ARTICLES

Sustainable Forest Management: Theory and Applications

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Using a very simple classification based on the development of timber volume over age (or time) two types of sustainable forest management are distinguished: Rotation forest management (*RFM*) and continuous cover forestry (*CCF*). The paper describes various methods of harvest control for *RFM* and *CCF* systems and methods that apply to both. The theory of sustainable forest management provides models for orientation and harvest control. However, we find that a good theory implemented in a computer system is no guarantee for good management. Especially in *CCF* systems, it is often necessary to establish a system of management demonstration plots for illustrating silvicultural objectives in the field. The concepts and methods of sustainable forest management can theoretically be applied to any landscape, including agricultural and urban landscapes.

Key words: sustainable forest management, continuous cover forestry, rotation, harvest control

Introduction

According to the statistics issued by FAO (1997) and BMELF (1996) the world forest area amounts to about 3.4 billion ha. The biggest share of this area is situated in South America and within the borders of the former Soviet Union, with over 800 mill. ha in each region. Forest areas of well above 500 mill. ha are found in each of the three important forestry regions Asia, Northern and Central America and Africa.

We know more or less where the forests are, but very little is known about the geographical distribution of the types of forest management. Sustainable forest management was one of the central topics of the 21st IUFRO World Congress held in Kuala Lumpur, Malaysia. The Congress was attended by 2300 delegates from 91 countries. A total of 7 delegates came from the three Baltic states: 4 from Latvia, 2 from Lituania and 1 from Estonia.

Sustainable forest management was one of the important topics of the congress and the congress proceedings contain a number of contributions which show that many tropical countries are faced with a serious problem of land degradation. During the five-year period 1990 – 1995 South America lost 24, Africa 19 and Asia 17 mill. ha of forest land (FAO, 1997). The priorities of forest use differ, depending on percapita income and forest cover (Fig. 1).

per capita income	*high*	***Environmental Issues***	***Sustainable Development***
	low	***Subsistence Issues***	***Economic Development***
		low	*high*

Per capita forest cover

Figure 1. Priorities of forest use, depending on per capita income and forest cover (Emborg and Larsen, 1999).

Major factors causing deforestation in many parts of the world are an exceptionally high rate of timber removals, grazing and shifting cultivation and conversion of natural forests into rubber, oil palm cacao or sugar cane plantations (Dada, 2000; Nik and Varques Bigcas, 2000; Abdul and Appanah, 2000). The economic gains from logging are heavily offset by long-term environmental damages and costs to society. Agroforestry and silvipastoral systems and woodlots with annual crop interplanting (Taungya) are very common in tropical regions, especially in Central America (De Camino, 2000; Beer et al., 2000).

One of the milestones of economic theory is the *tragedy of the commons*. Hardin (1968) argues that a common resource is condemned to disappear when there is free access and Bousquet et al. (2000) could verify typical patterns of forest depletion which support this theory. The problem can be solved by privatization or by controlling access to the resource, using regulatory or incentive mechanisms. Isolated forest remnants play a critical role in conserving biodiversity within the agricultural landscape (Harvey et al., 2000). The question is: how long can these remnants and isolated trees survive. Are agroforestry systems that depend on high forest trees really sustainable? New software such as the multiagent simulation software *MAS* (Bousquet et al., 2000) and the *FLORES* system (Vanclay et al., 2000) is being developed to explore the consequences of alternative landuse scenarios.

Sustainable Forest Management Systems

Today, we will be concerned with sustainable systems of forest management which is practiced only in a very small proportion of the world's forests. Using a very simple classification based on the development of timber volume over age or time we may distinguish two types of sustainable forest management system. Rotation forest management (*RFM*) systems with standard silvicultural treatments and continuous cover forestry (*CCF*) systems with selective harvesting (Fig. 2). The distinction is usually the result of decisions relating to the cost of timber harvesting, simplicity of management, or intangible benefits, such as ecosystem stability.

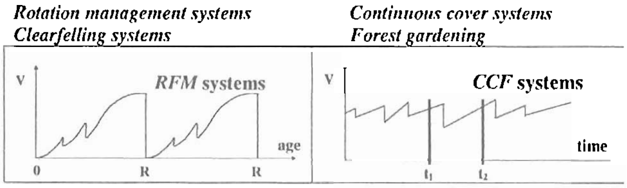


Figure 2. Sustainable systems of forest management

RFM type systems with fast-growing timber species and intensive silviculture are found in the Southern hemisphere (Chile, South Africa, Australia, New Zealand), in the South-Eastern United States, in many parts of Asia and in the Mediterranean Region. Low intensity *RFM* systems are usually found in regions controlled by timber processing companies requiring regular raw material supplies. Large timber reservoirs are found in the coniferous forests of the boreal region.

CCF systems are characterized by selective removals and are found in densely populated regions and in some tropical forests. Examples of this type are the so-called *plenter* forests found in France, Switzerland, Slowenia and Germany, forests in the *Northern Hardwood* region of North America and the *Knysna forests* of South Africa.

Theoretical aspects of Sustainable Forest Management

The theory of sustainable forest management provides models for orientation and harvest control. The Normal Forest Model, proposed by Hundeshagen in 1826, is defined by a yield table and a rotation. The model is used to calculate a sustainable harvest volume, based on the mean annual increment and the ratio of current to normal growing stock.

The effect of the rotation on the normal growing stock volume and the annual sustainable harvest may be illustrated using an example from the Southern United States (Clutter et al., 1983). A pulpmill needs 400 000 cunits (about 1.5 million m³) roundwood per year from pine plantations in Southern Georgia, USA (Tab. 1).

How many acres of forest land are required to secure a continuous harvest of the required timber volume? The most essential tool for addressing this problem is a yield model, such as the one shown in the second column of Tab. 1 (one *cunit per acre* is approximately equivalent to 7.2 m³ per ha). The annual cutting area, the required total area, the growing stock volume, the relative harvest rate and the mean annual increment are shown for different rotations.

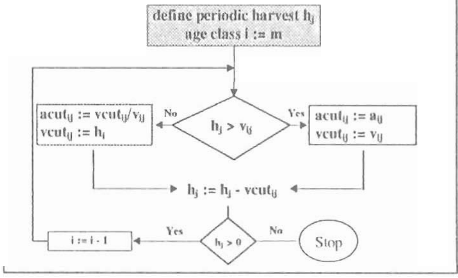
Table 1. Example of an application of the Normal Forest Model in the Southern United States.

rotation (years)	growing stock (cunits/ acre)	harvest area (acres/year)	total forest area (acres)	total growing stock (cunits)	annual harvest (proportion of growing stock)	MAI, (cunits/ac. /year)
(1)	(2)	(3) = 400 000/(2)	(4) = (1)•(3)	(5) = (2)/2•(4)	(6) =(2)•(3)/(5)	(7) = (2)/(1)
6	4.80	83 333.3	500 000.0	1200000	0.33	0.80
8	16.64	24 038.1	192 304.5	1600000	0.25	2.08
10	29.10	13 745.7	137 457.0	2000000	0.20	2.91
12	40.80	9 803.9	117 647.1	2400000	0.17	3.40
14	52.22	7 660.0	107 239.8	2800000	0.14	3.73
16	61.60	6 493.5	103 896.1	3200000	0.12	3.85
18	70.20	5 698.0	102 564.1	3600000	0.11	3.90
20	77.60	5 154.6	103 092.8	4000000	0.10	3.88
22	84.26	4 747.2	104 439.0	4400000	0.09	3.83
24	90.24	4 432.6	106 382.7	4800000	0.08	3.76
26	94.90	4 215.0	109 589.0	5200000	0.08	3.65
28	98.56	4 060.2	113 636.4	5600000	0.07	3.52
30	100.80	3 968.3	119 047.6	6000000	0.07	3.36

The growing stock which is available for the final harvest increases with increasing rotation age, which affects the annual sustainable cutting area, the required total area, the total growing stock volume, the relative sustainable harvest rate and the mean annual increment. The MAI reaches a maximum at the age of 18 years. This age represents the minimum-landbaserotation, i.e. the rotation where the area required for supplying 400 000 cunits per year is at a minimum (which is not necessarily the most economical one). The model of the normal forest is a standard which can be used for comparisons of current and normal growing stock volumes. Its value as a scenario model is rather limited.

Age class simulation

Quite useful, though equally simple, are methods based on age class simulations. In the simplest simulation approach, 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 i'th age class is equal to v_{ij}, and the planned total harvest volume for the jth felling period is h_j (Fig. 3).



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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 $h_i \geq v_{ij}$, then harvest the entire growing stock available in age class i;
       else harvest only $h_j$ $m^3$;
    c) subtract the volume harvested from $h_j$
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Figure 3. Algorithm for age-class simulation with flowchart and pseudocode. 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).

The technique, which is easily implemented as a spreadsheet program, has been demonstrated for various forest types, including fast-growing timber plantations and *Pinus silvestris* forests in Russia, based on Shvidenko's et al. (1995) yield model (cf. Gadow and Puumalainen, 2000).

As an example consider a *Eucalyptus grandis* Plantation of 1000 ha. The planned harvest volume is 15000 m^3/year. Starting with the oldest areas, age class 6 is totally cut, yielding 9570 m^3. The remaining 5430 m^3 is taken from age class 5, requiring a cutting area of 71.7 ha. The cut area, covering 171.7 ha is regenerated and the process repeated in the next cutting period (Tab. 2).

Table 2. Simplified example showing one iteration of a *Eucalyptus grandis* Plantation of 1000 ha.

Age	**1**	**2**	**3**	**4**	**5**	**6**	Total
m^3/ha	**0.0**	**16.0**	**35.4**	**55.5**	**75.7**	**95.7**	
ha before	200.0	200.0	150.0	150.0	200.0	100.0	1000.0
ha cut					71.7	100.0	171.7
m^3 cut					5430	9570	15 000
ha before	171.7	200.0	200.0	150.0	150.0	128.3	1000.0

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.

Area Change Models

Area change models predict transitions of forest states through time. They project the historical harvesting practice and have been used for timber supply projections in Japan (Konohira and Amano, 1986) and in Europe (Kurth and Dittrich, 1987; Kouba, 1989; Kolenka et al., 1996). One of the most famous applications is Suzuki's (1971) *Gentan* model.

We may define $p_i(n)$ as the probability that a randomly selected forest area is in state *i* at time *n* and t_{ji} as the conditional probability that state i moves to state j within a given time step, i.e. as the conditional probability that j will be reached provided the system is currently in i. Let $t_{j,1}$ be the probability that a forest stand which belongs to the j'th age class is harvested and thus moves to age class 1. Then $t_{j,j+1}$ is the conditional probability that a stand which belongs to the j'th age class survives and grows into the (j+1)'th age class. Normally, $t_{j,1} + t_{j,j+1} = 1$ and the general matrix of transition probabilities may thus be written as in the table.

The area change approach may have some potential as a scenario modelling tool, e.g. for forecasting the development of age structures on a regional and national scale. However, some work needs to be done to predict the transition probabilities more accurately (Blandon, 1985; Randall and Gadow, 1990). The transition probabilities are not independent of the current age class distribution and this is one of the main problems associated with their use.

Continuous cover forests

The large-scale application of new silvicultural systems has become a political reality in Europe. This involves a gradual transformation of traditional silvicultural practice towards *Continuous Cover Forestry*, also known as *forest gardening systems*, favouring mixed uneven-aged stands, site-adapted tree species and selective harvesting (Griesel and Gadow, 1995).

Selective harvesting systems have a long tradition, but the methods of calculating sustainable harvest levels have been practiced only in a few tropical forests (Laughton, 1937; Breitenbach, 1974; Seydack et al., 1995), in some Northern hardwood forests in the USA (Hansen, 1987) and in the European *Plenter* forests (Biolley, 1980; Schütz, 1994).

In a forest managed under the selection system, the stand age is undefined. Forest development does not follow a cyclic harvest-and-regeneration pattern. Instead, it *oscillates* around some ideal level of growing stock. The mean annual increment is not appropriate for measuring productivity and the *Normal Forest* concept and the traditional sustainability criteria are not applicable.

Various techniques have been devised for ensuring sustainable harvests in forest gardening systems. The most common type involves recurring visits to a given compartment and to simply skim off the accumulated increment at each visit. The principle resembles the normal forest and the aim is to ensure that timber can be harvested each year. First, we have to define the number of years between harvests in a particular compartment, ***r***. To ensure sustainable yields, the forest is then subdivided into land parcels each covering one r'th of the total area. Each land parcel represents a state which is characterized by the number of years that have passed since the last harvest (Fig. 4).

Fig. 4. Schematic illustration of the mapping of the progression of harvest locations using a recurrence cycle of 5 years

Assuming, for example, a recurrence cycle of 5 years, we can map the progression of harvest locations, as shown in Fig. 3 where in harvest period I, a harvest is due in the darkly shaded land parcel where the last visit occurred 5 years ago. The state-space distribution changes after each time step as a result of the harvest of the oldest parcel and the accumulation of harvestable timber in the other land parcels. In harvest period II the state-space distribution has changed and parcel 4 is up for harvest, and so on.

Target Diameter-distributions

The main problem in a continuous cover forest is to determine which trees are to be removed and which are to remain. The decision may concern tree size or a combination of tree size, species and timber quality. The aim of the traditional *Plenterwald* harvesting systems practiced in Switzerland, France, Italy, Slowenia and Germany, is to define an optimum forest structure by using an inverse J-shaped diameter distribution model (Fig. 5). The target distribution is re-established by periodic removal of trees in the different diameter classes.

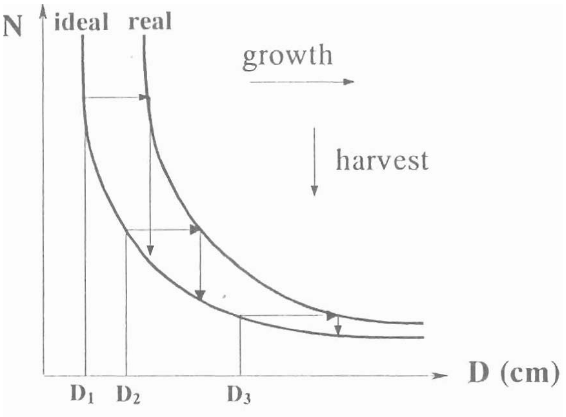

Figure 5. Optimum forest structure defined by an inverse J-shaped diameter distribution model.

In theory, the approach is very simple and logical. By comparing the real and the ideal diameter distributions, it is possible to determine the number of stems that should be harvested in each diameter class. In mixed fir, spruce and beech forests of the Trentino region of the Italian Alps trees are harvested with reference to the model defined by Susmel (1980; see also Virgilietti and Buorgiorno, 1997). Meyer (1933) proposed the function $ln(N) = \alpha - \beta \cdot D$ for specifying the ideal diameter distribution. In a *Femel* forest which is characterized by group harvesting and gap regeneration Meyer's β parameter assumes values ranging from 0.08 to 0.15, depending on the maximum diameter of harvestable trees. In a *Plenter* forest the β-values are usually much lower, ranging between 0.05 and 0.07.

Unfortunately, there is no generally accepted ideal distribution of tree sizes, but a rather wide range of distributions found in stable *Plenter* and *Femel* forests (cf. Mitscherlich, 1952). The Plenter guide curves are thus of limited use.

Basal Area Normalities

So-called *basal area normalities* are applied in some CCF systems. The first step involves a classification of different tree species and size classes on the basis of their current and future potential, e.g. I = mature trees of commercially valuable species; II = immature trees of commercially valuable species which will eventually reach class I; III = other non-commercial tree species; IV = undesirable exotic intruders. A normal basal area distribution will then be defined for each forest type and tree class. Fig. 6 shows basal area normalities for a medium-moist forest in the Knysna region of South Africa.

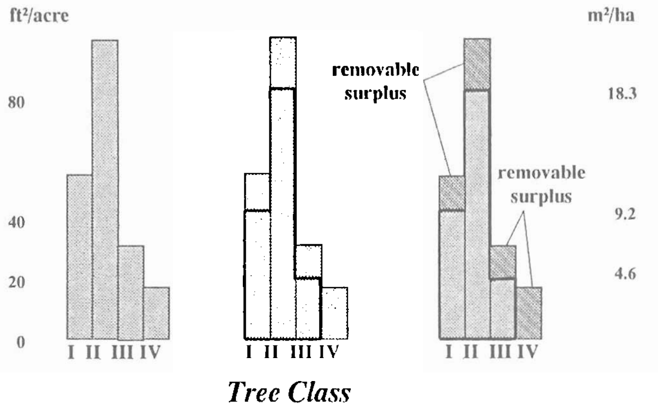

Figure 6. Optimum forest structure defined by a basal area distribution model. Left: basal area distribution over tree classes before the harvest, with normal basal area distribution superimposed (centre) and removable surplus (right)

The theory of sustainable forest management provides models for orientation and harvest control. There is a range of well-established techniques applicable to either rotation management forests or continuous cover forests. However, there are also techniques that can be used in any system of management.

The Model I Concept

An example of a theoretical framework that can be used in any system of management is the model I concept. For each land parcel i (i=1..I) with area A_i a range of treatment schedules or development paths are defined. Each treatment schedule j ($j=1..J_i$) is assigned a utility u_{ij} per unit area. Furthermore, the total sustainable periodic harvest M_t is determined for the entire management unit and the per hectare product yields v_{ijpt} are specified.

The space-time pattern of land use (i.e. the solution values of the X_{ij}) which maximizes the total utility of all the treatment schedules and also satisfies the periodic harvest constraints is then determined (Fig 7).

The Model I is a theoretical concept that can be applied in a great variety of forest management situations. It provides the methodical framework for evaluating a variety of *scenarios* of forest development. Each scenario represents a specific combination of development paths of individual land parcels. Each land parcel is spatially defined. The movement of a forested landscape through time can thus be shown as a series of maps depicting the effects of the periodic treatments in the different land parcels.

Objective function	$\sum_{i=1}^{I} \sum_{j=1}^{J_i} u_{ij} X_{ij} \rightarrow max.$	
Constraints	$\sum_{i=1}^{I} \sum_{j=1}^{J_i} v_{ijpt} X_{ij} = M_{pt}$	$\forall t, p$
	$\sum_{j=1}^{J_i} X_{ij} = A_i$	$\forall i$
	$X_{ij} \ge 0.$	

Figure 7. The Model I is a theoretical concept that can be applied in a great variety of forest management situations. Each land parcel is spatially defined and the movement of a forested landscape through time can thus be shown as a series of maps depicting the effects of the periodic treatments in the different land parcels, as shown on the right.

Management Demonstration Plots

The theory of sustainable forest management provides models for orientation and harvest control and there is a range of well-established techniques applicable to either rotation management forests or continuous cover forests. However, we find that a good theory implemented in a computer system is no guarantee for good management. It is often necessary to establish a system of management plots for illustrating silvicultural objectives in the field (Fig. 8).

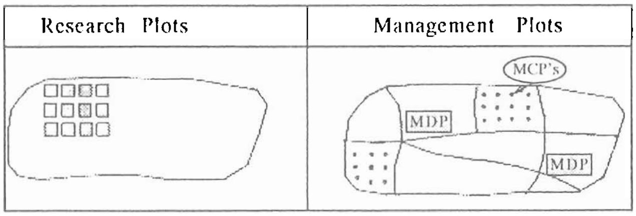

Figure 8. Schematic illustration of research plots (for evaluating treatments) and management plots (MDP's - management demonstration plots and MCP's management control plots).

Research plots are used to evaluate different treatments. We distinguish two types of management plots: Permanently marked management demonstration plots are used to demonstrate desirable management practices and to gather data for growth models. Event analysis with temporary management control plots are used to monitor silvicultural activity.

Urban Forestry Project

The concepts and methods of sustainable forest management can theoretically be applied to any landscape, including agricultural and urban landscapes.

Forests, Parks and trees are highly valued resources in urban areas.

For this reason, a number of related project proposals are presently being prepared. The common project title is *Evolution of Forested Landscapes in Urban Areas.* Evolution of Forested Landscapes embraces a multitude of modifications of biochemical-physical state variables and biological processes resulting from natural tree growth or the removal or planting of trees. Tree-related planning and decision-making needs to be communicated to interested and informed citizens, using information from a variety of disciplines. Effective communication and mediation is a prerequisite for successful urban development. One of the focal points of the project is an approach known as *tree event analysis*. Each tree removal or tree planting in a municipal forest, a park, along a street or in a garden represents a *tree event*. The analysis of a tree event calls for a concerted approach with contributions from the various disciplines, including the social sciences, the natural sciences and the engineering and information sciences.

Conclusions

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. To ensure that forest management scenarios are realistic, greater emphasis needs to be placed on models that predict and evaluate potential hazards.

There is a wealth of harvest control techniques for calculating sustainable harvest levels, but a shortage of methods for evaluating sustainability under risk. 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, based on previous observations. Kouba (1989), for example, used the Weibull function for modelling spruce forest survival, assuming a variety of hazards and their cumulative effect.

Over the past 200 years forest scientists have developed a rich assortment of methods for sustainable forest management. Some of the concepts are applicable in urban forestry and landscape management. The theory of sustainable forest management provides a range of useful models for orientation and control. These models can be usefully employed in the management of important biological resources in many parts of the world.

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