system of managing a beech forest, using a well-defined production period and even-aged conditions. It is reliable as long as there is no need for assigning a price difference according to log quality. Simulations showed the general path of NG values along the rotation to optimize growth rates. The objective of the paper is to demonstrate the use of a systematic search for evaluating silvicultural options.

Key words: beech (Fagus sylvatica L.), NG ratio, thinning optimization, growth and yield simulation, mortality.

Resumen

*Este artículo presenta un análisis de las secuelas de aclareo definidas para rodales de haya (*Fagus sylvatica *L.), usando un modelo de dos variables de estado de programación dinámica y un modelo de crecimiento derivado de datos provenientes de tablas de rendimiento. La mortalidad es estimada a través de un algoritmo basado en la curva de autoaclareo. La intensidad de aclareo y su periodicidad se evalúa con un modelo tradicional de Programación Dinámica (PD). El tipo de aclareo es definido por la razón NG, misma que describe la razón entre árboles removidos y las proporciones de área basal. Dado un número infinito de valores de NG para cada intensidad de aclareo el valor de NG se optimiza en cada estado. Tal optimización se realiza a través del algoritmo PATH, desarrollado por Paredes y Brodie dentro de un rango de valores de NG definido por los atributos físicos del rodal. Los resultados muestran que la combinación de un modelo simple de crecimiento y rendimiento dentro de un modelo de PD con indicadores de valores de NG como proxy del tipo de aclareo proporcionan buenos estimadores de secuelas prácticas de aclareo. La estrategia propuesta se limita a los sistemas de manejo regulares. El algoritmo es confiable en la medida en que no se introducen diferenciales de precio de acuerdo a tipo de trocería. Las* *simulaciones mostraron la trayectoria general de valores de NG a lo largo del turno cuando se optimizan tasas de crecimiento.*

*Palabras clave: haya (*Fagus sylvatica L.*), razón* NG*, optimización de aclareos, simulación del crecimiento y rendimiento, mortalidad.*

Introduction

Beech (*Fagus sylvatica* L.) is one of the most important tree species in Europe. The species favors a mild temperate climate and avoids regions with long and very cold winters and extended dry spells during the summer months. The geographical range is limited in Eastern and Northern Europe by low winter temperatures and dry spells, in the South by high summer temperatures and dry spells and in the West by wind exposure (Wenk *et al.*, 1990, S. 360; Fig. 1). Within its natural range, beech is currently one of the most, if not the most competitive of all indigenous trees species in Central Europe. Its economic and environmental value is very high. Studies comparing different treatment options in beech stands are therefore always relevant.

Figure 1. Natural geographical of beech (after Meusel et al., 1965).

Despite its commercial and ecological importance, systematic attempts to generate and evaluate alternative treatment schedules for beech are surprisingly rare. Numerous proposals have been made and arguments presented in favor of a particular treatment concept for beech forests. One of the most comprehensive studies was presented by Schober (1972). Other detailed studies include those of Freist (1962), Altherr (1971), Wilhelm et al. (1999) and Klädtke (2002). These analyses are detailed and thorough, but to our knowledge, none of the proposals has been based on an exhaustive comparison of possible alternatives.

More recently, strategies for the treatment of beech forests include particular types of selective management and the application of continuous cover forestry. A strategy may be defined by a so-called "forest development type" which an idealized description of the development of a managed forest. The example in Fig. 2, after Perpeet (2001), shows the desirable development of a beech forest. The management strategy attempts to mimic the natural succession of a beech ecosystem, involving a mixture of broadleaved species and natural regeneration.

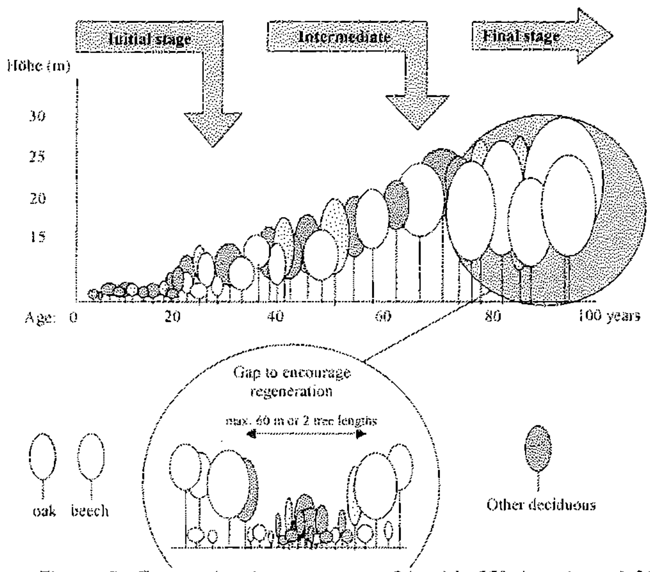

Figure 2. Forest development type 21 with 80% beech and 20% other deciduous species (after Perpeet, 2001).

The idea is to apply thinnings which mimic the natural succession, allowing a variety of species to grow with the dominant beech, and to encourage natural regeneration by creating gaps in the canopy with a width of about two tree lengths.

The objective of this paper is not to propose another specific silvicultural system, but to present a method for comparing treatment options for beech stands, based on the optimization technique known as Dynamic Programming (*DP*). Optimizing silvicultural treatment schedules is the classical stand level management problem. Thinning optimization has been attempted through various methods such as marginal analysis (Chappelle and Nelson, 1964), Dynamic Programming (Amidon and Akin, 1968), Nonlinear Programming (Roise, 1986), special numerical methods (Valsta, 1990) and even Neural Networks (Chung and Roise, 1993).

Among all these methods *DP* has been the most used technique given its flexibility to be adapted to different conditions and problem types. Dynamic Programming as a tool to determine optimal timing and removals of trees was initially proposed by Arimizu (1959) and operationalized by Amidon and Akin (1968). Since then, the tool has been applied to a wide variety of even-aged management problems at stand level (Brodie and Haight, 1985) such as timing and intensity of thinning, fertilization, pest control, rotation age decisions and even the optimization of other silvicultural activities and multiobjective production at stand level (Ritters *et al.*, 1982).

Early scientists used a two descriptor model (usually volume and age) in order to cluster each state (Brodie *et al.*, 1978; Chen *et al.*, 1980; Kilkki and Vaisanen, 1970). A three descriptor model was first proposed by Brodie and Kao (1979). Such a model was the first one linked to an existing growth simulator for Douglas-fir called DFIT and the first attempt to perform a forward recursion. This strategy of linking growth simulation models and dynamic programming optimization routines to optimize silvicultural treatments soon expanded to different species and objectives.

Despite the achievements in developing efficient algorithms to optimize with traditional dynamic programming, the tool had some limitations, specifically when linked to individual tree models. In such circumstances the memory requirements and the calculations involved grow exponentially. Paredes and Brodie (1987) resolved the memory and efficiency problem by using both, network and duality theories. However, their efficient way to solve for the optimal path (called the PATH algorithm) requires some monotonic behaviour for the production function. When such conditions are not met a strategy testing for different look ahead periods (stages) can be implemented (Yoshimoto *et al.*, 1988).

This paper describes an approach to identify optimal thinning schedules (timing and intensity) with a simple whole stand growth model. Thinning type is described by using the *NG* ratio which is also simultaneously optimized through the PATH algorithm (Paredes and Brodie, 1987) within a traditional *DP* framework.

The paper is divided into three main sections. The next section describes briefly the growth and yield prediction model. Then a summary of the traditional *DP* formulations for the stand level optimization problem is presented. In the same section the formulation to optimize *NG* ratios is discussed as well as the technical problems that need to be implemented. Finally, the last section shows comparative results including some sensitivities for different model parameters.

2. Model Description

2.1. Growth Model for Beech

The first yield models for beech stands were developed more than 200 years ago. An example is the yield table published by Paulsen (1795). Improved yield tables were developed towards the end of the 19th century and the beginning of the 20th century on the basis of better growth data (Baur, 1881; Schwappach, 1890; Eberhard, 1902; Grundner, 1904; Wimmenauer, 1914; Dietrich, 1925; Wiedemann, 1931). More recently, Schober (1972) compiled a beech yield table for North-Western Germany, which is based on the work of Schwappach (1911) and Wiedemann (1931). Another beech yield table, which is mainly used in Eastern Germany, was published by Dittmar *et al.* (1986).

Several single tree simulators were developed during the 1990's, *e.g.* the parametric models SILVA (Pretzsch and Kahn, 1998) and BWinPro (Nagel *et al.*, 2002), and the non-parametric model MIBEA (Hessenmöller, 2002). The single tree growth models typically tend to show a rather high proportion of unexplained variation (Windhager, 1999; Hessenmöller, 2002). Observed growth rates have been reported to exceed the maximum potential rates of the growth models (Gadow and Heydecke, 2000). Consequently, it was decided to select a stand model for this analysis. The basic model developed by Franz *et al.* (1973) can be used to predict total stand volume after thinning, before thinning and even the thinning volume if appropriate variables are used; it has the following form:

$$V = \left[d_1 + d_2 \cdot \left(H_{mG,A}\right) + d_3 \cdot \left(H^2_{mG,A}\right)\right] \cdot G_{G,A} \qquad [1]$$

Where H_{mG}= mean height of the stand before thinning or H_{mA} = mean height of the removed stand (m); $G_{G,A}$ = basal area of the stand before thinning or basal area of the removed stand (m²/ha); d_i corresponds to the *i-th* parameter which was estimated by ordinary least squares with the following estimates: d_1 = -4.01810 (t = -28.96); d_2 = 0.770533 (t = 64.55); d_3 = -0.004562(t = -18.62)

This model requires two basic variables at any age and at any condition (before thinning or after thinning) in order to yield estimates: mean height and basal area. The mean height of a stand (before thinning) is estimated from top height using an exponential model of the following form:

$$H_{mG} = c_{11} \cdot H_{100}^{c_{12}} \qquad [2]$$

where H_{mG} = mean height of the stand before thinning (m); H_{100} = mean height of the 100 tallest trees per ha (m). The model was fitted through ordinary least squares with the following estimates c_{11} = 0.641557 (t = 99.75); c_{12} = 1.122430(t = 372.71).

The mean height of the removed stand is also estimated from top height corrected by the proportional size of the thinned trees measured through the quadratic mean diameter. For this estimate we used the model:

$$H_{mA} = H_{100} \cdot \left(1 - e^{c_{21} \cdot Dq_A}\right)^{c_{22}} \qquad [3]$$

where H_{mA} = mean height of the removed stand (m); H_{100} = mean height of the 100 highest trees per ha (m); Dq_A = quadratic mean diameter of the removed stand (cm); The parameters were estimated through nonlinear least squares with following values c_{21} = -0.045669 (t = -19.87).; c_{22} = 0.265097 (t = 18.71).

These two models require an estimate of top height. For this component, the height model proposed by Sloboda (1971) was used:

$$H_{100} = b_1 \cdot \left(\frac{SI}{b_1}\right)^{\exp\left(\frac{-b_2}{(b_3-1)\cdot A_0^{(b_3-1)}} + \frac{b_2}{(b_3-1)\cdot A^{(b_3-1)}}\right)} \qquad [4]$$

where H_{100}= mean height of the 100 highest trees per ha (m); SI = site index (defined here as the top height at age 100, m); A_0 = reference age (100 years), and A = stand age. The parameters were estimated from data derived from yield tables for North-western Germany (Schober, 1987) through nonlinear least squares. The resulting estimates were: b_1 = 99.35485 (t = 9.50); b_2 = 6.261437 (t = 6.60); b_3 = 1.578726 (t = 34.94). Since mean height is driven by top height and this variable is uniquely defined by age (given that site index is considered constant in a simulation) then mean height can be defined at any age and given equations 2 and 4

Another important element of the stand volume model (1) is the basal area. Basal area growth is often estimated by using the path invariant algebraic difference form (also known as PID-type; Souter, 1968), which usually provides more accurate estimates when information is based on long term growth data, than a *differential equation* (DIF- type). The fitted model has the following form:

$$G_2 = \exp\left(\left(\frac{A_1}{A_2}\right) \cdot \ln G_1 + a_1 \cdot \left(1 - \frac{A_1}{A_2}\right) + a_2 \cdot SI \cdot \left(1 - \frac{A_1}{A_2}\right) + a_3 \cdot \left(\ln N_2 - \left(\frac{A_1}{A_2}\right) \cdot \ln N_1\right)\right) \qquad [5]$$

where G_2 = basal area at age A_2 (m²/ha); G_1 = basal area at age A_1 (m²/ha); *SI* = site index; N_2 = number of stem at age A_2; N_1 = number of stems at age A_1. The model was fitted through ordinary least squares (Gauss-Newton method provided by STATISTICA) by using yield table data from Germany and Denmark (Schober, 1978; Skovsgaard and Mosing, 1996). Successive values of age, basal area and number of stems were used as primary data to fit the model (5). The fit statistics were good (R^2 = 0.997, Standard error = 0.265, F = 1088175***) and the following parameter estimates were obtained: a_1 = 5.61650 (t = 77.05); a_2 = 0.005156 (t = 2.50); a_3 = -0.0955 (t = -15.41).

The main problem with this model is that it requires an estimate of mortality since the number of trees at the prediction age (N_2) is one of the variables. Natural mortality can not be estimated directly from yield tables given that successive values for the number of trees in the yield table only include thinned trees.Hence an estimate of mortality had to be derived. Such an estimate is based on the principle that predicted quadratic mean diameter derived from equation (5) can not exceed the size-density relationship defined by the maximum density line.

The estimate of the maximum density line was derived from the model described by Döbbeler and Spellmann (2002), which has the following form:

$$N_{G\max} = \frac{p_0}{t_0} \cdot \left(2 \cdot p_0 \cdot D_{G\max}\right)^E \quad , E = \frac{t_1}{p_1} - 1 \qquad [6]$$

where N_{Gmax} = maximum surviving trees per ha; Dq_{Gmax} = quadratic mean diameter (cm); The parameter values for beech reported by the authors are p_0 = 1.0829E - 07; t_0 = 8.3652; p_1 = 1.5374; t_1 = - 1.7365. Given the maximum density line, the estimation of mortality is summarized by the following algorithm.

Step 1	$N_2^* = N_1$ Mortality = 0
Step 2	Estimate G_2 using equ. (5); recover Dq_2 Calculate N_2^* from G_2 and Dq_2
Step 3	If $N_2^* \leq N_{Gmax}$ Then G_2 is accepted; Mortality = N_2-N_1 Else Go to step 4 End if
Step 4	Estimate Dq^*_{Gmax} given $N_{Gmax} = N_2$ from (6) Estimate $Dq_2^* = \frac{Dq_2 - Dq^*_{Gmax}}{2}$ Recover N^*_{Gmax} given Dq_2^* from (6) $N_2^* = N^*_{Gmax}$; Mortality = N_2-N_1 Go to Step 2

In this algorithm Dq_2^* represents the quadratic mean diameter along the maximum density line that will be used to estimate the maximum number of trees (N^*_{Gmax}) given a specific size. Convergence is guaranteed since the search is over a closed interval. The binary search approach regularly converges after 6-7 iterations for an error ε=0.001 cm. of *Dq*.

2.2. Optimization of Timing and Intensity of Thinning

The standard Dynamic Programming formulation for simultaneously optimizing rotation age, thinning intensity and thinning time can be stated as (Paredes and Brodie, 1987):

$$\max \ f_N(\mathbf{y}_N) = \sum_n r_n(\mathbf{t}_n) \qquad (7.1)$$

subject to

$$\mathbf{x}_n - \mathbf{t}_n + \mathbf{g}_{n+1}(\mathbf{y}_n) = \mathbf{x}_{n+1} \qquad \forall \ n = 1,2,\ldots,N-1 \qquad (7.2)$$

$$\mathbf{x}_n - \mathbf{t}_n = \mathbf{y}_n \qquad \forall \ n = 1,2,\ldots,N \qquad (7.3)$$

$$\mathbf{x}_N - \mathbf{t}_N = 0 \qquad (7.4)$$

Where

$f_N(\mathbf{y}_N)$ = objective function value of the sequence of thinning decisions in *N* management periods, yielding a final stand described by $\mathbf{y}_N$, which in an even aged management context corresponds to the stand after the final harvest cut.

$r_n(\mathbf{t}_n)$ = return yielded at stage *n* when thinning decisions at state *n* ($\mathbf{t}_n$) have been taken.

$\mathbf{y}_n$ = vector describing the stand at stage *n*, after thinning decision $\mathbf{t}_n$ has been taken in a stand described by $\mathbf{x}_n$. This vector describes the so called "residual stand", "state descriptor" or "state variable".

$\mathbf{x}_n$ = vector describing the stand at stage *n* after it has grown from state $\mathbf{y}_{n-1}$ (before thinning). It is also referred to as the "initial stand vector" or "stand before thinning".

$\mathbf{t}_n$=vector describing feasible thinning decisions (intensity) at stage n transforming the stand $\mathbf{y}_n$ into $\mathbf{x}_n$ and generating a return $r_n(\mathbf{x}_n,\mathbf{t}_n)$. It is usually referred as the vector of decision variables.

$\mathbf{g}_{n+1}(\mathbf{y}_n)$= vector of yield variables for a stand described by $\mathbf{y}_n$ at stage *n* to stage *n+1*. It is usually referred as the transformation function.

The above formulation is integrated by an objective function (7.1), a "state equation" (7.2) linking state variables, decision variables and time (the analogous "motion equation" used in optimal control applications), an "equilibrium equation" ensuring that changes in the state of the stand (7.3), within a stage, can only be derived from thinning decisions, and an equation showing the ending condition (7.4). This problem formulation assumes known initial stand conditions as well as the feasible vectors for all thinning decisions and state variables.

The solution to this problem formulation by *DP* requires inclusion of as many state variables as variables defining the vector y_n. The stand growth model for *Fagus sylvatica* L. requires three state variables, namely: age, basal area and number of trees per hectare. The first state variable is represented by the stage optimization index, and the other two must be considered in the state vector. Therefore, the recursive equation corresponding to the *DP* solution approach is given by:

$$f_n(\mathbf{y}_n) = \max_{\{y_{n-1}, t_n\}} \{ r_n(\mathbf{x}_n, \mathbf{t}_n) + f_{n-1}(\mathbf{y}_{n-1}) \} \qquad [8]$$

where $r_n(\mathbf{x}_n, \mathbf{t}_n)$ represents the return generated at stage n when thinning decision tn has been taken.

2.3. Optimization of Thinning Type

Simultaneous optimization of thinning type with whole stand simulation models has been incorporated by including a diameter distribution estimate throughout standard diameter distribution prediction methods (parameter prediction or parameter recovery methods) which use state variables to define diameter distributions at a given state and stage (Valsta and Brodie, 1985; Torres and Brodie, 1989). However, those predictions are reliable for unimodal and well behaved distributions, but very unreliable for multimodal or truncated diameter distributions, typical of beech stands. In these cases, the use of the *NG* ratio to define thinning type (Gadow, 1992; Kassier, 1993; Staupendahl, 1999) is very useful since it is independent of the form and continuity of the diameter distribution.

Staupendahl (1999) found that the type of thinning in beech stands can be defined by an interval of values for the *NG* ratio. *NG* values greater than unity represent a thinning from below while *NG* values lower than unity represent a thinning from above. Evidently, there is an infinite range of *NG* values (only few of them are feasible in practice) that can define a thinning to be from below or from above. Hence there is a possibility to find a (feasible) combination of state variables (basal area and number of trees per hectare) defining a specific type of thinning to optimize an objective function. According to Staupendahl (1999) this combination of *NG* ratios does not define the traditional form of a thinning from below (thinning from above), where the smallest (largest) trees are thinned, but a thinning where the average size of the thinned trees (measured in terms of the quadratic mean diameter) is smaller (larger) than the average size of the trees before thinning.

In order to optimize *NG* values it is necessary to find the feasible combinations of state variables for a given state (stand condition). This range of values can be defined just from the definition of the *NG* ratio, which is meant to be the ratio of number of stems removed (N_R) to the number of stems before thinning (N), divided by the ratio of basal area removed (G_R) to the basal area before thinning (G). Since basal area is just a linear combination of number of stems and quadratic mean diameter (Dq), *NG* can be redefined as the ratio between the square of the quadratic mean diameter before thinning and the square of the quadratic mean diameter of the removed stems as shown in the following equation.

$$NG = \frac{N_R/N}{G_R/G} = \frac{N_R/N}{kN_R Dq_R^2 / kNDq^2} = \frac{Dq^2}{Dq_R^2} \qquad [9]$$

If all the trees in the stand had the same size, *NG* should be equal for different types of thinnings. This is not true in real life, and different *NG* ratios will represent different types of thinnings. For example, assume any diameter distribution and consider a thinning from below. This thinning will yield a quadratic mean diameter of the removed trees lower than the quadratic mean diameter before thinning. Hence *NG* must be greater than one, and somehow has to have an upper bound (*UB*) defined by physical conditions (state variables).

$$\approx UB \geq NG = \frac{Dq^2}{Dq_R^2} > 1 \qquad [10]$$

How close *NG* is to unity depends on the variance of the diameter distribution. The smaller the variance, the closer the *NG* ratio can approximate to unity. These bounds are important for searching optimum *NG* values representing a specific type of thinning. Otherwise, *NG* optimization can yield an *NG* ratio representing an impossible combination of trees to be thinned or an undesirable type of thinning. The upper bound (*UB*) in a thinning from below can be obtained with a simple analysis of the *NG* relationship. Considering [9], the *NG* relationship can be rewritten as:

$$NG\left(G_R/G\right)N = N_R \qquad [10.1]$$

Since N must always be greater than N_R, we can state

$$NG\left(G_R / G \right) < 1 \Rightarrow NG < G / G_R \qquad [10.2]$$

Using similar reasoning, it can be demonstrated that the bounds for a thinning from above are:

$$N_R / N < NG = \frac{Dq^2}{Dq_R^2} < 1. \qquad [10.3]$$

Once the feasible range of *NG* values has been defined, it is possible to optimize *NG* at each state by nesting another network describing different paths resulting from state variable combinations. This new network can be nested in the traditional *DP* approach. Unfortunately, however, it increases the size of the problem. However, another strategy is to optimize *NG* at each state by using the PATH algorithm (Paredes and Brodie, 1987). This can be implemented considering that at each state there is a vector of thinning alternatives (each one defined by different *NG* values and considering that basal area is the control variable and number of trees is the state variable) which produces a return and a different combination of after thinning conditions (y_n vector). Consider Fig. 3; a two-stage traditional *DP* network (under the neighborhood representation) is shown with one initial condition y_{n-1}. The stand is projected to the second stage to reach state conditions x_n. At this stage, three thinnings of the same intensity (same basal area *G*) are simulated, each one with different residual numbers of trees per hectare, which yield different *NG*ratios.

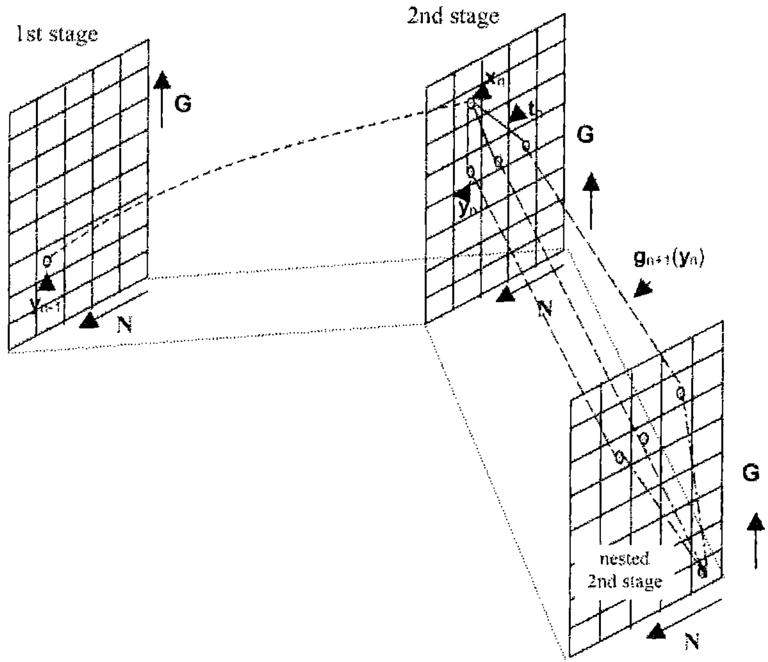

Figure 3. Nested Network in the traditional DP optimization approach

At this point a second optimization is performed (in a nested second stage) in order to decide which *NG* ratio is the best one to maximize total future yield. This optimization is made with the PATH algorithm through the following basic functional equation:

$$f_n(\mathbf{y}_n) = \max_{\mathbf{t}_n} \{r_n[\mathbf{t}_n, \mathbf{g}_{n+1}(\mathbf{y}_n)]\} + f_{n-1}(\mathbf{y}_{n-1}) \qquad [11]$$

In this function $r_n[\mathbf{t}_n, \mathbf{g}_{n+1}(\mathbf{y}_n)]$ represents the net revenue of total future yield and thinning at stage *n* to be algebraically added to the previous value of the functional equation. In this way a simultaneous optimization of type of thinning can be done either by increasing the range of feasible *NG* values to be evaluated by (6) or by considering the type of thinning as a third state variable (Torres y Brodie, 1990).

3. Results and Discussion

The DP network was validated with different values for the grid size defined by the state variables. Class widths less than 1.5 m^2 for basal area and less than 15 for trees per hectare yielded very similar objective function values. Hence the network was set to these upper bounds, assuming that solutions obtained by this size of the grid would approach those obtained from a continuous formulation of the problem.

Optimal thinning schedules can be obtained with different initial stand conditions, economic information (product price and input costs), residual basal areas, thinning types and objective function formulations. Hence several simulations were run to define the trend of *NG* values under different conditions. For all simulations the initial stand conditions were: age=45 years, basal area=27 m^2, number of trees per hectare=2400 trees and site index=35 meters. These values represent average conditions for a young stand of the species growing on a good site in the area of its geographical distribution (Fig. 1).

It is well known that when maximizing any economic criteria along the rotation, interest rate reduces the rotation age and requires heavier thinnings at the beginning of the rotation. For the case of beech (*Fagus sylvatica* L.) the optimal rotation age with no interest rate is about 130 years, with interest rates ranging between 1%-4%, the rotation age reduces to 120 years, between 5%-7% it reduces to 115 years, and from 8-12% the optimal rotation age is only 110 years. Fig. 4 presents the optimum residual basal areas for interest rates of 2, 8 and 15 percent.

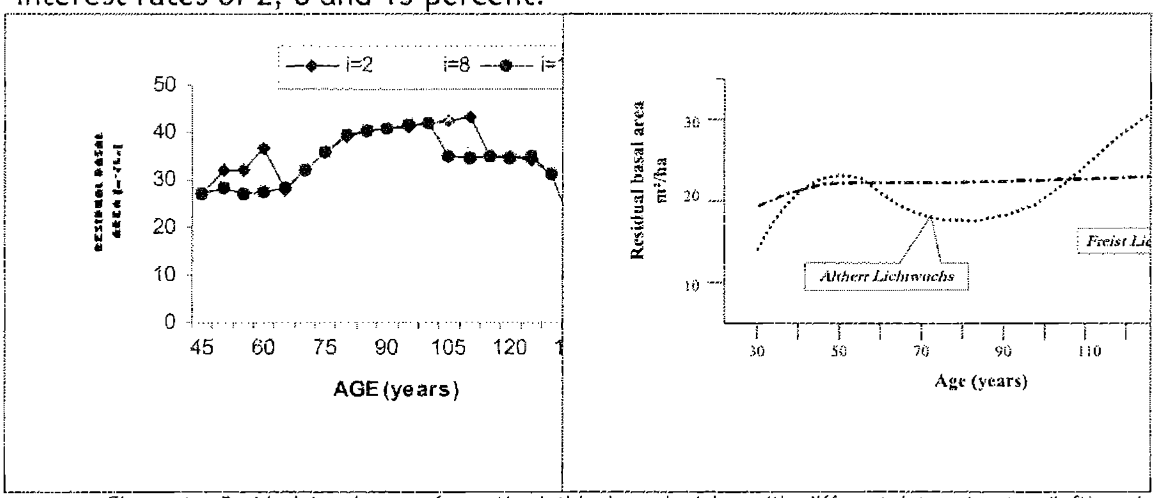

Figure 4. Residual basal areas for optimal thinning schedules with different interest rates (left) and residual basal areas recommended by Freist (1962) and Altherr (1971).

A result that looks interesting is the fact that optimal thinning schedules yield similar ranges of residual basal areas for different interest rates. Figure 4 (left) shows that the optimal residual basal area between 80 - 105 years is close to 40 square meters. At the end of the production period the optimal residual basal area is around 35 square meters per hectare. These basal areas are significantly higher than those recommended by Freist and Altherr (Fig 4, right). This discrepancy is explained by the fact that the price-size gradient has not been accounted for in the DP formulation. Low residual basal areas produce lower volumes per ha, but bigger tree dimensions at an earlier age. Furthermore, the risk of wood discolouring increases with increasing tree age. Further studies are required to account for these important facts.

Effect of Interest Rate on NG Ratio

The effect of the interest rate on the *NG* values is shown in Fig. 5. At the beginning of the rotation thinnings are heavy and directed at the removal of medium size trees. Then follows a period of no thinning between 70-85 years, possibly since this period seems to provide the age interval of the largest growth rate. NG ratios are high towards the end of the rotation when thinnings of small trees are preferred.

As the interest rate increases, the thinnings are becoming heavier sooner and more from above. In all cases similar residual basal areas are kept until the age when the heavy thinnings from above begin. These heavy thinnings are performed sooner as the interest rate increases in order to recover additional gains sooner, thus reducing the effect of the interest rate.

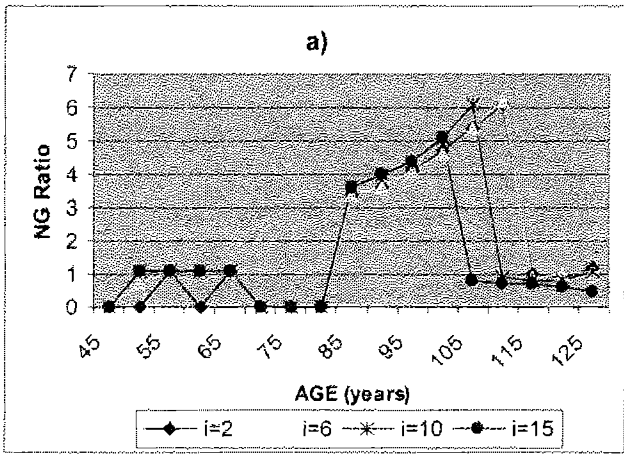

Figure 5. Residual basal areas for optimal thinning schedules with different interest rates (left) and residual basal areas recommended by Freist (1962) and Altherr (1971)

Effect of Production Objectives

$$Price / m^3 = 20 \cdot e^{0.04 \cdot DBH}$$

The type and weight of thinnings are silvicultural tools used to define the characteristics of the product at the end of rotation. Theory shows that in order to obtain large trees at the end of rotation, heavy thinnings must be performed during the early years. Optimal thinning schedules for beech show that valuable trees for sawn wood are obtained with heavy thinnings of medium size trees at the beginning of the rotation and one or two heavy thinnings from above at the time when the maximum growth rate is reached (Fig. 6). The distribution of the thinning type is similar to that defined when optimizing the production of pulpwood but directed to larger trees than the trees thinned when pulpwood is planned to harvest.

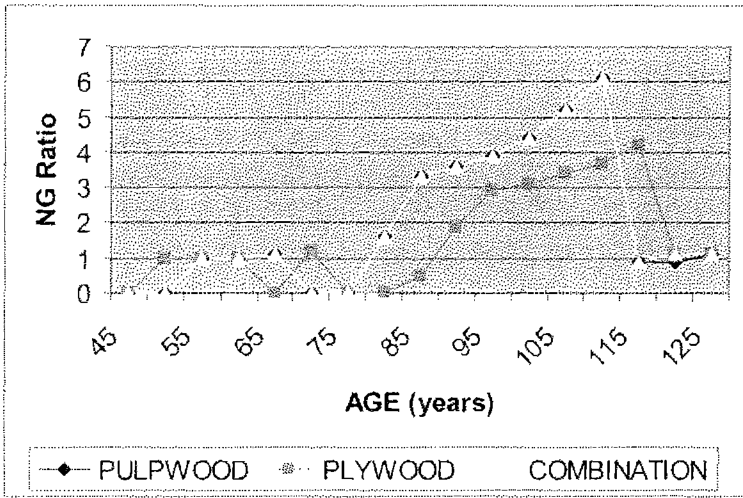

Figure 6. *NG* ratios for optimal thinning schedules with different production objectives

Optimal *NG* schedules under the assumption that logs can be sold to the best price (according to grading) follow a trend similar to that for pulpwood. The difference is in the intensity of thinnings. At the end of the rotation thinnings from above are more heavy than those for pulpwood production.

Effect of Initial Conditions

The optimal thinning weight and type depend on initial stand conditions. Four additional simulations were run assuming different initial density conditions at age 45. Two of them were respectively 20% and 40% lower than the standard initial condition (basal area = 27 m^2/ha and 2,400 trees per ha). The other two were 20% and 40% higher than the standard initial condition. Trends of *NG* ratios are shown in figure 7.

The trends shown by the optimal thinning schedules proof that as the initial conditions are more crowded it is optimal not only to increase the density of thinned trees but also to direct the thinning to medium and larger trees. On the contrary, given low density initial conditions it results optimal not only to postpone the thinnings, but also to thin smaller trees during the period of maximum growth rate.

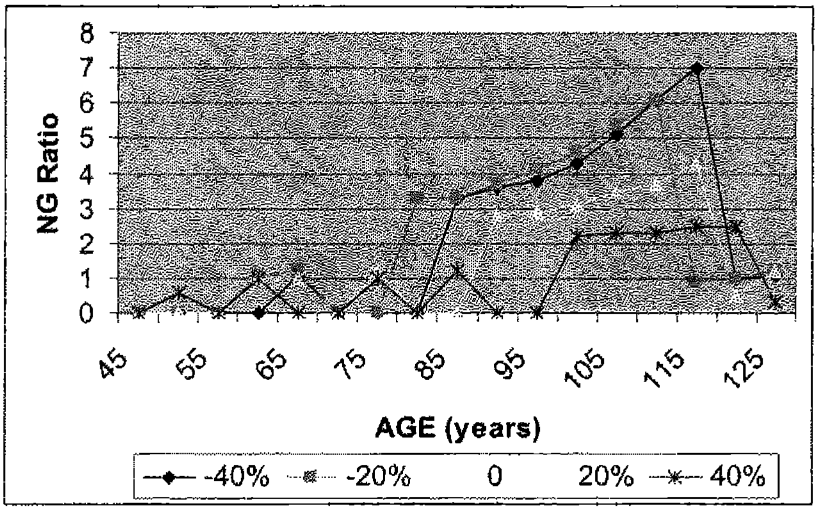

Figure 7. *NG* ratios for optimal thinning schedules with different initial conditions.

Conclusion

The purpose of this paper was to present a systematic search method for identifying optimum silvicultural regimes for beech forests in Europe. This is to our knowledge, the first application of Dynamic Programming to this particular problem. The study has shown that whole stand growth models for beech need to be improved. Additional observations are required for the extreme site and treatment conditions (e.g. very low stocking);that thinnings can be described by simple parameters and that NG ratios are useful for defining thinning types;that the method of dynamic programming, and especially the PATH algorithm, are very effective for identifying optimum treatment schedules for a range of objective functions and constraint conditions;that further investigations are needed to include the effects of tree size and quality attributes on timber price.

The authors had to make simplified assumptions, but this has shown the lack of an empirical data base which will allow an exhaustive search in the future. It is hoped that in time these deficiencies will be overcome. The use of NG ratios to define the thinning type is very useful tool within this optimization framework which not only provides a practical sense about the type of thinning to be implemented, but also does not carry the disadvantages of traditional diameter distribution prediction approaches since it is independent of the diameter distribution. The approach can be replicated from traditional yield table information and once the model is built can be adapted to any economic and stand condition to define practical thinning schedules. As shown in this paper, optimization results derived from the model follow expected trends **No!!!** and may be used as a basis for practical silvicultural recommendations.

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