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SCIENCE-BASED FOREST DESIGN

Klaus v. Gadow[1], Chun Yu Zhang[2], Xiu Hai Zhao[3]

[1]*Professor, FFS&FE, Georg-August-U. of G., Göttingen, Germany. Ph./FAX: +49[0]551 39-3471/9787*

[2]*Scientist,* [3]*Professor, Department of Forest Management, Beijing Forestry University, China*

Abstract. Approximately 3000 million ha of the world's forests have been classified as productive, and are subject to some kind of management. Considering their environmental and social importance, the managed forest ecosystems are not receiving as much scientific attention as the few remaining unmanaged ones. This is especially true in the growing urban landscapes where managed forest ecosystem provide a range of important services. Most societies today demand integrated and wide-ranging approaches to forest management that address social, ecological, and economic goals. These demands can be met if simplistic philosophies and unverified doctrines are replaced by new paradigms that require a wider understanding of social demands and natural system dynamics. In theory, involving science directly in the management of a wooded ecosystem appears to be logical, but the practical implementation of this idea is not a trivial task. This paper presents a theoretical framework for the science-based management of a forested landscape that includes three key elements: forest design, research and demonstration and harvest event analysis. This framework is introduced, explained by means of examples, and supported by concrete evidence. The paper is based on an updated version of Gadow (2005) (Gadow 2005. *Science-based forest design and analysis.* P. 1-19 in Proc. FORCOM 2004. Japan Society of Forest Planning Press. Utsonomiya University), and it is not intended as a manifest, but as a contribution to a much-needed discussion about forest management as a scientific discipline.

Keywords: survival, growth and yield, relative spacing, self-thinning

1 Introduction

Forests are estimated to cover almost 30 percent of the continental surface area of the world. They represent a remnant wilderness of high recreational value in densely populated societies, a threatened natural resource in some regions and a renewable reservoir of essential raw materials for the wood processing industry. An area of approximately 3000 million ha, or 23 percent of the continental surface area, has been classified as productive forest (Solberg, 1996). Most of this area is managed under some type of rotation forest management system. Continuous cover forest management systems, which are characterized by selective harvesting, uneven-aged structures and the use of natural regeneration, are most frequently found in densely populated industrialized regions where forests represent a last wilderness, that is not only used commercially, but also for outdoor recreation and other non-commercial purposes.

During the past 200 years, the scientific discipline known as forest management has developed a rich assortment of methods for ensuring the sustainable use of the forest resources. Technical developments and greater complexity of decision-making have resulted in an increasing number of disciplines joining the forestry teaching and research institutions, such as forest genetics, forest biometrics, forest climatology or forest policy. The result was a remarkable expansion of the research and teaching activities of the forestry faculties during the second half of the 20th century. More recently, however, several of the basic sciences (e.g. genetics, mathematical statistics, physics, chemistry, political science) have also become involved in forest research. The outcome of these developments is increased specialisation, which has generated many new insights. These very positive developments have often taken the limelight. However, there are also negative effects, including fragmentation of research and loss of a common focus, and a blurred image of forestry as a scientific discipline. Thus, it is important that these challenges are addressed. There is a need for new theoretical concepts that can facilitate and guide the development of coherent approaches in forest research. In view of the enormous practical consequences of forest management, we propose that such a theory should cover three aspects:

a) **forest design**, which refers to the development of a coordinated, spatially explicit design of future forest development;

b) **research and demonstration**, which involves the establishment and analysis of field experiments and the additional use of such experiments in demonstrating the effects of particular treatments to an interested public;

c) **harvest event analysis**, which deals with the preemptive analysis of harvest events and their expected effects.

Because of the long-term consequences of harvest-related modifications of forest ecosystems, we propose that this framework represents a comprehensive approach to sustainable forest management. The three components are complementary and can facilitate the direct involvement of the different scientific disciplines in the design and daily management of a natural resource, such as a forest ecosystem. The ultimate objective of forest research is to generate information that is useful for management. An important objective of forest management, on the other hand, is to utilize all research information that is useful. These two objectives are not always easy to match in a scientific environment that rewards highly specialized investigation.

As the name implies, the purpose of the research and demonstration concept is to gather empirical observations about the resource and at the same time to present useful information to an interested public. Most of the long-term field experiments designed and managed by forest scientists are available for demonstrating the effects of specific silvicultural treatments to an interested public.

A harvest event involves a dramatic modification of forest structure and forest value that cannot be rescinded. Forest density is reduced with associated effects on the microclimate, the ground vegetation and nutrient cycles. Harvest event analysis provides good opportunities for research and teaching by linking the disciplines in a coherent analysis. Evidence of such opportunities was provided in a teaching module entitled "Analysing a Harvest Event," which has been part of the undergraduate curriculum at the University of Göttingen in Germany for a number of years. Harvest event analysis is also useful for management by improving transparency and enhancing professional credibility. Evidence of its usefulness was provided by a particular management system practiced in South African timber plantations.

It is often postulated that forest management should be sustainable, be based on validated research results, conform to acceptable environmental standards, and be transparent to the public. This contribution presents a proposal of how these objectives can be achieved, using the potential of forest design, research and demonstration and harvest event analysis.

2 Forest Design

A forested landscape typically consists of geographical units that are known as stands or compartments. Each stand may follow a variety of management paths through time. A management path is a unique succession of growth periods, interrupted by harvest events and unexpected environmental hazards. Accordingly, at least three processes have to be considered when simulating a management path for the time period t0 .. t1 (Fig. 1): the harvest events (Ei) at time i, the natural growth (ΔWj) and unplanned hazards (rj) in response to the events during the period j.

A harvest event is the only component of forest development that can be controlled, and the effects of specific harvest events can be evaluated within a medium- or longterm context. Each is a part of a chain of activities (Kramer, 1988, p. 186) and the analysis of forest management paths is therefore an important task of forest research. Growth and hazard models are needed to simulate a management path for any arbitrary initial state. But equally essential are quantitative models of future harvest events, which describe the effect of a thinning on forest value and structure.

2.1 Estimating Tree Growth. Scientists involved in the study of forest growth are engaged in developing practical forecasting tools, proposing concepts for effective data gathering, and recognizing fundamental principles of forest dynamics. A growth model implies some generalisation, based on a synthesis of specific case studies. Sometimes, this allows a better understanding of complex interactions between specific population structures and change processes in an ecosystem. Growth models provide an essential scientific basis for the medium- and long-term planning of forest development. They may be developed for different needs and classified according to the level of resolution. The following simplified classification is sometimes used in the literature:

a) Whole stand models are used to describe the development of a population of trees in reaction to specific treatments and site conditions. A Whole Stand Model provides information about means (such as the dominant stand height) and area-based variables (basal area or stem number per ha)[1].

[1]Examples of Whole Stand Models have been presented by García (1984); Wenk et al. (1990); Murray and Gadow (1993); Hui

Figure 1: Schematic representation of a particular management path during the time window t0 .. t1. An arbitrary path is characterized by harvest events (Ei) at time i, and by natural growth (ΔWj) and unplanned hazards (rj) in response to, and between, these events.

b) Representative tree models provide a somewhat finer level of resolution. Trees with similar attributes are grouped and treated as one tree, the Representative Tree. These models are applicable when distributions of tree attributes, such as diameters, are available[2].

c) Individual tree models represent an even finer level of resolution. They describe the growth of a specific tree, usually in response to its competitive status. The competition effect may be described with distance-dependent or distance-independent methods[3].

The density-dependent whole stand models are responsive to changes in site and forest density. The accuracy of projections can be easily evaluated and the specification of different types of harvest events is a simple matter. A density-dependent whole stand model thus combines the advantages of a yield table with those of a high-resolution model. However, its use so far has been limited to monocultures. Multispecies forests require representative tree models or individual tree models. In addition, gap simulators are evolving as a useful modeling tool. An exhaustive description of growth models would distract from the focus of this paper. An excellent review of growth modeling is provided by Ritchie (1999). A widely used, spatially explicit, growth modeling system, which can be used to examine different forest management scenarios, is "OPTIONS". This system is applied in Canada and various regions in the United States by the forest industry and local governments (see Cieszewski et al., 2004a,b; Low et al., 2003; Liu et al., 2009; Mang et al., 2009)

2.2 Estimating Potential Hazards. In ancient times, those who brought bad news often ran the risk of losing their head. This fear seems to exist to the present day. According to Bungartz (2004) companies are usually not very devoted to analysing potential hazards and risks. Due to the long production periods, and the great variety of biological, economic and technical hazards that can influence forest development, the analysis of uncertainty and risk is an important task of forest management. This may appear to be logical, but practical applications of risk analysis are surprisingly rare when compared, for example, to studies of forest growth.

According to the United Nations Department of Humanitarian Affairs (1992), 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 a product of the damage and its probability. Example: The probability of a spruce tree being damaged by wind increases with increasing tree size (Thomasius, 1988). The damage itself (in monetary terms) is the result of an increase in the harvesting costs and a decrease in the log price (Waldherr, 1997). Thus, 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 (Yoshimoto, 2001).

The measurable increase in the average temperature is expected to modify environmental conditions in a variety of ways, with consequences for the forest ecosystems on different sites (Bradshaw et al., 2000; Shaver et al., 2000; Redfern and Hendry, 2002; Räisänen et al., 2004; Bravo et al., 2008). The specific site requirements of the tree species have evolved during an extended evolutionary process and are relatively stable. What complicates any climate-related hazard analysis is the fact that expected climate changes will have diverse effects on the different sites. Generalizations about the competitive potential of the different tree species are difficult, but it is likely that the anticipated climate changes will mostly affect

and Gadow (1993); Hui (1997); Gurjanov et al. (2000); Sánchez-Orois et al. (2001); Vilčko et al. (2003); Cieszewski (2002 ; 2003) ; Corral et al. (2004).

[2]Examples of representative tree models are given by Gadow (1984); Forss et al. (1996); Westphal (1997); Hessenmöller et al. (2001); Schröder et al. (2002); Trincado et al. (2003); Sanchez-Orois et al. (2003); Temesgen and Gadow (2004).

[3]Examples of individual tree growth models are presented by Sterba (1990); Kramer (1994); Stüber (1996); Schübeler (1997); Lee and Gadow, (1997); Schröder and Gadow (1999); Schmidt (2001); Pretzsch (2001); Hessenmöller (2002); Hessenmöller and Elsenhans (2002); Tewari and Gadow (2008); Van Laar et al. (2003); Lee et al. (2004); Albert (2004).

young forests. In forestry, contrasting with agriculture, short-term modifications of production systems are not possible (Lindner, 2000). This has been demonstrated by Reed and Errico (1985, 1986) who evaluate the long-run effects of a fire hazard on long-run timber yields and optimal harvest scheduling.

2.3 Modeling Future Harvest Events. Growth models estimate the development of a forest stand between harvest events. Harvest event models are needed to translate forestry language (e.g. low thinning, group selection) into spatially explicit removal algorithms. These algorithms mimic the expected modification of forest structure, which is compatible with the words that are used to describe a particular harvest event (Albert, 1999; 2002 (153-161)). They are very important elements of simulators, which are used to generate alternative forest management paths [4].

Theoretically, the number of possible paths for a particular stand may be very high. For example, if we assume that only two options, thinning or no thinning, are possible in each one of n years, then the number of paths within a time window of n years is equal to 2^n. Hinrichs (2006) used a method for generating paths, which is based on the maximum density of a forest ($B_{\max}$). A harvest event takes place when the maximum density $B_{\max}$ or a relative density like 90 percent of $B_{\max}$ is reached (Fig. 2).

At the start of the simulation and after each growth period, the simulated density is compared with the maximum permissible density. The number of harvest events, the maximum allowable density during a particular growth period, and the thinning weights may be prescribed. Assuming a constant thinning type, the number of possible paths is equal to:

$$\sum_{i=\min DF}^{\max DF} n(rG) \cdot n(\%B_{\max})^i \qquad (1)$$

where: $\min DF$ is minimum number of thinnings; $\max DF$ is maximum number of thinnings; $n(rG)$ is the number of thinning weights; and $n(\%B_{\max})$ is number of maximum densities.

A path is only accepted if it remains within the allowed management space for the entire duration of the time window. Because of practical constraints, the number of paths is usually much less than implied by eq. (1).

2.4 Forest Design. The design of a forested landscape is an active process, which evaluates the spatially explicit effects of human activities on future developments. An accepted theoretical basis for any arbitrary landscape is the Multiple Path Model, which assumes that a forested region is made up of spatial units known as stands. The task of designing the development of the landscape is simply to find the optimum combination of management paths in the different stands. Among the often-great number of possible forest designs, we select the one that maximizes some utility.

It is possible to compare the different combinations of stand paths and to identify the most desirable one. This concept is easy to understand. It also provides an excellent basis for incorporating knowledge from various scientific disciplines. The goal is to maximize or minimize an objective function $\mathbf{Z} = \mathbf{c}'\mathbf{x}$, subject to constraints of the form $V\mathbf{x} = \mathbf{b}$, where $\mathbf{x}$ is a vector of stand areas following a particular development path, $\mathbf{c}$ is a vector of utilities associated with the paths, V is a coefficient matrix and $\mathbf{b}$ is a vector of constants representing available inputs or required outputs. The structure is sufficiently general to allow a great variety of specifications, including particular spatial objectives for specific time periods. This is an active field of research pursued by a number of scientists. A useful overview of forest-level management planning in North America during the period 1950-2001 is provided by Bettinger and Chung (2004). Many methodological details have been published[5].

Two successful examples of systems that have been used for many years to generate an optimum design of a forested landscape are MAX-MILLION (Clutter, 1968; Ware and Clutter, 1971) and MELA (Kilkki and Siitonen, 1976; Siitonen et al., 1996; Nuutinen, 2000). The JLP algorithm in MELA (Lappi, 1992) uses the generalized upper bound technique, which makes it possible to deal with very large forest areas of up to 50000 stands. MELA has become an important forest planning tool in Finland. It is used by forest companies as well as small forest owners (Redsven et al., 2004). MONSU is another spatially explicit planning system, which is based on Multiple Path theory (Pukkala, 2008). MONSU has been adapted to a variety of design situations in different countries. Specific growth and hazard models are introduced for a particular case study, but the general concept remains to be valid.

3 Research and Demonstration

Credible forest management is based on empirical research. The aim of the early field experiments, which were established during the 19th century, was to mea-

[4] Examples of studies in connection with harvest event models were presented by Zucchini and Gadow (1995); Füldner et al. (1996); Hui (1997); Daume et al. (1998); Gadow and Hui (1998); Staupendahl (1998); Albert (1999); Hessenmöller (2002); Albert (2002).

[5] See for example Kilkki and Siitonen (1976); García (1991); Gadow and Bredenkamp (1992); Lappi (1992); Bettinger et al. (1997); Öhman and Eriksson (1999); Chen and Gadow (2002); Bettinger and Kim (2008); Pukkala (2008).

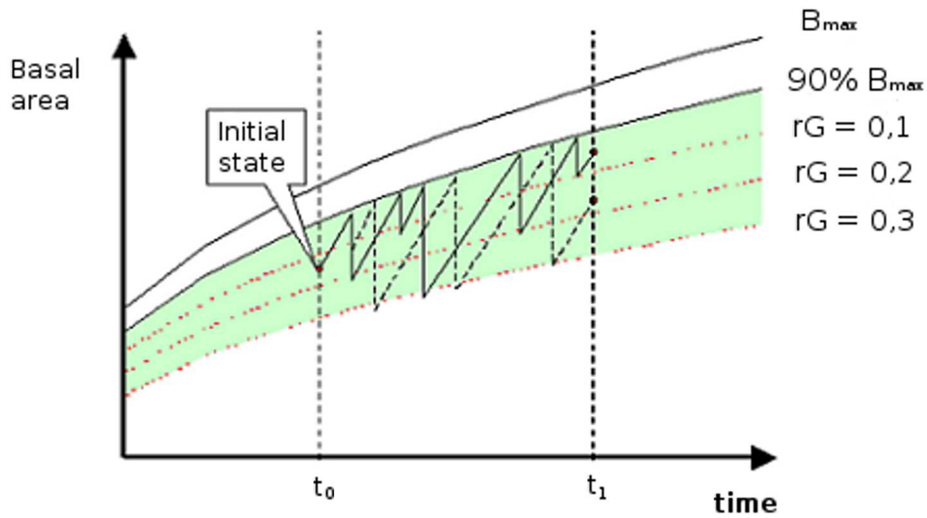

Figure 2: The management space (the shaded area) is defined by the maximum allowed density (e.g. 90% of $B_{\max}$), the thinning weight (rG = proportion of basal area removed) and the length of the time window (t0 , t1).

sure timber yields on different growing sites in response to specific thinning treatments. Some of these experiments have been re-measured for over a century, providing valuable information on long-term developments (Fig. 3). The information to be gathered in forest experiments has to be weighed against the estimated cost of collecting it. Available resources are limited and time is also a major constraint.

The validity and effectiveness of an experiment is influenced by its design and execution. Thus, attention to the planning of field experiments is important. The ultimate objective of forest research is to generate information that is useful for management. An objective of forest management, on the other hand, is to utilize research information that is useful. These two objectives are not always easy to match in an increasingly fragmented scientific environment that rewards highly specialized investigation. A possible solution may be found in the establishment of a system of observational field trials, so-called Research and Demonstration Areas. As the name implies, the purpose of a research and demonstration area is to gather empirical observations about the resource and at the same time to present the information to an interested audience.

According to Nöllenheidt (2000) a Research and Demonstration Plot represents the core area (ranging in size between 0.1 and 1.0 ha) within a management demonstration stand. Roschak (1998) used a research and demonstration plot of 0.6 ha to provide detailed information about the species and size distributions, the spatial structure and the changes caused by a harvest event. Assessments are not limited to one discipline. Research and demonstration areas can be used to obtain comprehensive empirical data about forest development in response to specific treatments. Their size is often related to the operational areas required by forest management. Large plots are more common, for example, in North America; small areas may be more suitable in Europe where forestry is practiced on a smaller scale.

4 Harvest Event Analysis

A harvest operation modifies the spatial structure, the species composition and the value of the standing crop. Forest density is reduced with associated effects on the microclimate, the ground vegetation, the genetic structure and nutrient cycles. An analysis of a harvest event provides good opportunities for research and teaching by linking the disciplines. It is also useful for management by improving transparency and enhancing professional credibility. The modifications caused by a harvest event are abrupt and often drastic, and it has been observed that foresters, when given the same set of silvicultural instructions, are not always unanimous in their judgments when marking trees for removal (Zucchini and Gadow, 1995). This results in a great variation of possible outcomes. Harvest event analysis is a method designed to monitor management activity. However, the concept requires that forest assessments coincide with harvest events. A practical approach involves an assessment after the trees have been marked for removal and before they are removed (Fig. 4).

The appropriate timing ensures that the activities of resource assessment and management control can be effectively combined. Forest development is inherently un-

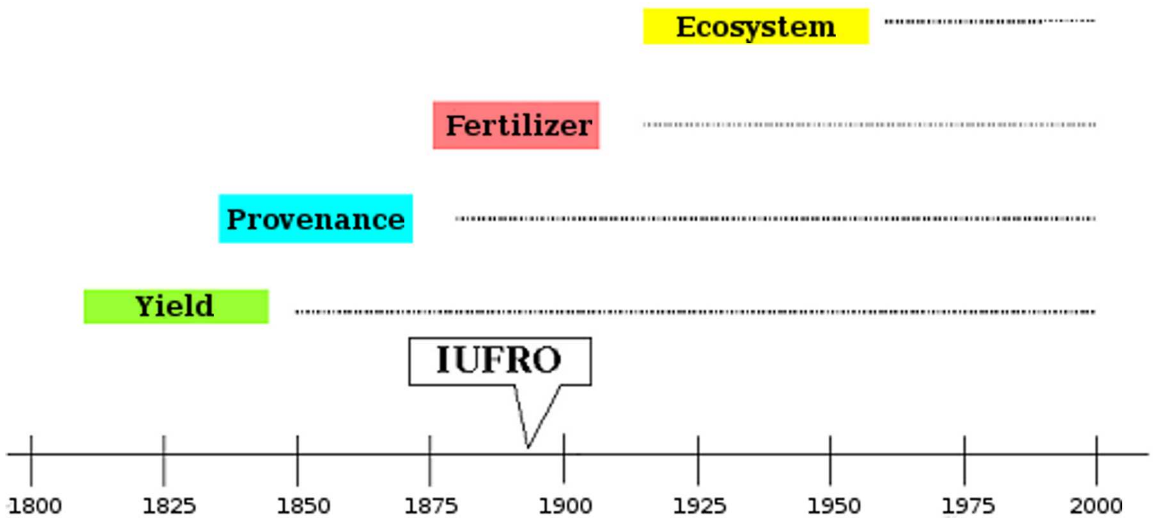

Figure 3: Approximate beginning of different types of field studies during the past 150 years (after Mårell and Leitgeb, 2004). The International Union of Forest Research Organisations (IUFRO) was established during the last decade of the 19th century, with the initial objective of improving the coordination of field experiments in Europe.

certain, and it is easier to put into practice the often-postulated Adaptive Management approach by implementing a harvest event analysis system.

The purpose of a harvest event analysis is to evaluate changes. A change from one state to another can be evaluated by measuring the differences between the two. This is not difficult, if only the diameter distributions are considered. To measure the proportion of distribution X, which has to be changed to make it identical to distribution Y, we only need to add up the absolute differences between the relative frequencies of distribution X and Y, and divide the sum by 2. However, measuring the difference between two species distributions is not such a trivial problem. Gregorius et al. (2003) proposed to use:

$$\Delta = \min \sum_{a,b} \hat{s}\,(a,b) \cdot d\,(a,b) \tag{2}$$

where $d(a,b)$ is a suitable measure of the differences between the attributes (e.g. tree species) a and b; $s(a,b)$ is an arbitrary shift-transformation of the relative frequencies of attribute a in the population X, such that the distribution X is equivalent to Y; $\hat{s}$ is the transformation weighted with the difference between a and b, which transforms the distribution X at minimum cost into the distribution Y, a typical transportation problem of linear programming. Consider an example with two stands, both featuring several tree species, which occur in different relative proportions. To make both stands identical in terms of their species distributions, we can try to obtain a measure of their distance. Unlike in the diameter distribution example mentioned above, it is possible to transfer species from stand i to stand j in several different ways. To obtain a unique solution, we need to apply an optimisation approach. The objective function, for example, could aim at minimizing the total distance between the two species distributions i and j:

$$min \rightarrow Z = \sum_{i}^{m} \sum_{j}^{n} distance_{ij} \cdot X_{ij} \tag{3}$$

subject to $\sum_{j}^{n} X_{ij} \leq available_i$ and $\sum_{i}^{m} X_{ij} \geq required_j$ where the X_{ij} are the relative species frequencies transferred from stand i to stand j. The main practical problem is to define the distances, i.e. appropriate measures of differences between the species. Quantifying trait differences between species is a specific problem in addressed by geneticists. The Swedish biologist Carl von Linné developed a taxonomy, in which the organisms are classified according to the attributes of their reproductive organs. His binomial classification expresses a degree of closeness, i.e. two trees that belong to the same family and genus are more closely related than two trees that merely belong to the same family. This classification is not complete, because improved methods of analysis show a much greater variety of life forms. The project "Tree of Life (ToL)" informs in more than 9000 websites about the history of evolution (Phylogenetics, see http://www.tolweb.org/tree/). This molecular systematics uses data from DNA sequencing and can be

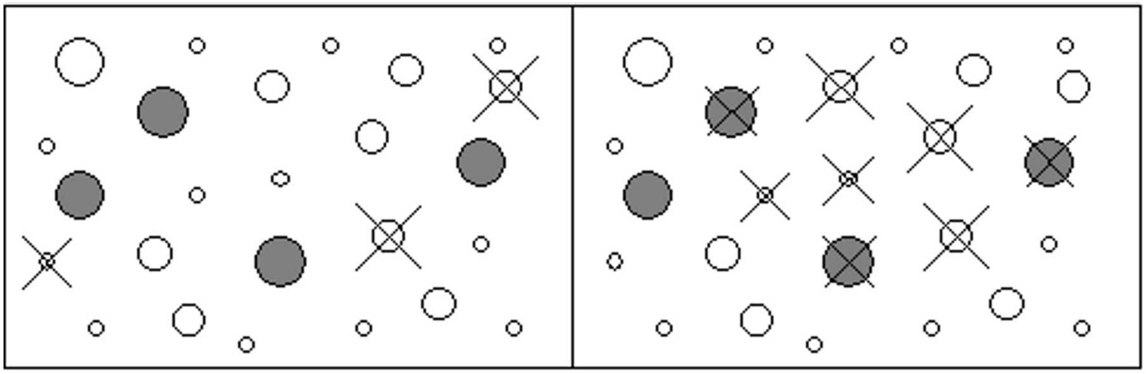

Figure 4: A harvest event may be evaluated in terms of a change in forest density, forest structure and forest value. The diagram shows a hypothetical forest section, which may be modified by a harvest event in two different ways; different shadings represent different tree species; crossed trees are those marked for harvesting.

used to measure distances between tree species. An interesting source is P.F. Stevens' website on the phylogenetics of the angiosperms (version 9 of June 2008). The study by Li et al. (2004) is an example of an analysis that specifically deals with forest trees. By quantifying the n(n-1)/2 distances between n tree species, and assuming that the natural species distribution can be defined, it would be possible to evaluate a harvest event in terms of its potential to transform a given forest to one that is more natural, in terms of the species distribution after the harvest.

Harvest event analysis is a concept that has already been successfully applied on a large scale in commercial timber plantations where economic success depends on the timing and intensity of harvest operations (Gadow and Bredenkamp, 1992). Harvest event analysis has also been practiced in a multi-disciplinary teaching module at the University of Göttingen in Germany. Many disciplines participate in this particular teaching module, which has been an important part of the curriculum for a number of years. Students mark the trees that will be harvested in a particular stand and then carry out detailed analyses of the effect of the removals on genetic structure and biodiversity, economics, radiation, soil compaction and nitrogen processes. This particular module not only facilitates, but also enforces and strengthens the much-needed disciplinary interchange. Thus, the application of harvest event analysis has shown that it can be used as a new and effective platform for involving the basic sciences directly in the evaluation of forest management.

5 Conclusions

Considering their environmental and social importance, it seems that the managed forest ecosystems are not receiving as much scientific attention as the few remaining unmanaged ones. This is especially true for the managed wooded areas within urban landscapes where forests represent a last remnant wilderness that is not only used commercially, but also for outdoor recreation and other important uses. Multiple uses on the same land (in contrast to spatial segregation of land use) is preferred in many densely populated societies that have a limited land base. These societies today demand integrated and wide-ranging approaches to forest management that address social, ecological, and economic goals (Gadow and Pukkala, 2008)[6] . In theory, to involve science directly in the management of wooded ecosystems appears to be logical, but the practical implementation of this idea is not a trivial task. A practical theoretical framework for the science-based management of a forested landscape includes three elements: forest design, research and demonstration and harvest event analysis.

An important task of the science of Forest Management is to recognize, describe and evaluate the great variety of possible forest developments. This means that all the potentially acceptable paths need to be generated for all the stands within a forested landscape. Compared with the main task of generating a set of feasible combinations of paths, the search for the optimum solution is a relatively easy problem. This problem can be solved using a variety of efficient search algorithms. The Finnish MELA system and Pukkala's MONSU system (Pukkala, 2008) are two examples of successful applications of the Multiple Path Theory.

A second important element of science-based forest management is the research and demonstration area. Research and demonstration areas may be used to gather

[6]Although many societies would prefer science-based landuse philosophies that integrate social, economic, and ecological concerns, not all do. For example, refer to Park (1990); Türker (2007).

empirical observations about a variety of changes resulting from forest management activities or natural processes. At the same time these areas can be used to demonstrate different types of silviculture in the field. The concept can be used to make accessible some of the wealth of information that is available within an increasingly specialized and fragmented scientific landscape.

The third element of science-based forest management involves an analysis of harvest events. A harvest operation modifies the spatial structure, the species composition and the value of the standing crop. Forest density is reduced with associated effects on the microclimate, the ground vegetation and nutrient cycles. The modifications caused by a harvest event are abrupt and sometimes drastic. Harvest event analysis is not only interesting for scientists, but also useful for management by improving transparency and enhancing professional credibility. Evidence of its practicability was demonstrated by the large-scale application of thinning control in South African plantations. An analysis of a harvest event provides good opportunities for research and teaching by linking the disciplines, and evidence of its usefulness is provided in the project-based teaching module, "Analyse eines Forstlichen Eingriffs" at Göttingen University in Germany.

The appropriate design of a forested landscape requires ongoing empirical research to improve growth and hazard predictions for different climate scenarios. Research is also needed to model future harvest events. Three processes have to be considered when generating a path for a given time window: the harvest events, the natural growth and unplanned hazard events. Each forest stand within a wooded landscape offers a multitude of silvicultural treatment options that need to be evaluated using the experience of the different scientific disciplines. The selection of a particular management path depends on the relative importance of the different objectives and on the forest-wide constraints. Simplistic philosophies and unverified doctrines are increasingly replaced by new paradigms that require a wider understanding of social demands and natural system dynamics. The allowable management space is not defined by idealistic silvicultural dogmas, but by the current potential of a particular stand. In this sense, the traditional scientific discipline known as forest management can make a substantial contribution to the sustainable use of forest resources. The Multiple Path theory of forest design is a logical extension of the traditional paradigms of age-class normality and longterm planning. Unlike ecosystem management, multiple path design has a clear structure: what to manage, where to manage, how to manage (Zeide, 2001). In many regions of the world, this theory may be readily implemented using effective tools that have been developed by forest scientists.

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