Evaluating Risk in Forest Planning Models

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The purpose of forest scenario modelling is to evaluate multiple management options and to answer what if questions relating to a particular development path of a given forest. Forest scenario planning can reduce uncertainty in management outcomes by anticipating the future in a systematic way, thus reducing the likelihood of unexpected events. It can also improve the chance that future developments will agree with specified objectives. Numerous techniques have been proposed for generating and evaluating scenarios of forest development. Some of the techniques are limited to applications in simple forest production systems while others are suitable for any type of forest management, including individual tree selection systems. Risk is defined as the expected loss due to a particular hazard for a given area and reference period. An expected loss may be calculated as the product of the damage and its probability. Risk analysis, risk evaluation and risk management are formal procedures for quantifying, evaluating and managing risk within a given hazard domain. Applications of risk analysis in forest scenario planning are rare and greater emphasis needs to be placed on hazard prediction. The aim of this contribution is to discuss some aspects of risk analysis, including examples of specific modelling tools. In a forest planning model risk can be considered in the form of specific constraints limiting the total risk in a given time period. Expected hazards can be used to exclude certain risky alternatives and finally, risk can be calculated and used to reduce the value of an objective function coefficient.

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1 Introduction

For forestry planning purposes one must be able to produce accurate descriptions of future management activities. This task is relatively easy to accomplish in even-aged forests with a specified lifetime. The development follows a succession of cutting cycles, usually defined by a rotation. The repetitive life cycles of an even-aged production forest are characterized by thinnings, prunings, periodic clearfellings and re-plantings. The task of projecting the development of a *continuous cover forest* which is characterized by selective harvesting of individual trees and by a kind of silviculture appropriately known as *forest gardening*[1)] is more difficult. The forest remains in a state of undefined age, oscillating about a specified level of growing stock (Fig. 1). The modifications of forest structure caused by harvesting operations are difficult to predict, there is no distinction between thinnings and final harvests and age-based measures of forest production and valuation, such as the *mean annual increment* or the age-based *net present value*, are not appropriate.

Numerous techniques have been proposed for generating and evaluating forest management schedules and forest development scenarios. Some of the techniques are limited to the use in even-aged forests while others are suitable for any type of forest management, including continuous cover systems. The variety of planning models is great, but applications of risk analysis are surprisingly rare in forest planning. The aim of this contribution is to discuss some aspects of risk analysis, including examples of specific modelling tools. Forest management, in contrast to industrial safety management, is affected by exogeneous hazards that cannot be controlled and a practical approach which can be used in forest planning models is to estimate age-dependent cumulative survival rates for a given set of hazard factors.

2 Risk Analysis

Before discussing specific methods, it appears to be necessary to agree on the terminology in connection with risk assessment and evaluation. *Damage* is loss expressed in monetary terms. The *damage potential* includes all the potential threats within a given *hazard domain*. *Risk* has been defined as the expected loss due to a particular hazard for a given area and reference period (United Nations 1992). An expected loss is the product of the *damage* and its *probability*. Example: The probability of a spruce tree being damaged by wind increases with increasing tree size (Rottmann 1986; Thomasius 1988), whereas the damage is the result of an increase in the harvesting costs and a decrease in the log price (Gehrmann 1975; Waldherr 1997)[2)]. *Risk assessment* is a formal procedure for quantifying risk with regard to the damage potential including all the possible threats within a given hazard domain. Example: Evaluation of all the potential hazards (the *hazard chain*) during the life of a spruce stand (Otto 1994). A *risk evaluation* is concerned with the economic evaluation of potential threats and benefits. Finally, *risk man-*

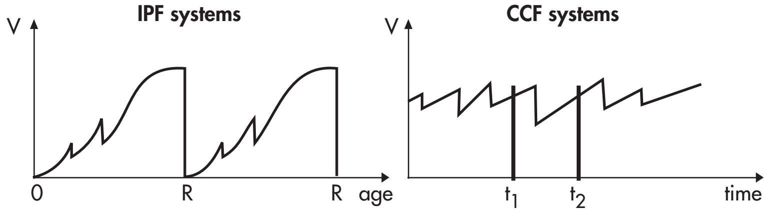


Fig. 1. Simplified representation of the development of timber volume over age/time in a planted production forest with intensive silviculture (IPF) and a continuous cover forest with selective harvesting (CCF).

Table 1. Classification of technical risks in Switzerland (after Hollenstein 1997, p. 67).

	Accident	Major accident	Catastrophy		
Dead people	4	20	100	500	2500
Damaged ecosystem (km^2)	1	10	100	1000	10000
Discounted cost (mill SFR)	20	80	400	2200	10000

agement includes strategies and actions for reducing risk (Hollenstein 1997).

Thus, risk is not the same as uncertainty. Uncertainty presents a risk if the result of the uncertainty is an expected loss. Applications of risk analysis in forest planning are very rare and approaches are presented in this paper which may be applied when analysing risk in forest planning. It is important to delineate the system and to identify potential hazard factors. More difficult is the assessment of hazard factor probabilities because forest management, in contrast to industrial safety management, is affected by exogeneous hazards that cannot be controlled. A practical approach which can be used in forest planning models is to estimate age-dependent cumulative survival rates for a given set of hazard factors.

2.1 Delineating the System

The subject of a risk analysis is a given system which includes valuable objects that might be lost or damaged. The system needs to be defined in terms of time and space and the seriousness of the expected hazard. Within the scope of forest planning, the scales of time and space may range from a year to a century and from an individual tree to an entire forest region.

The degree of seriousness of the expected damage is a matter of definition. An example of a classification scheme is the one which has been developed for technical risks in Switzerland (Table 1). Valuable objects such as trees, buildings or forest roads may be affected by natural hazards, such as gale force winds, fire or floods.

Short- to medium-term tree-based risk analysis is essential for economic evaluation of removal decisions in selective thinning models for continuous cover forests (Albert 1999). Medium-term stand-based risk analysis is required in areas affected by specific abiotic or biotic hazards affecting particular types of stand structure, species or age class. A typical system delineation in medium-term forest scenario planning is a major loss expected within a decade on a compartment level. Long-term risk analysis for larger forest regions is concerned with the choice of tree species and silvicultural system.

2.2 Identifying Potential Hazard Factors

The analysis of the hazard potential evaluates the exposure of valuable objects to certain kinds of damage that might occur. The dangerous process is identified, without considering the extent of the possible damage. The various qualitative techniques include a variety of checklist methods which are based on similar principles[3)]. The checklist methods produce a list of potential hazards and critical system elements using specific terms that define deviations from a normal state. The disadvantage lies in the subjectivity of the assessments and the possibility that the analysis is not exhaustive. The different risks are not quantified, but arranged in some systematic order to see if safety objectives are being violated. Critical components or system states and their interactions with the environment are identified. An example of a checklist approach is the list of potential hazards that might occur during the life of a spruce stand (Fig. 2).

An important factor influencing risk is the type of forest management. For spruce forests Kramer (1988) could show that small crowns and high height/diameter ratios are associated with high risks of windthrow and snow damage. These observations were refuted by Richter (1996, 1998)

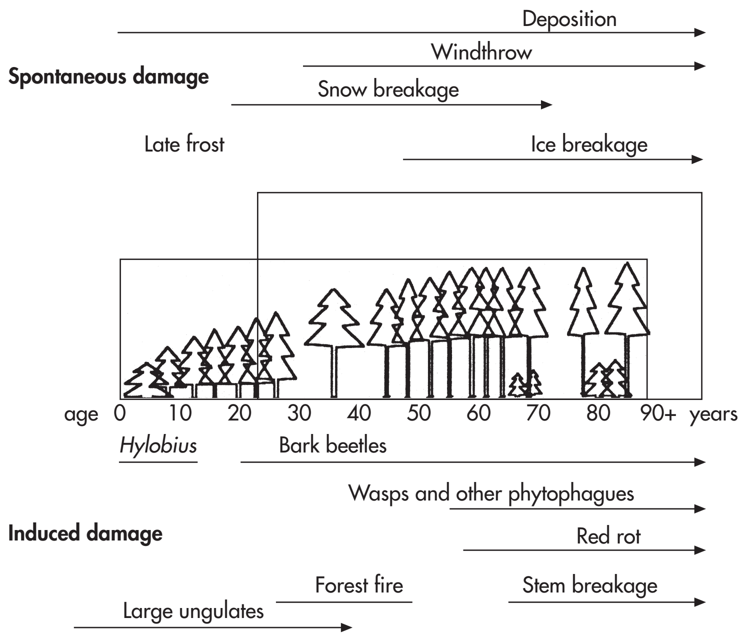


Fig. 2. Example of the potential hazards during the life of a spruce stand (Otto 1994).

who found that the bigger trees with large crowns were damaged more often.

Among the most common methods for identifying potential hazard factors in industrial applications are the fault tree analysis (FTA) and the event tree analysis (ETA). *Fault tree analysis* allows quantitative statements to be made about the probability of failure of certain system elements, even in the absence of statistical evidence. An application evaluating the effects of acid rain in the Adirondacks was presented by Hoffmann (1994). The information derived from an FTA can be used in an *event tree analysis* which is based on a bottom-up approach, starting with an initiating event.

It appears that, although extensive experience about various kinds of damage to forest trees exists, reliable models for predicting the potential hazards related to forest management are rare. The identification of potential hazard factors is thus heavily dependent on expert knowledge.

2.3 Assessing Hazard Factor Probabilities

A potential hazard presents a risk if it occurs with a probability greater than zero and if its occurrence will cause damage to a valuable object. The probability of occurrence of a given hazard factor may be defined by a probability distribution depicting the frequency of certain events on the basis of previous observations (Fig. 3).

The system is tolerant against wind, flooding or drought within a given range of wind speed or rainfall. Outside this range, damage may occur. The amount of the damage increases while the probability of occurrence decreases with increasing distance from the mean value. It is possible to derive probability distributions for wind speeds or amounts of rainfall per unit of time from the official metereological stations. König (1995) was able to relate the hazard potential in spruce stands to a number of site conditions, stand attributes, weather conditions and types of forest management while Kellomäki and Peltola (1998) predict mean wind flow and gustiness based on wind tunnel data and bending moments required to overturn a tree from experiments with trees pulled

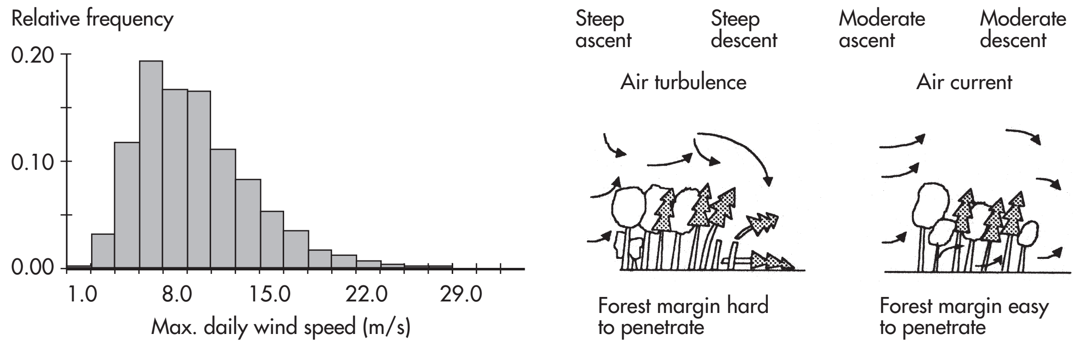


Fig. 3. Left: empirical distribution of maximum daily windspeeds (König 1995); right: the effect of the forest margin on wind damage (Otto 1994).

over using a winch on a range of soil types.

Risk has been defined as the expected loss due to a particular hazard for a given area and reference period. Disregarding the cost of capital, the *expected loss* (*r*) may be calculated as the product of the *damage* (*s*) expressed in monetary terms and its *probability* (*p*), $r = s \cdot p$.

2.4 Estimating Survival Rates

Kouba (1989) used the following form of the Weibull function for modelling spruce forest survival, assuming a variety of hazards and their cumulative effect:

$$R(t) = 1 - F(t) = e^{-\lambda \cdot t^{\alpha}} \tag{1}$$

with R(t) = survival rate and t = forest age. The parameters α and λ can be estimated on the basis of two values of R and t using $\alpha = \ln\{\ln(R_1) / \ln(R_2)\} / \ln\{t_1 / t_2\}$ and $\lambda = -\ln(R_2) / \{t_2^{\alpha}\}$, however, this approach is not likely to be reliable. When more observations are available, regression techniques should be used to obtain the parameter values.

In this fashion Kouba (1989) derived survival estimates for spruce forests considering empirical evidence associated with establishment, snow damage and windthrow. His parameter estimates are presented in Table 2.

The second column in Table 2 gives the probability that stand establishment does succeed, which is valid only for a certain time after planting during which seedling survival is controlled. The third and fourth columns give the probability that snow/wind damage has not occurred, or has not destroyed the forest.

Introducing an asymptotic elimination rate c, the following equation can be used to model survival probability over age for an arbitrary hazard factor:

$$R(t) = c \cdot e^{-\lambda \cdot t^{\alpha}} + (1 - c) \tag{2}$$

The occurrence of a hazard, such as a strong wind, damages only part of a forest rather than completely destroys it. Therefore, the term survival probability is not considered very appropriate by statisticians who prefer to estimate the probability of occurrence of a hazard during a given period of time. In this context, we can interpret $R(t)$ to represent the share of a forest area which has survived the specified hazard up to a given age.

Table 2. Weibull parameter estimates for modelling survival rates in spruce forests after Kouba (1989).

	Establishment	Snow	Wind
R_1	0.333	0.990	0.90
R_2	0.100	0.001	0.20
t_1	1	19	100
t_2	2	90	200
Weibull α	1.0663	4.2002	4.2002
Weibull λ	1.09961	4.3E-08	3.5E-10

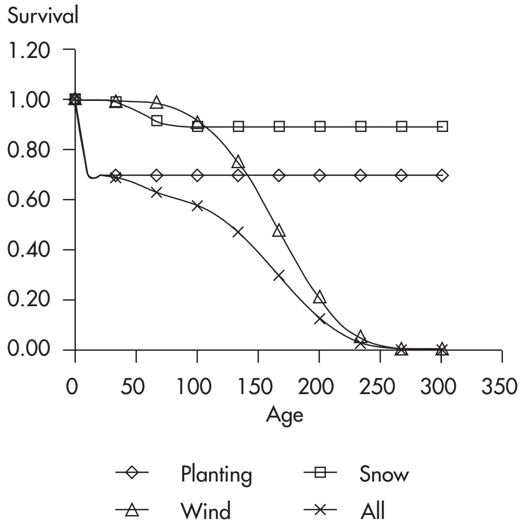


Fig. 4. Survival over age for three hazard factors in a spruce forest (after Kouba 1989).

The graphical representation of the relationship between forest age and survival is shown in Fig. 4, based on the data in Table 2. Considering the three hazard factors *planting*, *snow* and *wind*, the combined survival rate up to the age t, $R_{all}(t)$, is a function of the individual survival rates, as follows: $R_{all}(t) = R_{planting}(t) \cdot R_{snow}(t) \cdot R_{wind}(t)$

where

$$R_{planting}(t) = \begin{cases} e^{-\lambda \cdot t^{\alpha}}, for\, t \le t_0 \\ e^{-\lambda \cdot t_0^{\alpha}}, for\, t > t_0 \end{cases}$$

and where t_0 is the number of years after planting during which period establishment-related survival is checked.

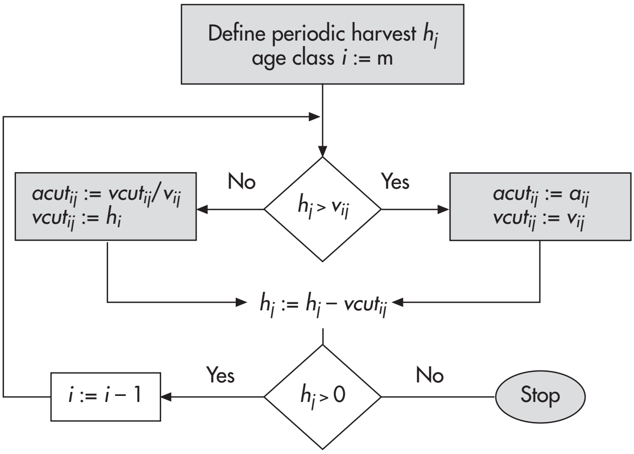
Very few data are available about extreme events, such as a soaking rain followed by a gale force wind or a fire during a dry spell associated with strong winds. The uncertainty about such rare events is high and expert opinion is often used to complement empirical observations using Bayesian methods, fuzzy logic or *Delphi* techniques. Numerous applications of expert system technology for assessing environmental risk factors have been reported (see for example Schmoldt 1987; Rust 1988; Messing et al. 1989; Hamilton 1989; Guay et al. 1992; Ball 1997).

3 Harvest Scheduling and Scenario Techniques

To successfully maintain an industry based on timber products, forest planning must ensure that there are always stands at the right stage of development and in sufficient number – including stands in remote areas not owned by the company – to yield the desired product mix coming from the forest. This problem has been addressed using a variety of methods which are often referred to as harvest scheduling. The purpose of harvest scheduling, and in a broader sense that of forest scenario modelling, is to evaluate multiple management options and to answer *what if* questions relating to a particular development path of a given forest. Forest scenario planning can reduce uncertainty by anticipating the future in a systematic way, thus reducing the likelihood of unexpected events. It can also improve the chance that future developments will agree with specified objectives.

3.1 Methods Suitable for Simple Forest Management Systems

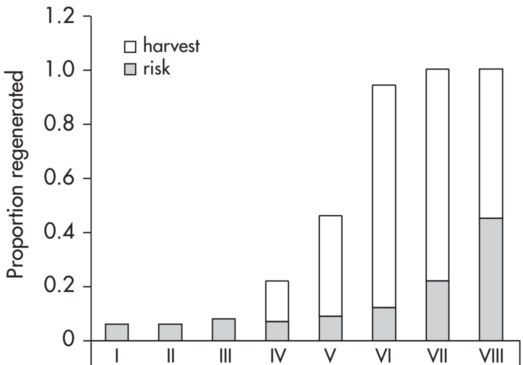
Quite useful, though not very sophisticated, are scenario methods based on age class simulation. The forest area is subdivided into m age classes each covering an area of a_{ij} ha in the jth felling period (i = 1..m; j = 0..n). The available timber volume in the ith age class is equal to v_{ij}, and the planned total harvest volume for the jth felling period is h_j. The algorithm presented in Fig. 5 may be used to simulate the effect of a given harvest level on the development of the age class distribution of a regional forest resource. Obviously, the method involves considerable aggregation over growing sites, forest types and management regimes, and the predictions have to be interpreted with the necessary caution. However, an age-class simulation is often the only feasible way to predict the dynamic development of a forest resource for large timber growing regions.



For each harvest period j, do:
For each age class i, starting with the oldest one, and while $h_j > 0$, do:
a) calculate the available growing stock volume v_{ij};
b) if $h_j \geq v_{ij}$, then harvest the entire growing stock available in age class i; else, harvest only h_j m^3;
c) subtract the volume harvested from h_j

Fig. 5. Algorithm for age-class simulation with flowchart (left) and abbreviated pseudocode (right). a_{ij} = forest area available in age class i (i = 1..m) and period j (j = 1..n); v_{ij} = timber volume available in age class i and period j; $vcut_{ij}$ = timber volume harvested in age class i and period j (m^3); $acut_{ij}$ = harvested area in age class i and period j (ha); h_j = specified harvest volume for period j (m^3).

In any forest there is a proportion of the growing stock which is expected to be eliminated by some natural hazard and a proportion which is available to be harvested in the normal fashion, i.e. when the stands have reached rotation age. Fig. 6 shows the proportions of hypothetical 20-year age class areas which are a) beyond management control, i.e. which are expected to be eliminated by some hazard (lower part of column) and b) available to normal management, i.e. which may be harvested. The harvest scheduling problem that needs to be solved is how much to cut in the different age classes, given a suitable objective function and relevant constraints. Numerous applications of mathematical programming dealing with this particular problem have been published (see for example Buongiorno and Gilles 1987).



	I	II	III	IV	V	VI	VII	VIII
harvest	0	0	0	0.15	0.37	0.82	0.78	0.55
risk	0.06	0.06	0.08	0.07	0.09	0.12	0.22	0.45

Age class

Fig. 6. Proportions of 20-year age class areas which are expected to be eliminated by some natural hazard ("risk") and proportions which are available to be harvested ("harvest"), after Kouba (1989).

Another method for generating a scenario of forest development using highly aggregated information is based on a stochastic process and involves the use of *area change models* which predict transitions of forest age class vectors through time. These models have been used especially in Japan (Konohira and Amano 1986) and in Europe (Kurth et al. 1987; Kouba 1989). One of the most prominent applications is Suzuki's *Gentan* model (Suzuki 1971; Blandon 1985). The transition probabilities are not independent of the current age class vector and this seems to be one of the main problems associated with the use of area change models.

3.2 Methods Suitable for Any Forest Management, Including CCF Systems

A managed forest typically consists of a discrete number of geographical units known as *compartments*. Each compartment develops over time in response to forestry operations such as plantings, prunings or removals of varying type and intensity. If appropriate tools are available, the characteristics of a given development path, such as the terminal growing stock, the silvicultural costs, the windthrow hazard and other risks can be calculated. A *scenario model* embraces all the possible development paths of all the compartments within the forest and a particular *scenario* of forest development represents a specific combination of treatment schedules for the different compartments within a specified forest area. The aim of forest scenario modelling is to find the optimum combination of treatment schedules over all compartments, including risk. Various techniques have been developed to achieve this objective, usually without reference to risk. The most popular method is constrained optimization which has been used for about three decades, after the basic structure was developed by Ware and Clutter (1971) which later became known as the Model I:

$$\max Z = \sum_{i=1}^{I} \sum_{j=1}^{J_i} c_{ij} X_{ij}$$

subject to

$$\sum_{i=1}^{I} \sum_{j=1}^{J_i} a_{ijpt} X_{ij} \begin{Bmatrix} \le \\ \cong \\ \ge \end{Bmatrix} M_{pt}\ , \forall p,t$$

$$\sum_{j=1}^{J_i} X_{ij} = A_i, \forall\, i \quad \text{and} \quad X_{ij} \ge 0$$

where

I = number of compartments

J_i = number of treatment schedules for compartment i (i = 1..I)

c_{ij} = objective function value

X_{ij} = area of compartment i managed according to treatment schedule j (ha or proportion of area; j = 1..J_i)

a_{ijpt} = amount of item p produced or consumed per ha in period t

M_{pt} = total amount of item p produced or consumed in period t

A_i = area of compartment i

The optimization models have in common that a discrete number of treatment schedules are generated for a given set of compartments, that each schedule is associated with a vector of input and output quantities over time and that the decision maker is interested in the aggregated output values over all compartments and treatment schedules. Various solutions have been offered for similar applications of linear programming to timber harvest scheduling[4)]. Pukkala and Kangas (1993) present a practical optimization method which is based on an additive utility function. The relative weights of the different objectives are obtained using $n(n-1)/2$ pairwise comparisons based on the method proposed by Saaty (1980; see also Steinmeyer and Gadow 1994).

Usually, when considering risk in an objective function coefficient, assumptions based on estimates of reduced timber selling prices or increased harvesting costs can be made. Sometimes, outcomes are linked to certain risk categories, assuming that a given risk category is associated with a specific hazard probability. An example is presented by Waldherr (1997): the average timber price for spruce logsort *H4* under normal conditions is equal to 104.37 DM per m^3 while the price for wind-damaged timber is 61.43 DM per m^3. For a given *risk category (II)* the probability of damage is assumed to be 20%. Thus, the per-tree risk equals 0.2(104.37 – 61.43) = 8.59 DM. Such or similar kinds of information (c.f. Mai 1999) could make harvest planning and scenario modelling more realistic.

4 Discussion

Risk can be considered either in the form of a constraint limiting the total risk in a given time period or as a "filter" excluding certain risky alternatives in a harvest scheduling or scenario model. When developing management alternatives, for example, those options that are known

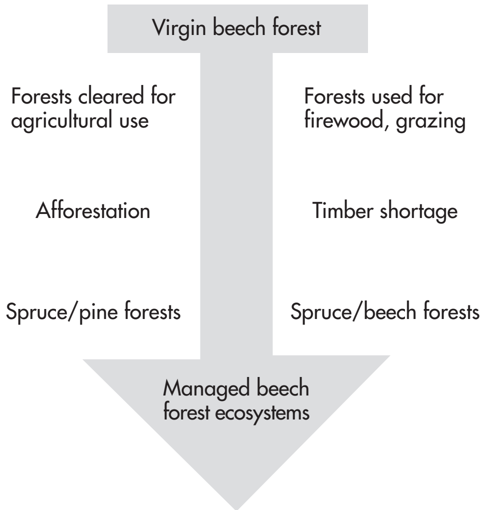


Fig. 7. Historical perspective of the beech forest ecosystem as an attractor influencing forest development (Palmer 1994).

to be associated with a high hazard potential, e.g. high stand densities or severe thinnings, can be excluded. Rules based on experience using indices of stability, such as mean height/diameter ratios, may be applied to eliminate risky options. The most obvious approach would be to consider risk as a cost factor which reduces the value of an objective function coefficient. Neither of these methods appears to have been used in forest planning.

The classical models of forest development are based on scenarios that evaluate alternative timber harvest strategies and their effect on the future development of the resource. The scenarios derived from harvest scheduling models are useful when the forestry activities are limited to operations that generate timber output, such as clearfellings. They are of limited use in forest management situations where operational scenarios are required that may include a great variety of economic benefits and environmental effects that have to be considered simultaneously. Typical constraints are available labour units or machine hours or a minimum share of young stands which are more effective in absorbing excess nitrogen deposition (Rothe et al. 1999). Of particular interest in Central European forest scenarios is the beech forest ecosystem which acts as an attractor[5)] of forest development (Fig. 7).

Harvest scheduling has always been a central issue in forest management, but harvest scenarios do not necessarily produce feasible plans. Felling volumes are often specified and, by some magic, assumed to be available at the prescribed time. Forestry is affected by numerous hazards, many of which cannot be controlled.

To ensure that scenarios are feasible, greater emphasis needs to be placed on models that predict future forest management activities and the effects of such activities on the required input of essential resources and on the output of certain goods and benefits. Accordingly, the chosen technique of harvest planning and scenario modelling should be adapted to the type of forest management with due regard of potential hazards and risky alternatives.

Notes

1 A term derived from the French *jardinage*.
2 This is not always true, e.g. when the tax rebate that can be claimed after wind damage exceeds the loss.
3 e.g. the *Failure Mode and Effect Analysis* (FMEA) investigates system components and assesses critical components and interactions with the environment. The *Hazard and Operability Study* (HAZOP) aims at optimizing the reliability of production systems. The *Zurich Hazard Analysis* (ZHA) classifies all possible events according to their frequency and the extent of the possible damage (Kroeger 1992; Hollenstein 1997) that was caused by wind.
4 See for example Siitonen 1983; Garcia 1991; Lappi 1992; Eid 1993; Peyron 1993; Pesonen 1995; Rodriguez 1996; Hoganson 1996; Hoen 1996.
5 An attractor is a concept used in the study of thermodynamics, referring to a target state which the system will eventually attain, irrespective of its present state. The terminal state is characterized by a high degree of stability and associated low risk. This appears to be true for beech forest ecosystems, although there is some uncertainty regarding the effects of climate change (Lindner et al. 1999).

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